Cognitive Handoff and Mobility for the Future Internet: Modeling and Methodology.

By

Francisco Alejandro González-Horta
M.Sc., ITESM

Thesis submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF SCIENCE IN ELECTRONICS

at the

National Institute for Astrophysics, Optics, and Electronics
May 2012
Tonantzintla, Puebla, México

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Keywords: Cognitive Handoff, Multipurpose Mobility, Future Internet, Handoff Modeling, Handoff Methodology, Handoff Scenarios, Handoff Optimization

Dedication

"Science means to decode the logic of He who has created the world."
Galileo Divine Man. A. Zichichi, 2009.

Dedicated to

God, Ram, and Amira

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Abstract

Current handoffs are not designed to achieve multiple desirable features simultaneously. This weakness has resulted in handoffs that are seamless but not adaptive, or adaptive but not secure, or secure but not autonomous, or autonomous but not correct, etc. To face this limitation, we propose a new kind of multipurpose handoff that simultaneously is seamless, autonomous, secure, correct, and adaptive, where each desirable handoff feature can be associated to one specific purpose. A *cognitive handoff* is a multipurpose handoff that trades-off different objectives to reach its intended goals, makes decisions considering information from the entire handoff environment, and exhibits good performance in any handoff scenario.

The main purpose of this dissertation is to create a model-based framework intended to understand, develop, and evaluate cognitive handoffs. Using a holistic approach, we produce a new taxonomy of handoff scenarios, organize handoff variables into context domains, and make structured definitions of many desirable features. Then, using foundations on problem-solving, functional decomposition, and model-based design, we develop a methodology for systematically building cognitive handoffs. Applying such methodology, we generate a cognitive handoff functional architecture and strategies for evaluating the performance of multi-objective handoffs. Finally, changing to a reductionist approach, we execute particular models that integrate the functional architecture. As a proof of concept, we take the handoff control state-based model and develop a case study about a particular type of multi-objective handoff named *correct handoff*. We craft a virtual instrument that measures the performance of the correct handoff algorithm. A statistic analysis and probability models provide experimental evidences that support the worthiness of multi-objective handoffs.

Abstract in Spanish

Las transiciones actuales no están diseñadas para desarrollar múltiples características deseables simultáneamente. Esta debilidad ha resultado en transiciones que son transparentes pero no adaptables, o adaptables pero no seguras, o seguras pero no autónomas, o autónomas pero no correctas, etc. Para enfrentar esta limitación, proponemos una nueva clase de transición multipropósito que simultáneamente sea transparente, autónoma, segura, correcta y adaptiva, considerando que podemos asociar un propósito específico a cada característica deseable. Una transición multipropósito que balancea diferentes objetivos para alcanzar sus metas, toma decisiones usando información del entorno completo y tiene un buen desempeño en cualquier escenario es llamada *transición cognitiva*.

El propósito principal de esta tesis es crear un marco de trabajo basado en modelos dirigidos a comprender, desarrollar y evaluar transiciones cognitivas. Usando un enfoque holístico, producimos una nueva taxonomía de escenarios, organizamos las variables de transición en dominios de contexto y definimos de forma estructurada varias características deseables. Después, usando la teoría de solución de problemas, descomposición funcional y diseño basado en modelos, creamos una metodología para construir transiciones cognitivas. Aplicando esta metodología, generamos una arquitectura funcional y estrategias para evaluar transiciones multiobjetivo. Como prueba de concepto, tomamos el modelo basado en estados del control de la transición y desarrollamos un caso de estudio sobre un tipo particular de transición multiobjetivo llamada *transición correcta*. Construimos un instrumento virtual que mide el desempeño del algoritmo de transición correcta. Un análisis estadístico y probabilístico sobre los datos producidos proveen evidencias experimentales que soportan la factibilidad de las transiciones multiobjetivo.

Preface

A handoff or handover is an essential service for supporting the mobility and quality of communications of any wireless network, both from the early, the existing, and the future network technologies. Although the traditional handoff concept is widespread related to the idea of seamlessly transferring the flow of voice communications from one base station to another during a cellular call, the modern concept of handoff is much more complex and generalized than that.

In today scenarios, communications combine a variety of multimedia traffic, which is transported over different types of networks, which are managed by diverse service providers, who subscribe many classes of users, who are connected through a plethora of multimode terminals. Therefore, current handoffs involve the seamless switching of packet flows among different kinds of networks, providers, terminals, or their combinations. Such diversity of elements involved during a transition clearly complicates the handoff process. Many vertical or heterogeneous handoff schemes have been deployed in the last few years, but they still are focusing only in one goal, the preservation of user communications during transitions or seamless handoffs.

Although seamlessness is the main desirable feature of a handoff, certainly it is not the only one. Current and future handoff scenarios are extensive, heterogeneous, and dynamic; therefore, the handoff process should also be able to adapt to any handoff scenario. A handoff should also be secure, or at least, able to avoid new threats from appearing during the transition. A handoff should also be autonomous, that is, promoting the fewer amounts of human interventions. A handoff should also be correct, in the sense that it should provide the greater benefits at the lower costs. In conclusion, current and future handoffs are trending to be multipurpose, that is, to achieve multiple desirable features of handoff simultaneously.

A multipurpose handoff that simultaneously is seamless, autonomous, secure, correct, adaptive, and uses context information from both the external and internal handoff environment to make decisions, and exhibits a "good" performance at any random handoff scenario is named a cognitive handoff. We argue that cognitive handoffs are needed to face the challenges of the future wireless networks; thus, we shall discuss the evolution from single-purpose handoffs in the first generation networks to cognitive handoffs in the next generation networks.

The focus of this research work is on building models for understanding the functionality and complexity of the *cognitive handoff problem*. Some of these models will be computer models for simulating and validating the behavior of multi-purpose handoff solutions. We also pay special interest in defining a new model-driven methodology for designing and developing cognitive handoff solutions systematically. As a proof of concept, we developed a particular type of multi-purpose handoff algorithm and validated its behavior by a simulation model driven through a *virtual instrument.* This instrument allows testing the performance of our algorithm over a variety of simulated handoff scenarios. However, the validation tests using experimental test beds or real production networks are out of the scope of this research work.

This thesis contributes to the evolution of networking technology by making cognitive mobility more understandable and by helping to make it valuable for the mobility and communications experience of the average user. This thesis is embedded in a paradigm shift from the traditional concept of single-purpose mobility schemes, like *Seamless Mobility*, towards a new and more general multi-purpose mobility concept named *Cognitive Mobility*. While seamless mobility is mainly intended to preserve the *service continuity* of users roaming across access networks, cognitive mobility is aimed to preserve, maximize or minimize multiple purposes simultaneously. For instance, cognitive mobility might be addressed to keep the user always connected to the best available network, minimizing the number of handoffs, the number, duration and intensity of service disruptions, the rate of user interventions, and the number of vulnerabilities during the handoff process, but maximizing the amount of mobility scenarios where the cognitive handoff process is adapted successfully.

In summary, this doctoral dissertation presents a new model-based framework for understanding, developing, and evaluating cognitive handoffs. We consider that cognitive handoffs will be used in the future wireless networks to improve the efficiency of mobility management architectures. The proposed framework includes a cognitive handoff algorithm based on Pareto's heuristic multi-objective optimization. The algorithm has been evaluated through large populations of random handoff scenarios using proof-of-concept simulations with probability success rates above 90%.

We invite the dedicated reader and researcher to use this work as a foundation for further research and knowledge expansion of this fascinating field. You may contact the author of this manuscript, the thesis advisor, or others collaborators of the research papers associated to this dissertation, through their respective email addresses defined in the publications.

Contents

Publications

As a result of this research work, four original research papers were produced, of which three are published in refereed international conferences and one in international journal. The first paper in the following list received the conference Best Paper Award by the International Academy, Research, and Industry Association (IARIA) in Lisbon, Portugal, in November 26, 2010.

Paper 1. González-Horta F.A., R.A. Enríquez-Caldera, J.M. Ramírez-Cortés, J. Martínez-Carballido, and E. Buenfil-Alpuche; "Towards a Cognitive Handoff for the Future Internet: Model-driven Methodology and Taxonomy of Scenarios," The Second International Conference on Advanced Cognitive Technologies and Applications (COGNITIVE 2010), ISBN: 978-1-61208-108-3, IARIA, pp. 11-19, Lisbon, Portugal, Nov. 21-26, 2010. **(Best Paper Award)**

Paper 2. González-Horta F.A., R.A. Enríquez-Caldera, J.M. Ramírez-Cortés, J. Martínez-Carballido, and E. Buenfil-Alpuche; "Towards a Cognitive Handoff for the Future Internet: A Holistic Vision," The Second International Conference on Advanced Cognitive Technologies and Applications (COGNITIVE 2010), ISBN: 978-1-61208-108-3, IARIA, pp. 44-51, Lisbon, Portugal, Nov. 21-26, 2010.

Paper 3. González-Horta F.A., R.A. Enríquez-Caldera, J.M. Ramírez-Cortés, J. Martínez-Carballido, and E. Buenfil-Alpuche; "Mathematical Model for the Optimal Utilization Percentile in M/M/1 Systems: A Contribution about Knees in Performance Curves," The Third International Conference on Adaptive and Self-Adaptive Systems and Applications (ADAPTIVE 2011), ISBN: 978-1-61208-156-4, IARIA, pp. 85-91, Rome, Italy, Sept. 25-30, 2011.

Paper 4. González-Horta F.A., R.A. Enríquez-Caldera, J.M. Ramírez-Cortés, J. Martínez-Carballido, and E. Buenfil-Alpuche; "A Cognitive Handoff: Holistic Vision, Reference Framework, Model-Driven Methodology and Taxonomy of Scenarios," International Journal on Advances in Networks and Services, ISSN: 1942-2644, vol. 4, no. 3&4, year 2011, pp. 324-342, Apr. 30, 2012.

The following Internet links stand for the IARIA conferences and IARIA journals where these papers were presented and published. The papers are archived in the free access ThinkMind™ Digital Library where papers can be downloaded.

- http://www.iaria.org/conferences2010/COGNITIVE10.html
- http://www.iaria.org/conferences2011/ADAPTIVE11.html
- http://www.iariajournals.org/networks_and_services/
- http://www.thinkmind.org/
- http://www.thinkmind.org/index.php?view=article&articleid=cognitive_2010_1_30_30066
- http://www.thinkmind.org/index.php?view=article&articleid=cognitive_2010_2_30_30070
- http://www.thinkmind.org/index.php?view=article&articleid=adaptive_2011_4_40_50070
- http://www.thinkmind.org/index.php?view=article&articleid=netser_v4_n34_2011_7

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Chapter 1

Introduction

This chapter introduces the concept of cognitive handoff, provides a literature review, and explores the tendency towards the concept of cognitive handoff. Also this chapter points out this work significant contributions and objectives. Finally, the chapter presents the thesis outline.

1.1 Motivation and Problem Statement

The current concept of *handoff* is that of a process intended to preserve the user communications while moving to different networks, providers, and terminals. The main desirable feature of handoffs is *seamlessness*, whose purpose is to maintain the continuity of services before, during, and after the handoff, without disturbing the user. A handoff that achieves this fundamental purpose is called *seamless handoff*. The relation between "seamlessness" and "service continuity" describes a one-to-one correspondence between desirable features and purposes; thus, a seamless handoff is a *single-purpose* handoff.

Despite the relevance of seamlessness as the main desired feature of handoffs, the vast literature on the topic has revealed many types of single-purpose handoffs or handoffs that exhibit a single attractive feature at a time; for instance, seamless [1], adaptive [2], autonomous [3], secure [4], correct [5], transparent [6], reliable [7], flexible [8], robust [9], balanced [10], immune [7], fast [11], soft [12], smooth [13], lossless [14], efficient [15], proactive [16], predictive, reactive [17], and many more. Current literature shows that handoffs are not designed to optimally achieve multiple desirable features simultaneously; i.e., they may successfully achieve one attractive feature but ignore others. For instance, there are seamless handoffs with poor or null adaptation to other scenarios or technologies [18], or adaptive handoffs that do not consider any security goal [2], or secure handoffs that ignore the user autonomy [4], etc.

The variety of single-purpose handoffs is not enough to face the challenges of the future Internet as long as they operate separately. The rationale for this claim is as follows: a seamless handoff provides service continuity, but it is worthless if it works only for the specific scenario to which it was designed; therefore, a handoff should also be adaptive to any possible scenario. Now, a seamless-adaptive handoff is useless if it demands frequent user interventions; consequently, the handoff should also be autonomous. Even so, a seamless-adaptive-autonomous handoff is fruitless if new security risks appear during the handoff; thus, the handoff should also be secure. Moreover, a seamless-adaptive-autonomous-secure handoff is still unproductive if it does not perform correctly (i.e., if it does not maximize the connection time to the best available network and minimize the handoff rate). This rationale will eventually lead to a valuable *multi-purpose handoff*, that is, a seamless-adaptive-autonomous-secure-correct handoff. Therefore, a *cognitive handoff* is a multi-purpose handoff that achieves many desirable features simultaneously.

Although several desired features have been described in the literature, many of them are not clearly defined and are not properly evaluated. This has brought a growing confusion or misuse of similar terms, e.g., seamless → transparent → smooth → soft → efficient → fast → timely → reliable → robust → etc. Besides, there is a lack of performance metrics for measuring how well each desired feature performs along the handoff process. Therefore, it is necessary to define corresponding metrics to quantify seamlessness, adaptability, autonomy, security, correctness, or any other relevant handoff feature; and at the same time, to define how to measure the global success of a multi-purpose handoff. Moreover, there is no currently any systemic methodology that indicates how to merge several desired features into a single handoff process. Finally, a clear relationship between desired features and handoff context data is also missing. In summary, the following important issues in handoff literature remain unsolved. (1) How to develop a single handoff process that can achieve many purposes simultaneously? (2) What relevant handoff features are needed to face the challenges of the future mobility scenarios? (3) What handoff context data, variables, or parameters should be considered to achieve a particular desirable feature? (4) How to define every desirable feature to avoid confusion or misuse in the literature? (5) How to qualify and quantify the performance of single handoff features and the global success of multi-purpose handoffs? This research work is an effort to fill these gaps around the handoff.

1.2 Previous and Related Work

Dr. Nishith D. Tripathi, in his outstanding thesis work published in 1997 [9], was the first author in considering handoffs that can simultaneously achieve several desirable features. His work served for many years as a basis for developing high performance handoffs. However, Tripathi's handoff concept was limited to lower-layer transitions between radio channels or between base stations. This handoff concept was suitable for the handoff scenarios from 1997, but today's handoff scenarios have changed significantly. A handoff today is a much more elaborated cross-layer transition among different networks, providers and terminals. The reductionist approach of Tripathi's handoff concept has brought in consequence that his algorithms and models become today special cases of more general models. Thus, a holistic approach to study our proposed cognitive handoff is therefore relevant to provide a long-term solution to the handoff problem.

Another author who described several desirable handoff features was Nasser [7] in 2006. However, neither Tripathy, nor Nasser, defined a relationship between a particular desirable feature and its corresponding purpose, objectives, goals, and metrics. We argue that a cognitive handoff model needs to establish a clear correspondence between such former concepts in order to reduce the ambiguity or subjectivity of desirable features. This way, we associate a quality property (purpose) and quantitative measures (objectives and goals) to each desirable feature using handoff metrics. By doing so, we can qualify and quantify the performance of individual features or its comparison with others. Therefore, we say that current handoffs are not designed to optimally achieve multiple desirable features simultaneously.

Despite the Tripathi's advice to develop handoffs with multiple desirable features since 1997, few authors have recently published handoff schemes with multiple desirable features; for instance, Sethom in 2005 [4] for secure and seamless handoffs; Altaf in 2008 [12] for secure, seamless, and soft handovers; Cardenas in 2008 [19] for fast and seamless handoffs; and Singhrova in 2009 [2] for seamless and adaptive handoffs. These examples show now a clear tendency toward the concept of cognitive handoff, although they did not define such desirable features or measures for evaluating their performance. We associate the low production of solutions to the fact that many works have focused on understanding and controlling very specific handoff scenarios (reductionist approach) instead of managing complex and generic handoff scenarios (holistic approach).

Holism and reductionism are two complementary and opposing approaches for analyzing complex systems [20]. In fact, in this research dissertation we have used both approaches: the holistic approach to model the system architecture of cognitive handoffs and the reductionist approach to develop a case study of multi-objective handoff. The holistic vision to the handoff problem has been studied by Dr. Mika Ylianttila in his thesis work [14] published in 2005. He presented a holistic system architecture based on issues involved in mobility management areas (e.g., mobility scenarios, handoff strategies, handoff control, handoff algorithms, handoff procedures, mobility protocols, mobility parameters, performance measures, and handoff metrics.) The work of Ylianttila improved the architecture of handoff issues that Pahlavan [21] published in 2000. However, both architectures have some drawbacks: i) they did not include the context management problem in their models; ii) they did not mention the issue of tradeoffs that handoffs should consider in a multi-objective scenario; and iii) their architectures are based on types of issues and not in functional aspects of the handoff process.

Besides the above related work, we use two criteria to classify handoff schemes that are approaching to cognitive handoffs: the number of desirable features they achieve and the amount of context information they use.

Handoff schemes like the ones proposed by So [18] and Zhang [22] attain one desirable feature using limited context information; they provide seamless handoffs between particular network technologies and specific mobility scenarios. Moreover, the schemes proposed by Siddiqui [23] and Hasswa [24] use broad context information, but they are focused only in seamlessness. Conversely, the solutions proposed by Sethom [4] and Tuladhar [25] provide seamless and secure handoffs on a variety of handoff scenarios using broad context information. The schemes proposed by Singhrova [2] and Chen [26] achieve seamless and adaptive mobility, but they cannot adapt to any handoff scenario because they use limited context. Finally, the scheme proposed by Altaf [12] achieves seamless, secure, soft, and adaptive handoffs, but just between WiMAX and 3G networks because it is limited in context.

The information the handoff process uses for making decisions increases as more "intelligent" handoff systems are being deployed. While handoffs in the first generation wireless networks (1G) were called *single-criterion,* because they were mainly based on signal-strength or link quality parameters, in 2G networks the handoffs were known as *multi-criteria*, because they included criteria from distinct sources; e.g., they might consider the battery load from the terminal and the traffic load from the network. At the beginning of 3G networks, several handoff schemes were deployed using information from the entire external handoff environment; they were called *context-aware* handoffs. In 2003, Prehofer [27] proposed context-management architectures for addressing the problem of collecting, compiling, and distributing handoff context information. This remarkable work started a new stage in the development of handoffs. Part of this architecture was used by Pawar [28] in 2008 for developing context-aware handoffs applied to mobile patient monitoring. Finally, at the dawn of 4G networks, a new type of handoffs, called *self-aware*, started to use parameters from its internal environment to self-adapt its behavior according to different performance goals. It is obvious that for the future networks, an *environment-aware* handoff will be using information from both, its external and internal environment.

Despite the recent advances in context-management architectures and applications, the lack of a clear relationship between handoff context information and handoff desirable features is adding unnecessary complexity to the process of handoff. The handoff decision making process should be oriented to attain more than just one desirable feature. Therefore, we consider that in contrast with current handoff schemes, a *cognitive handoff* is aware of its external and internal environment and optimally achieves multiple desirable features simultaneously.

Now, regarding the previous work of standardization bodies, like the IEEE 802.21 and the IETF MIPSHOP, we observed that they are considering seamless handoffs only. The IEEE work group concentrates on layer-2 and below handoffs while IETF on layer-3 and above handoffs. The IEEE 802.21 standard provides media independent handoff services to application layers for handoff implementations, and the IETF MIPSHOP provides mobility protocols for handoffs between IP networks (MIP, SIP, HMIP, etc.) However, the definition of handoff decision algorithms, handoff strategies, handoff metrics, handoff scenarios, and handoff policies are outside the scope of the standard. Therefore, IEEE and IETF do not restrict the definition of cognitive handoffs. Emmelmann [29] discusses ongoing activities and scopes of these standardization bodies.

1.3 Significant Research Contributions

The following is a list of significant contributions of this research:

i. *Development of a New Holistic Vision of Handoffs*. Many current handoff solutions follow a reductionist approach; they achieve one desirable feature, use a small amount of handoff criteria, and work in one specific handoff scenario. All such solutions provide understanding and control of particular situations, but they quickly become special cases of more general models. We claim that the handoff problem for the future Internet requires a *holistic vision* in order to create handoffs that can *achieve multiple desirable features*, use a *great diversity of context information*, and *operate with good performance* in any handoff scenario.

ii. *Development of a New Model-Based Framework for Cognitive Handoffs*. We propose the concept of a new class of handoffs for the next-generation networks. This new kind of handoffs is characterized to be multi-purpose, environment-aware, policy-based, and goal-balanced. This manuscript provides the conceptual model or framework for cognitive handoffs and deploys its first level of functional decomposition.

iii. *Development of a New Model-Driven Methodology to Build Cognitive Handoffs*. This methodology allows developing cognitive handoffs using our proposed model-based framework. The proposed methodology is founded on a synthesis of holism, reductionism, functional decomposition, model-based design, and scientific problem-solving theory. It considers the design and development process is similar to the general problem-solving process; therefore, this methodology establishes a general procedure that starts with the problem statement and ends with the solution implementation. We start by creating a conceptual model and then, by functional decomposition, we divide it into modules or sub-models representing sub-problems. All sub-models are organized into the developed framework and then the process of validation and verification starts. Once all models are verified and validated then the implementation phases may begin. As a result of following this methodology, this thesis identifies a clear correspondence between desirable handoff features, handoff purposes, handoff objectives, handoff goals, and handoff environment information. Moreover, the handoff environment information is organized according to its source and its role that plays within the handoff process.

iv. *Development of a New Taxonomy of Handoff Mobility Scenarios*. A new classification of handoffs is explored by considering all the feasible combinations of elements involved during the transition: radio channels, base stations, IP networks, service providers, and user terminals. It is very important for the adaptive characteristic of our cognitive handoff scheme to identify the type of handoff scenario that is in progress, so that it can prepare and select the more appropriate execution and decision-making method.

v. *Development of an Original State-Based Model for the Handoff Process*. A major component of the cognitive handoff architecture is the handoff control system. This control system is modeled by a five-state diagram which describes a deterministic and reactive behavior of handoffs. This key component coordinates the stages before, during, and after the handoff. The five basic states that reflect the control handoff behavior are: disconnection, initiation, preparation, execution, and evaluation. This state-based model was validated through its implementation into a handoff algorithm whose performance was evaluated by means of computer simulations. Such proof-of-concept simulations allow us to create a specific cognitive handoff case study.

vi. *Development, Analysis, and Evaluation of a Cognitive Handoff Case Study*. This case study is intended to show the viability of cognitive handoffs. Thus, a particular type of cognitive handoff, named *correct handoff*, is examined. A correct handoff is a multipurpose handoff addressed to optimize two conflicting objectives: minimize the rate of executed handoffs (rEHO) and maximize the rate of dwelling-time in the best network (rTiB). A *control handoff algorithm*, called Algorithm R, was implemented and tested under a bulk of random handoff scenarios. A *handoff simulation instrument* was built and verified specially to test the handoff algorithm. This instrument provides samples of bivariate data (rTiB, rEHO) representing the performance of the algorithm. A *statistical analysis* and *probabilistic models* were deployed using such data. The instrument helped to establish the hit rate of our correct handoff to be above 90%.

1.4 Research Objectives

General Objective:

- Build a model-based framework for understanding, developing, and evaluating cognitive handoffs.

Specific Objectives:

- Create a conceptual architecture that identifies and relates the main functional parts of the cognitive handoff systems using a holistic approach.
- Discuss the difficulties of developing cognitive handoffs and propose a model-driven methodology for their systematic development.
- Examine the problem of evaluating cognitive handoffs and use a reductionist approach to analyze the case of handoffs that optimally tradeoff two conflicting metrics: the dwelling-time in the best network and the number of executed handoffs. For this purpose, design a multi-objective handoff algorithm that produces optimal and balanced

outcomes. To test the algorithm behavior, build a simulation instrument that creates a variety of handoff scenarios and runs the algorithm on each scenario. After collecting the test results obtained from simulation, perform statistical analysis and probabilistic models to predict the algorithm's hit rate.

1.5 Thesis Outline

This thesis manuscript contains five chapters. The remaining of this manuscript is described as follows.

Chapter 2 provides background information and a theoretical frame for cognitive handoffs. This chapter investigates the evolution of handoffs from single-purpose to multi-purpose, the major challenges and trends in the future Internet, and shortly discusses the theoretical foundations that support the cognitive handoff concept.

Chapter 3 presents the construction of a model-based framework addressed to understand, develop, and evaluate cognitive handoffs. This chapter splits the discussion into four parts. The first part describes the new cognitive handoff holistic vision through the study of multiple desirable handoff features, the structure of the handoff environment, and the development of a new taxonomy of handoff mobility scenarios. The second part presents a new model-driven methodology for the systematic development of cognitive handoffs. The third part depicts and explains a high-level functional architecture of a cognitive handoff system. This third part also presents the handoff control system represented by a cognitive handoff state-based model. Finally, the fourth part examines the challenge of evaluating cognitive handoffs and presents strategies to perform this task.

Chapter 4 proceeds top-down from holistic to reductionist in order to examine a particular type of cognitive handoff named correct handoff. This chapter presents a case study about a multi-objective handoff algorithm which is characterized as deterministic, reactive, heuristic, autonomous, adaptive, and correct. Furthermore, this chapter describes the construction of a virtual instrument designed to test the handoff algorithm under a variety of scenarios and collect handoff data for offline analysis. Finally, this chapter provides a detailed discussion of the handoff results collected from the simulation instrument and their corresponding statistical analysis under probabilistic models in order to evaluate the multi-purpose handoff computational model.

Chapter 5 concludes the dissertation and describes the future work. The concluding remarks summarize the major accomplishments attained by this doctoral dissertation. Finally, the chapter presents the major areas of future work that are significant to continue this research work.

Chapter 2

Foundations of Cognitive Handoff

This chapter is divided into two parts. The first part provides basic terminology and background information about cognitive handoffs for the future Internet. The second part describes the main areas of knowledge that supply the theoretical foundations of cognitive handoffs.

2.1 Background Information

A fundamental challenge in wireless networks is to forward the incoming packets from a single source toward multiple mobile targets. This problem, known as *mobility management* [30], is quite simple to state but extremely difficult to solve. To face this problem, mobility management gets divided into two components: *location management* and *handoff management*. The former is needed to track the location of mobile targets; i.e., to determine where the targets are and how to reach them at any time. Handoff management, on the other hand, is needed to preserve the flow of packets toward targets while they move from one location to another, and thus, keep the connections active. Therefore, location management and handoff management are two complementary operations that support mobility in wireless networks. Mobility management has widely been recognized as one of the most important problems for a seamless access to wireless networks and services. This way, it is quite clear the existing relationship between handoff and mobility.

The handoff is a network service essential to support the mobility and quality of communications of users roaming within a single wireless technology (*homogeneous handoff*) or among a variety of wireless access technologies (*heterogeneous handoff*). The process of handoff is designed to transfer the user communications while they change among different radio channels, base stations, IP networks, service providers, network operators, user terminals, or any feasible combination of these *transition elements*. Handoff is important for both static and mobile users, who may use desktop computers connected to wired/wireless networks or mobile handsets enabled to operate with multiple wireless interfaces simultaneously. In a traditional cellular system, when a user terminal moves to the edge of its serving cell, a handoff to a new and better cell may be the only way to avoid disrupting the communications. In today's wireless overlay networks, a static user may also reach a variety of wireless connection options from a single place. If the quality of the current connection begins to degrade, or a new wireless connection gets better than the current one, then a handoff to the new available connection may be the only way to improve the Quality of Service (QoS) of user communications. These changing networks would give a relative mobility to a supposed static user and thus, making such a situation a particular case of a kind of a very restricted mobility. Therefore, a handoff is a key enabler for supporting mobility and quality of communications in the early, the existing, and the future wireless technologies.

In what follows, we explore the origin of seamless (single-purpose) handoffs in the first generation wireless networks (1G), the deployment of multi-purpose handoffs in the fourth generation wireless networks (4G), and the major challenges and trends in the future Internet which are important to develop the cognitive handoff concept.

2.1.1 Evolution from Single-Purpose to Multi-Purpose Handoffs

A seamless handoff is a handoff whose purpose is to *preserve* the data flow between source and targets during transitions in connectivity; thus, seamless handoffs are single-purpose handoffs. However, in order to face the challenges of the next-generation networks, the handoff process should deploy some other significant purposes more than just preserving the continuity of services; that is, the handoff process should become multi-purpose. The following paragraphs describe this evolution.

2.1.1.1 Origin of Single-Purpose Handoffs in 1G Networks

The thoughtful study of handoffs started in the early 1990s with the first generation cellular networks (e.g. AMPS [31]) aimed to provide mobile phone services to subscribers. In these wireless systems the desired coverage area is divided into a number of *homogeneous cells*, each one controlled by a centrally located and low-powered *base station*. Similarly, the system bandwidth is divided into a number of channels arranged into groups assigned to individual cells. Two cells far enough apart could be assigned the same group of channels. This allowed every channel to be reused throughout the system's service area. An important consequence of dividing the service area into cells and system bandwidth into channels is the need to transfer a call from one channel to another or from one base station to another, that is, a *hand off* process.

Figure 2-1 shows a geometric model of mobility used in homogeneous cellular systems and two common types of handoffs. In this example, the system service area is divided into four cells A-D and the system bandwidth is divided into 12 channels, arranged into three groups F1, F2, and F3. Cells A and D are far enough, so they can reuse the group of channels F1. The figure shows a mobile terminal moving within the cellular system. Along the trajectory of the mobile terminal, depicted with a dashed line, an *inter-channel handoff* is produced in cell A when the call is transferred from channel 1 to channel 3. The overlap zones between cells represent the geographical areas where the *inter-cell handoff* occurs. Inter-cell handoffs are performed as the terminal moves away from the weak current cell and approaches to a new and stronger cell. The *association* of a mobile terminal to one specific base station determines the terminal's location at any time. The handoff zones represent the critical places where the terminal changes its connection point from one base station to another and re-associates to the next base station.

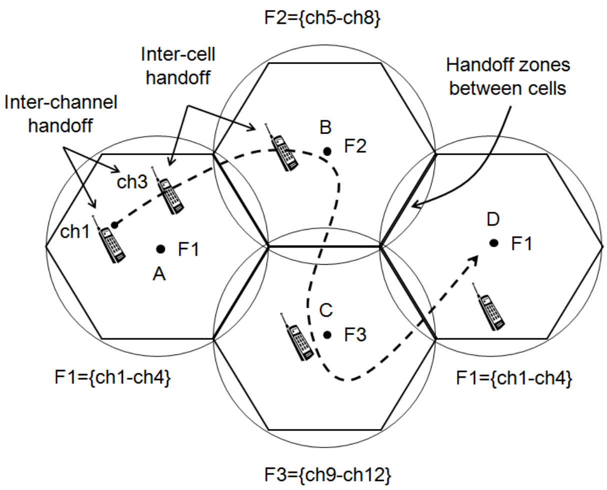


Figure 2-1. Architecture of homogeneous mobility in a cellular network.

Initial works in handoff literature [32, 9] defined a handoff as a process intended to *preserve* the conversations of users while the mobile phone changed between *channels* or *base stations*. In such traditional handoffs, the decision to execute a handoff was made only on the basis of signal strength measurements and its execution should not be perceptible to a user. For this reason, the AMPS system required a *handoff latency* lower than 100 ms to avoid the possibility of dropping a syllable of speech [31]. The *seamless requirement* is to make the end-user notices, as little as possible, when changes occur at the network level and he is not interrupted while having a communication session [33].

Nowadays, many wireless technologies have emerged (e.g. GSM, GPRS, EDGE, UMTS, cdma2000, WiMAX, etc.) and everyone has defined its own mechanisms to support mobility between their own cells and channels, that is, within the same system. This type of *horizontal* or *homogeneous* mobility has had successful results providing a seamless roaming experience for end-users. In today's cellular networks an end-user making a voice call on his cellular handset will not notice a network handoff when he moves to another cell. Therefore, the seamless requirement in homogeneous handoffs is already fulfilled, but now the challenge is to implement the same concept across administrative domains, heterogeneous networks, and end-user devices. Better yet, the great challenge is to transform a seamless handoff, that is, a single-purpose handoff into a cognitive handoff, and therefore a tacit multi-purpose handoff across networks, providers, and terminals.

2.1.1.2 Deployment of Multi-Purpose Handoffs in 4G Networks

Since the early times of the 1G network, many wireless access technologies of different capacities and coverage have emerged and they appear geographically overlaid. According to the size of its service area, wireless networks can be classified as WPANs (e.g. Bluetooth), WLANs (e.g. Wi-Fi), WMANs (e.g. WiMAX), and WWANs (e.g. UMTS). WPANs have coverage areas within an office or meeting room (pico-cells). WLANs may expand its coverage inside a building, or across a campus-area, or in public "hotspots" (micro-cells). WMANs can be extended in public areas of different size, from one street to a whole city (macro-cells). Finally, WWANs are designed to cover large geographic areas, whether metropolitan and rural areas, or global coverage (mega-cells). 4G networks focus on seamless integration of existing wireless technologies including WWANs, WMANs, WLANs, and WPANs. A typical architecture of heterogeneous mobility across different wireless overlay networks is illustrated in figure 2-2.

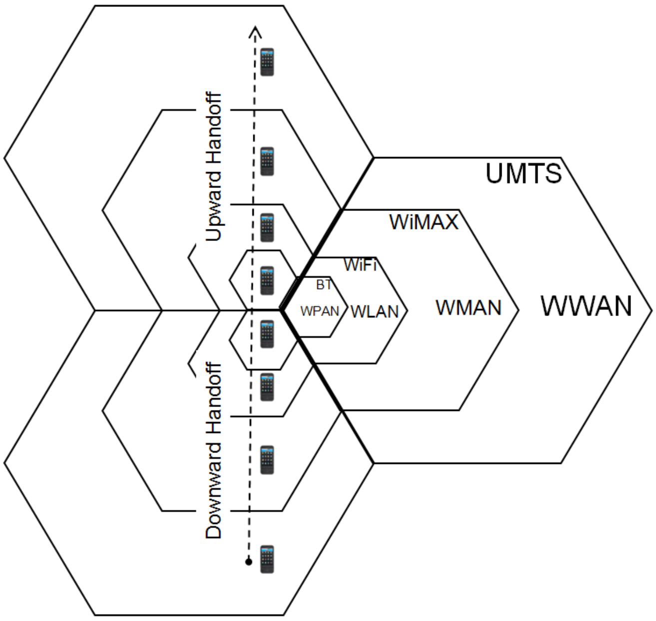


Figure 2-2. Architecture of heterogeneous mobility in 4G networks.

Mobility across heterogeneous networks, that is, within different systems, is also called *vertical* or *heterogeneous mobility*. The coexistence of various wireless access technologies makes possible two kinds of handoffs: *horizontal* and *vertical* handoffs. Horizontal handoffs occur when a terminal is moving within the same network technology. Vertical handoffs occur when a terminal is changing between different network technologies. Due to vertical handoffs are usually *asymmetric*, they can be further classified into two types namely, *upward* and *downward* handoff [34], as illustrated in figure 2-2. Thus, a handoff to a wireless overlay with a larger cell size and lower bandwidth per unit area is an upward vertical handoff while, a downward vertical handoff is a handoff to a wireless overlay with a smaller cell size and usually higher bandwidth per unit area.

The implementation of vertical handoffs is more challenging as compared to horizontal handoffs because the next reasons:

- Horizontal mobility is defined by each network technology, whereas vertical mobility requires the coordination of several technologies to develop a standard model of vertical mobility.
- Homogeneous cells typically preserve the same operating characteristics (e.g., coverage, bandwidths, frequencies, access methods, etc.) while heterogeneous cells may have very different operating characteristics. Therefore, vertical mobility exhibits a greater variety of mobility scenarios that demand greater adaptability.
- Horizontal handoffs require the terminal moves to the handoff zones to perform inter-cell handoffs (see figure 2-1). On the other hand, heterogeneous handoffs can be produced with a static terminal or with a moving terminal (see figure 2-2).
- Horizontal handoffs use mobile terminals enabled with a single access technology (mono mode), while heterogeneous handoffs demand terminals enabled with multiple access technologies (multi mode).

So far, much research work has been done to provide a seamless vertical roaming experience to end-users. This means that these works are focusing on pursuing seamless handoffs, i.e., handoffs with a single purpose in mind, to preserve the continuity of services. However, there are many other significant characteristics that combined can yield a different type of handoff, and consequently, a different type of mobility namely cognitive. As seamless mobility is expected to occur in the 4G networks, we believe that cognitive mobility might be implemented in the Next Generation Internet (NGI) if cognitive handoffs prove to enhance the performance of seamless handoffs.

2.1.2 Major Trends and Challenges in the Future Networks

A major trend in the future networks or 4G networks is the coexistence of *multiple dimensions of heterogeneity* created by the diversity of users, terminals, networks, applications, and providers. A major challenge is to integrate such heterogeneity into a *seamless*, *universal*, *uniform*, *ubiquitous*, and *general-purpose* network. Thus, in this global network, anyone or anything will be able to access any service, from anywhere, at any time, using any terminal. This future network is *cognitive* in the sense that it should be aware of its environment and be able to achieve several characteristics simultaneously; seamless*,* if it hides all dimension of heterogeneity to users; universal*,* if it is available to anyone or anything with any terminal; uniform*,* if it is an all-IP based network; ubiquitous*,* if it is available anywhere and anytime; and general-purpose*,* if it conveys any kind of service or application.

2.1.2.1 Multidimensional Heterogeneity

We envision the future networks characterized by a myriad of users, machines, and sensors, located literally at any place, static or moving at different speeds, interacting with diverse end-user devices, connected to different wireless access technologies, running a variety of mobile multimedia applications and services, which are created and managed by a diversity of service providers. Within this vision allows identifying five dimensions of heterogeneity; they are depicted in figure 2-3 and explained as follows:

I. *Diversity on service providers and network operators*. They deploy different wireless technologies around the world, they make different roaming agreements and alliances with other providers and operators, they offer different classes of services, and they have diverse billing models, security policies, and fees.

II. *Variety of applications and services*. This variety intends to fulfill distinct ways of human communications, e.g., voice, video, data, images, text, music, TV, telephony, games, etc. Multimedia produces different types of traffic with different QoS requirements. All applications and services are transported over IP.

III. *Assortment of access network technologies*. Include wired and wireless access technologies, e.g., Ethernet, Bluetooth, WiMAX, Wi-Fi,

UMTS, MBWA, IMT-2000, GPRS, GSM, EDGE, LTE/SAE, DVB-HS, and many others [35]. They differ in terms of electrical properties, signaling, coding, frequencies, coverage, bandwidth, QoS guarantees, mobility management, media access methods, packet formats, etc. Currently, there is no single network access technology that is able to simultaneously provide high bandwidth, low latency, low power consumption, high security levels, and wide area services to a large number of mobile users in any mobility scenario. All access layer technologies use IP as the integrating mechanism.

IV. *Plethora of mobile user terminals*. Users can be humans, machines, or sensors. Terminals for machines are integrated parts of machines like vehicles, cameras, refrigerators, or wash machines, equipped with telecommunications capabilities. Sensor terminals collect context information from networked sensors and send sensory information only when the data has an unusual status, like in the prediction of natural disasters. Terminals for humans are mobile and multimode. They change its factor form from those looked like computers (laptops, net books) to those looked like cellular phones (smartphones, PDAs). They use different saving energy characteristics.

V. *Numerous user mobility states*. User terminals can be located anywhere – in space, on the ground, under the ground, above water, underwater, and they can be fixed in a geographic position or moving at any speed – pedestrian, vehicular, ultrasonic.

Future cognitive networks will allow users on the move to access large volumes of information, data, pictures, high-quality voice, high-definition video, anywhere, anytime, through high-data-rate wireless channels. For instance, figure 2-3 depicts with dashed lines, the communications flow that might happen when a person aboard a high speed train is watching on his laptop a Mobile TV online program, broadcasted by scuba divers from the bottom of the sea exploring characteristics of the sea life. The dashed lines going up from user to provider and going down from provider to user depict two different handoff scenarios created by instantiating different objects in each dimension.

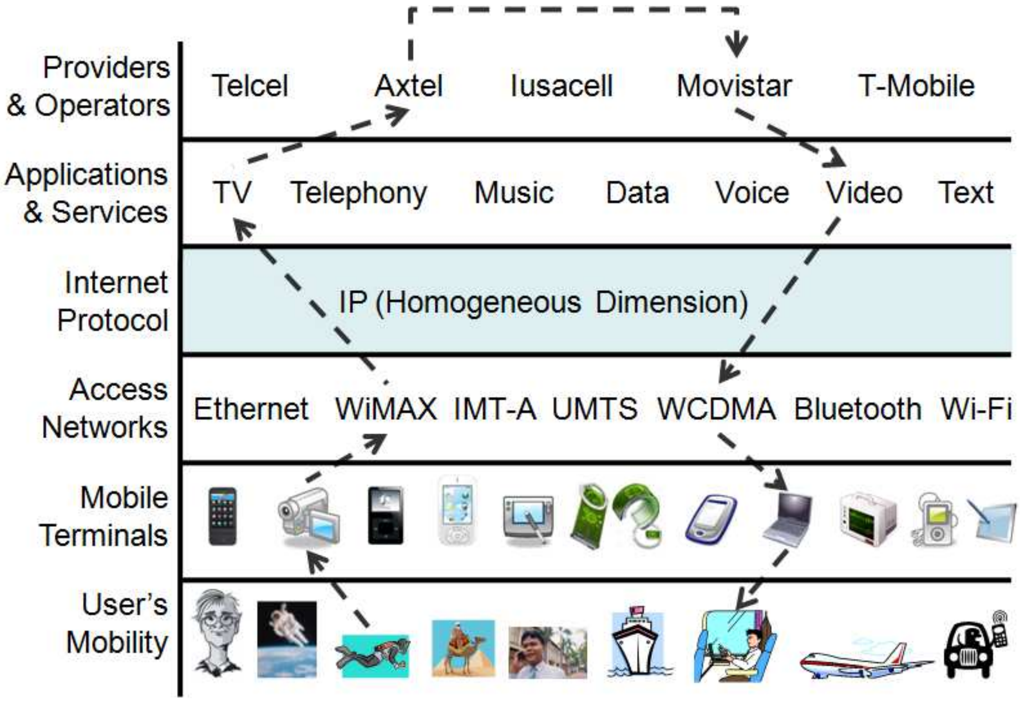


Figure 2-3. Multidimensional heterogeneity in the future networks.

Multidimensional heterogeneity has two main attributes. (1) It is *inevitable* because there is no single access technology, terminal device, mobile application, service provider, and mobility style that best adapts to all human communication necessities and mobility requirements; moreover, every single element in each heterogeneity dimension exist to satisfy very particular user needs. (2) It is the source of great amounts of handoff context information and handoff scenarios. If we define a handoff scenario as an array (d_1, d_2, …, d_n) where every d_i is an instance of the set D_i that represents the *i*th dimension, then, there will be $|D_1|\times|D_2|\times\ldots\times|D_n|$ distinct handoff scenarios with different complexities. This number can be very large or even infinite, depending on the degree of heterogeneity of each dimension. Each dimension represents a source of handoff context information, identified by users, terminals, networks, applications, and providers.

2.1.2.2 Integrating Multiple Dimensions of Heterogeneity

Multidimensional heterogeneity brings several design and deployment challenges to the future cognitive networks, which are about integrating terminals, networks, services, and providers to satisfy the increasing user demands. Key challenges and proposed solutions are briefly discussed.

Integrated terminals: The challenge of integrated terminals is to design lightweight and powerful end-user devices that can run a wide range of applications provided by multiple wired/wireless networks. Thus, an integrated terminal is a *multimode* and *multiservice* device that can be used in very different working environments and mobility states.

Multimode terminal

It is a single-user terminal that can operate in different networks simultaneously or separately by changing from one network to another. A software-defined radio approach (SDR) can be used to design multimode terminals [36]. An SDR terminal is equipped with a reconfigurable hardware platform that can be adapted by means of software modules to any wireless technology. The software module that reconfigures the communication platform, called Cognitive Radio by Joseph Mitola III in [37], has the ability of monitoring the external environment, learn from the history, and make intelligent decisions to adjust the interface transmission parameters according to the state of the external environment.

Multiservice terminal

It is an end-user device that can overcome design problems, such as limitations in device size, display resolution, power consumption, processing capacity, and other limitations, in order to adapt a wide range of applications to run in such device. A middleware-based approach can be used to design multiservice terminals. Applications and services can be adapted according to the available hardware resources so that an ad-hoc version of the application is able to run in that limited device. Reconfigurable hardware with software modules is contributing to create true universal terminals.

Integrated networks: An integrated network is a virtual network having the following characteristics:

- It integrates any number of wireless systems into a single wireless network that is independent of the access technology. It creates the illusion of being a single homogeneous wireless network.
- It uses IP technology as a common method for interworking different access technologies and transporting different applications and services over IP.
- It integrates different telecom operators and service providers creating the illusion the network is managed and operated by a single ISP.
- It spreads across the entire world and is available anytime.
- It keeps the mobile user always best connected.
- It enables any integrated terminal moves seamlessly within the network.
- It integrates any application or service, created and delivered by any service provider, or third party, and it is transmitted over any access network.

Wireless systems integration

A key challenge is to design scalable integration architectures that can integrate any number of wireless heterogeneous networks of different service providers, even if they do not have previous roaming agreements or alliances. Mohanty [38] proposes a scalable integration architecture using the services of a third party, called NIA, which eliminates the need of creating direct agreements between different telecom operators. Internet has shown that IP technology is the best choice for interworking and integration of various radio access technologies. In order to achieve convergence and interworking of different access technologies, all signaling between various entities in networks is exchanged at IP-layer. This way, IP contributes to separate the access network from the core network, and to let a single core network may have multiple access networks; e.g., an UMTS core network may support GSM access, Wi-Fi access, GPRS access, etc. In general, as Salina described in [35], access networks can be added, upgraded and removed without impacting on the core network.

Ubiquitous mobile access

This challenge deals with deploying wireless overlay heterogeneous networks globally, so that they can be available anytime and anywhere. In order to achieve a solution to this issue, 4G networks are considering integrating the existing wireless technologies, from WWANs to WPANs and from 2G to 3G networks. Moreover, 4G intends to integrate satellite broadband, wireless ad-hoc networks, and wireless sensor networks spread in deserts, forests, oceans, etc, in order to extend the network coverage area. Also, the case of Wi-Fi in the public "hotspots" is being deployed by mobile operators around the world with the aim to offer seamless mobility with WWANs and ubiquitous connectivity [39].

Always-best-connected

Gradually is becoming more common a mobile user can have several networks to access the Internet using an integrated terminal. In order to make an efficient use of such variety of networks, the user communications must always flow through the *best* available network. However, not all the networks are available all the time and not always they have the same quality or performance; i.e., the best network may be changing frequently and randomly. Therefore, there is a need to manage the terminal's interfaces efficiently, in order to perform *handoffs* to the most appropriate access network at the right time. This means that one of the major challenges of an integrated network is to keep the mobile user always best connected [34]. Figure 2-4 illustrates a mobile terminal roaming across different wireless overlay networks that may belong or not to the same administrative domain.

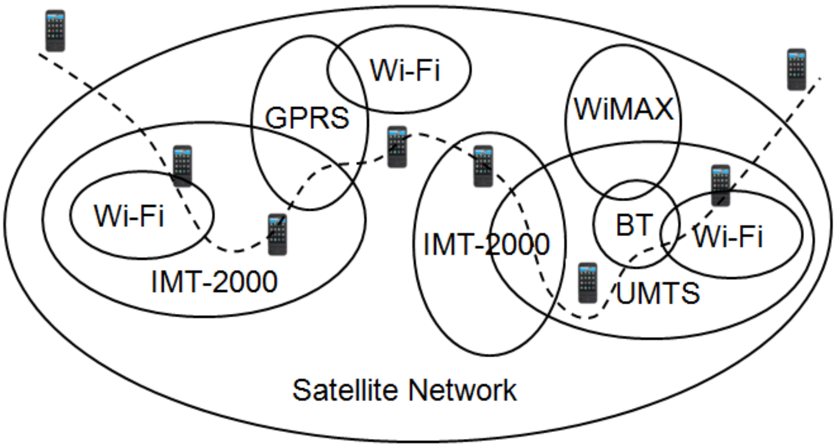


Figure 2-4. An integrated terminal moving seamlessly across heterogeneous wireless overlay networks.

The ABC problem was initially set by Gustafsson [40] in 2003, but there are still many issues that need to be faced before we can see a correct solution to this problem. The multidimensional heterogeneity has complicated the meaning of "best" network and the basic tasks of discovery, selection, execution and evaluation of handoffs.

Meaning of best or better

Clearly, the word "best" or "better" may have different meanings to different actors. As Kristiansson discussed in [41], there may be conflicts of interests between end-users and ISPs. End-users might view ABC as a way of saving money by switching to the lowest cost operator, whereas an ISP might not see any benefit from allowing a user to switch to another operator. Such conflicts of interests can be solved through novel win-win negotiation schemes. Moreover, as Salina pointed out in [35], the telecommunications industry is moving toward a model of operation driven by customer needs. In this model, the operator is not supposed to enter in conflict with the needs of the customers; on the contrary, operators are intended to apply technology to satisfy the customer needs.

Wireless system discovery

The discovery problem is to discover available wireless systems by processing the signals sent from different wireless systems. *Discovery latency* and *discovery energy consumption* are two performance metrics in conflict that must be minimized. User- or system-initiated discoveries, with adaptive techniques according to the terminal's battery load are solutions proposed by Siddiqui in [42].

Wireless system selection

The selection of the most suitable wireless system for a particular service at a particular time and place is complicated. The most suitable wireless system can be selected according to best possible fit of user QoS requirements, available network resources, or user preferences; the difficulty arises because the network quality function may change frequently and randomly which may lead to choose a wrong network. Many authors have proposed different utility functions combined with multiple criteria and priorities, e.g., [7, 15, 24, 26, 43-45].

Handoff triggering

Once the best available network has been identified, making the decision of when to execute the handoff is another issue. Clearly, requiring that users manually control handoffs is not a sustainable solution. Again, the difficulty comes from the fact that the performance of networks fluctuates stochastically. Therefore, there is always a risk that handoffs are triggered back and forth between two or more networks causing instability and seriously degraded performance. This classical problem is the ping-pong problem [41]. The standard solution is to add hysteresis with the drawback of adding even more delay to the handoff.

Handoff evaluation

The handoff evaluation task is a significant challenge because its outcome is commonly used as feedback to change the future behavior of the handoff process. The evaluation task requires of metrics to measure the achievement of individual handoff goals and optimization techniques to trade-off handoff objectives in conflict. The global evaluation task obtains a combined result of the achievement of multiple objectives. Common metrics used to measure the performance of the handoff process are: the handoff latency (HOL), the number of executed handoffs (nEHO), the handoff signaling overload (HOSO), the dwelling-time in the best network (DTiB), etc. Optimization techniques are used for balancing objectives in conflict, such as, minimizing nEHO and maximizing DTiB.

Seamless mobility

An integrated network must allow a user terminal move seamlessly across this heterogeneous wireless system. However, seamless mobility results from performing seamless handoffs. Seamless handoffs provide service continuity and no noticeable interruption to running applications. This means that in order to solve this issue, handoff latency and packet loss must be kept to a minimum. *Handoff latency* is the time interval during which an MN cannot send or receive any packets during handoff. *Packet loss* is the number of lost packets during handoffs and is proportional to handoff latency. Many seamless handoff schemes have been proposed and examined, but most of them are designed to run in very specific mobility scenarios, ignoring other desirable features.

Integrated services: The challenge of integrated services is to allow that users can use multiple services from any service provider through any available access network. Currently, users are demanding more services than just telephony and instant messaging offered by most telecom operators. A wide diversity of IP services, collectively known as 'electronic applications' or 'e-applications' including e-government, e-learning, e-health, e-banking, e-tourism, etc. are being developed by service providers and third parties. Traditionally, most operators have controlled the service creation and delivery in order to protect their revenue. However, the future demands on IP services are beyond most current operators' capabilities. Thus, there is a need of enabling third parties (or new providers) to develop and deliver such applications. Salina in [35] proposed a Service Network Architecture to face this issue. This architecture has the following distinguishing characteristics:

- The service layer and network layer are decoupled. This means that providers can add, upgrade or remove services without touching the transport network. This way, service creation and service delivery become independent tasks. Providers create services, and separately, services are delivered through distinct networks.
- The separation between the core and the access network allows the addition or the removal of an access network without changing the core network. This way, the delivery of the same service through all kinds of access networks is possible although with a service quality that can be different.

Figure 2-5 depicts in a Crow's Foot diagram the relationships that can exist between each dimension of heterogeneity. This diagram represents entities as boxes, and relationships as lines between the boxes. Different shapes at the end of these lines represent the cardinality of the relationship. A provider creates at least one service and one service is created by at least one provider. A service is delivered through any transport network and a network may transport any kind of service. A network connects zero, one, or many terminals and a terminal is connected to zero, one, or many networks. A terminal is operated by exactly one user at a time, but one user can operate several terminals simultaneously.

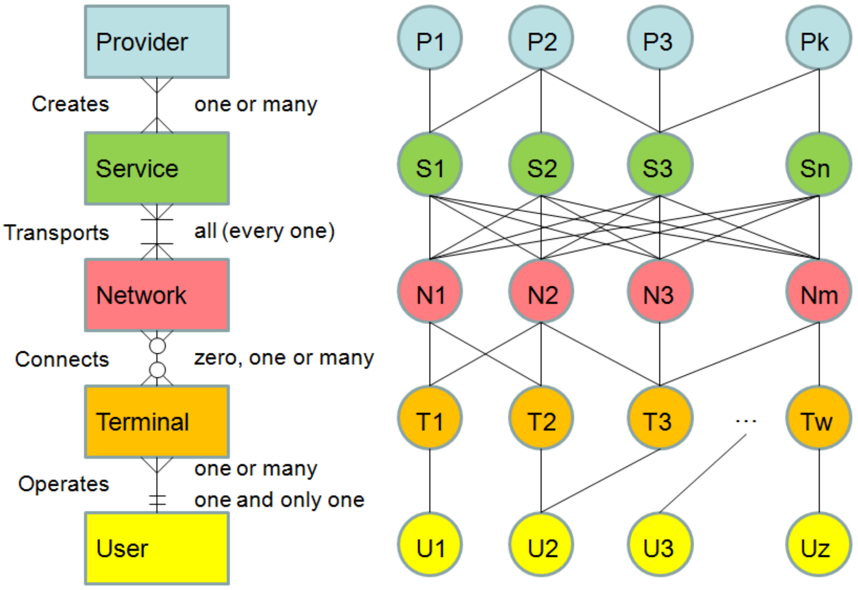


Figure 2-5. Crow's Foot diagram of relationships between heterogeneity dimensions.

<u>Integrated users:</u> Users reside in widely different locations, have quite different occupations, belong to different economic classes, and have different communication needs; therefore, the challenge of integrated users is to meet the demands of these diverse users. One way to solve this issue is by letting the service providers design personal and customized services for different classes of users without modifying the existing information and communication infrastructure. Examples of the kind of services that can be personalized are: flexible connectivity and personal mobility.

Flexible connectivity

As connectivity and services get separated, providers will offer extremely flexible connectivity including: simplex or duplex connections; point-to-point, point-to-multipoint, multipoint-to-multipoint connections; symmetric or asymmetric connections; and person-to-person, person-to-device or device-to-device connections.

Personal mobility

According to the customer subscription type, the provider can grant personalized mobility. This covers two aspects: (a) global usability and reachability of a user for communication, no matter where he or she is and if he or she is moving; and (b) seamless communications when a user is on the move across different access technologies, different networks, and different countries, in space or moving across the sea.

Integrated providers: The challenge of integrated providers is that they can efficiently share services, networks, and users in order to create the illusion that networks and services are managed and operated by a single provider. This way, one customer buys a subscription to only one provider, and that provider is able to offer him (her) any service through any network. Naturally, the difference between providers is the price and quality of their offered services. One user typically selects the best provider according to the costs and quality of services and the billing methods employed by the provider. Various billing systems and frameworks for managing the customer's accounting information from multiple service providers are being proposed [39].

Before closing the first part of this chapter, we would like to mention one final trend and one final challenge which are important to our work; they are *cognitive mobility* and *context-management*, respectively.

Cognitive mobility

It is a proposed generalization to seamless mobility. While seamless mobility is intended to preserve the service continuity of users roaming across access networks, cognitive mobility is aimed to preserve, maximize or minimize multiple purposes simultaneously. For instance, cognitive mobility might be addressed to be seamless, autonomous, secure, correct, and adaptive. This would imply to achieve several objectives simultaneously:

- To maximize the dwelling-time in the best available network; i.e., to keep the user always best connected.
- To maximize the successful handoff rate; i.e., to maximize the number of handoff scenarios where the cognitive handoff process is successfully adapted.
- To minimize the handoff rate; i.e., to minimize the number of executed handoffs in order to reduce the traffic overload in the network, which might degrade or interrupt the active communications.
- To minimize the number, duration and intensity of service disruptions; i.e., to reduce the handoff latency and the rate of lost packets during handoffs so that the user perceives a continuity of the services.
- To minimize the rate of user interventions; i.e., to reduce the user's interaction with the handoff control process so that handoff autonomy is enhanced.
- To minimize the number of security threats; i.e., to reduce the number of vulnerabilities that may appear during the handoff process.

As we showed in Chapter 1, cognitive mobility is a trend in the current mobility management literature. Chapter 3 will provide a more detailed development of this topic.

Context-management

Context management is a significant challenge that needs to be efficiently solved in order to develop the variety of services at the application level and network level. Applications and network services require of timely and accurate context information so that they can correctly operate and make decisions. However, context information is *extensive*, *dynamic*, *distributed*, and *highly heterogeneous*. Therefore, the challenge of context management is to collect, compile, store, and deliver context information to each active service entity that require such information. Several context-management architectures have been proposed; e.g., Wei [46], Mendes [47], and Prehofer [27]. However, a major issue that we can visualize in these architectures is *scalability*; Signaling traffic generated by the context manager scheme increases exponentially as new context data integrate to the context definition and new service entities enter in operation. We proposed in [48] a hierarchical context management architecture that could save this issue.

2.2 Theoretical Framework

Cognitive handoffs are complex software systems, adaptive and distributed, that demand the support of many areas of knowledge. However, we believe the theoretical foundations of cognitive handoffs can be grouped into three broad fields: theory and analysis of complex systems; theory of design and modeling; and multi-objective optimization theory.

In particular, we use two complementary and opposing approaches from the theory of complex systems for understanding cognitive handoffs, *holism and reductionism*, and one method from the same theory for identifying the parts of complex systems, *functional decomposition*. To develop cognitive handoffs we propose a methodology based on concepts of *model-based design* and *design as scientific problem-solving*. To illustrate the dynamics of a control handoff process we use modeling dynamic systems under its technique representation language of *state-based modeling*. To evaluate the performance of cognitive handoffs, we use *heuristic optimization* in balancing opposing objectives that need to be satisfied simultaneously. To implement a multi-objective handoff algorithm we use *goal programming* whose statistical results being bivariate or *multivariate data* are analyzed using probabilistic models.

2.2.1 Holism and Reductionism

Holism and reductionism are two sides of a coin [20]; each side is meaningful and satisfying in its own way, but none is a complete description of what the world is. Holism and reductionism represent different views of the relationship between the whole and the parts. In reductionism, complex systems are broken down into their components and each part is studied individually; moreover, a reductionist approach states the behavior of parts determines the behavior of the whole. However, holism states that parts cannot explain the whole; moreover, a holistic approach states the whole determines the behavior of parts. Reductionist models are simplistic representations of the *properties of parts* of the system without considering its relationships with other parts. Holistic models are complex models that pretend to consider all the individual parts and the *relationships between them* in order to understand the purpose of the whole. Thus, there are no necessary contradictions between the two approaches. The one focuses on the properties of parts, the other on the relationship between them [50].

2.2.2 Functional Decomposition

The process of functional decomposition is related to the concept of *modularity* and functional composition relates to the concept of *abstraction*

[51]. A module is a functional part of a system. It is one of a set of separate parts which, when combined, form a complete whole. The process of decomposition [52] is undertaken for the purpose of gaining insight into the behavior and properties of the constituent components. On the contrary, the composition or integration of modules is undertaken for the purpose of gaining insight into the behavior and properties of the whole system.

2.2.3 Model-Based Design

The model-driven design paradigm has emerged as one of the best ways to confront complex systems. Models are systematically used in the design process of complex software systems. According to Dr. Hoffman [53], models can capture both the structure of the system (architecture) and behavior (dynamism). Model-based systems engineering [54] helps to address complexity by raising the level of abstraction, enabling developers to view system models from many perspectives and different levels of detail while ensuring that the system is consistent. The Systems Modeling Language (SysML) [53, 54] is becoming an accepted standard for modeling in the systems engineering domain. Using SysML for modeling helps to reduce ambiguity in models. In fact, models can now show the dynamic behavior of systems, including how they change between states and how the system behaves overall. Designers can use models with simulation tools to rapid prototyping, software testing, and verification.

2.2.4 Design and Scientific Problem-Solving Theory

In his inspiring paper, Braha [55] showed the similitude between systems design and scientific solving-problem theory. We developed this foundation and proposed a methodology establishing a general procedure that starts with a problem statement and ends up with the solution deployment.

According to Polya [56], the solving-problem process starts by (i) *understanding the problem*, which in our case it means to define conceptual models in order to identify the parts and relationships between the parts. Next, the challenge is (ii) *conceiving a solution plan* or method of solution to the problem. For this purpose, we define a methodology for developing cognitive handoff systems. After that, the process continues by (iii) *executing the solution plan* or applying the methodology. In this way, we identify a special case of study of a cognitive handoff that is developed in order to study its properties and behavior. As a final point, the process ends up by (iv) *examining the obtained solution* or verifying and validating results. We validate and verify the obtained results from simulation through the development of statistical analysis and probability models defining trends and characteristics of handoff results.

2.2.5 State-Based Modeling

A dynamic model describes how a system changes in time. There are many representational styles used in dynamic models (e.g., timed automata, Petri nets, differential equations, transition systems, state charts, finite-state machines, activity diagrams, etc.) as it is described by Fishwick in [57]. However, we believe that state-based modeling is a good approach that helps to create better code and documentation when planning and implementing a software project. State diagrams are used quite commonly and there are convenient software tools that can expedite their creation. As it is also explained by Carmeli in [58], the employment of an FSM model has become fairly common in many software applications.

2.2.6 Heuristic Optimization

Heuristic optimization [59] or heuristic programming [60] seek "good" feasible solutions to optimization problems in circumstances where the complexities of the problem or the limited time available for solution do not allow to obtain the optimal value (in the single-objective case) or the set of optimal values (in the multi-objective case). Therefore, heuristic optimization algorithms are a common approach when it is too difficult or perhaps impossible to obtain optimal results. Fast and good approximate solutions to optimization problems are produced by heuristic programming at the cost of optimum results. The growing use of new real-time decision-making applications (e.g. cognitive handoffs) has made the development of heuristics a major area within the field of operations research.

2.2.7 Goal Programming

Heuristics produce approximate solutions to optimization problems, but heuristics not *always* produce *good* approximations. Therefore, it is necessary to define measures to determine the quality and frequency of such approximations, and constraints or goals to decide about the success of the heuristic optimization algorithm. Goal programming [61] is a branch of multi-objective optimization addressed to handle multiple conflicting objective measures, where each of these measures is given a goal or target value to be achieved. Unwanted deviations from this set of target values are intended to be minimized. Good solutions are those that fall within specific margins, meeting certain minimal performance constraints.

2.2.8 Multivariate Data Analysis

The evaluation of heuristics can be made through *probabilistic analysis* of algorithms or empirically by applying procedures to a collection of specific instances and comparing the observed solution quality and computational burden. This way, masses of data result and multivariate analysis [62] arises as a *statistical* technique used to predict events.

With all the previous theory we are in possibility to consider the study of handoffs that can achieve many desirable handoff features. Every desirable feature associates to a general purpose that can further be divided into a number handoff objectives and handoff goals. The achievement of several purposes, objectives, and goals, requires the handoff to be environment-aware; i.e., context-aware and self-aware. A context-aware handoff adapts its behavior according to the conditions of its external environment. A self-aware handoff changes its behavior according to its internal environment. For this reason, we analyze and create models for the external and internal handoff environment. A cognitive handoff as a policy-based handoff defines rules designed by the user or provider to customize the handoff process according to their particular needs. Finally, the goal-balanced feature reflects a handoff that trades-off multiple conflicting objectives to reach its intended goals.

Chapter 3

Modeling and Methodology for Cognitive Handoffs

This chapter presents the construction of a model-based framework addressed to understand, develop, and evaluate cognitive handoffs. For this purpose, we split the chapter into four parts. The first part presents the cognitive handoff holistic vision. The second part provides a model-driven methodology for the systematical development of cognitive handoffs. The third part depicts and explains the cognitive handoff functional architecture. Finally, the last part examines a proposal for evaluating cognitive handoffs.

3.1 The Cognitive Handoff Holistic Vision

The holistic vision of cognitive handoffs starts by analyzing the structure of the external and internal handoff environment. The internal environment defines multiple desirable handoff features that we consider relevant to face the challenges of the future Internet. The external environment identifies the sources of handoff context information and the transition elements involved in multiple handoff mobility scenarios.

3.1.1 External and Internal Handoff Environments

We envision a cognitive handoff as a process that is both context-aware and self-aware. This implicates to make the handoff process aware of its external and internal environment. We borrowed the term ‘cognitive’ from Dr. Dixit's vision of *cognitive networking* [49]. He defines cognitive networking as an intelligent communication system that is aware of its environment, both external and internal, and acts adaptively and autonomously to attain its intended goals. In our case, cognitive handoffs not only should behave adaptively and autonomously to attain its intended goals, but also seamlessly, safely, and correctly. Thus, our cognitive handoff must know its external and internal context so that it can adapt itself to changes in the environment.

On one hand, the external environment is directly related to the external entities that provide a source of context information to the handoff process. These entities correspond to dimensions of heterogeneity previously described. A cognitive handoff should adapt to any kind of users, terminals, networks, services and providers. These entities maintain a strong cyclic relationship described as follows: users operate terminals, terminals are connected to networks, networks transport services, services are created by providers, and providers subscribe users. Figure 3-1 depicts a pentagon of external entities providing context information to the handoff process. This cyclic relationship between external entities suggests that all the external context information emanates just from these five basic entities and no more; hence, if we ignore information from any of these entities (or dimensions), the handoff process will not adapt properly to all the handoff scenarios. Therefore, a cognitive handoff should consider factors from these five external entities.

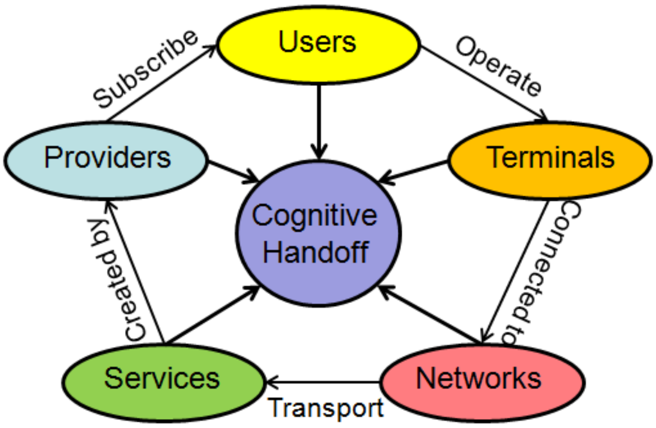


Figure 3-1. Entities and structure of the external handoff environment.

On the other hand, the internal environment is another source of context, but this internal source is directly related to the behavior or performance of handoffs. This behavior depends on the desirable features that a cognitive handoff is intended to achieve. Figure 3-2 illustrates multiple desirable features that can modify the performance of a cognitive handoff. A quality measure is associated to each desirable handoff feature.

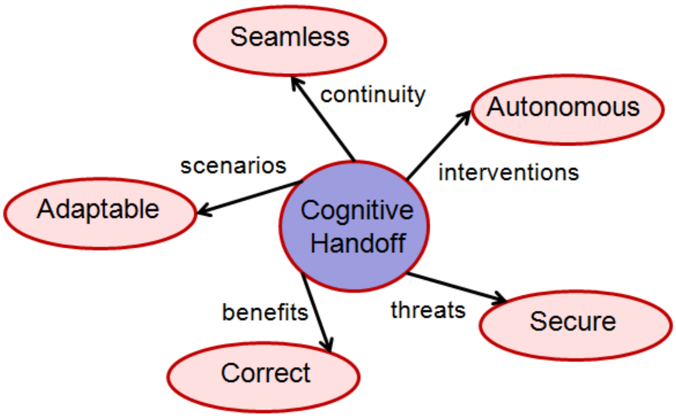


Figure 3-2. Entities and structure of the internal handoff environment.

3.1.2 Multiple Desirable Features of Handoff

Cognitive handoffs should achieve the following desirable features simultaneously in order to face the challenges of the current and future handoff scenarios.

Seamlessness

It means to preserve the *continuity* of services, without noticeable service degradation or service interruption [8]. Service degradation may occur due to a continuous reduction in link quality, network quality, handoff quality, QoS guarantees, and energy savings. Service interruption may occur due to excessive service degradations or unwanted large handoff latencies after a "break before make" handoff approach. There are various performance parameters whose values must be preserved within a tolerance range to avoid service degradations or service disruptions. These parameters include: packet delay, packet jitter, packet loss, network load, signaling traffic overhead, handoff latency, disruption time, authentication latency, energy consumption, etc. The tolerance range of some of these parameters is defined by the QoS requirements of running applications, however, the lower these parameters are, the better the performance of a seamless handoff is.

Autonomy

This desirable feature is closely related to seamlessness. If communication services get interrupted for a time, longer than the application timeout, then user *interventions* might be required to restore the stalled services or reconfigure the terminal. Moreover, if after handoff, the terminals change their endpoint IP addresses, then applications cannot continue using the same logical connection, needing the intervention of the user for session reestablishment. Thus, a handoff is autonomous, automatic, or autonomic when no user interventions are required during a handoff in progress. However, this does not mean that user interventions are not required in handoffs. It is desirable that users participate in the handoff configuration process by defining their preferences, priorities, or necessities; but, it is convenient that users can perform this activity offline to prevent any distraction during online communications.

Security

Security in handoffs is an important issue because during handoffs new *vulnerabilities* may appear in the mobility management service. The challenge of handoff security is to avoid new *threats* to appear along the handoff process and the security signaling traffic does not overload the network to a level that it may degrade the communication services. Therefore, it is desirable the security services (e.g., confidentiality, authentication, no repudiation, integrity, availability, etc.) be kept at least to the same level of security before and during the handoff. This is a very challenging task because there are many security mechanisms and security services that may provide handoff security, but also many types of security attacks that may compromise the security of information during handoffs. We believe that by minimizing handoff latency, authentication latency, and security signaling traffic, the risk of new threats appearing during handoffs may be directly or indirectly reduced. Pre-authentication and encryption schemes are especially important in heterogeneous wireless environments as different radio access networks are likely to be managed by different administrative domains and different security protocols. By reusing the security association each mobile node has with its mobile network operator, the operator can help to build up a trust chain among participant nodes allowing transparent end-user authentication across heterogeneous networks. This way, the end-user should not be bothered with technology specific mechanisms such as providing username/password or filling in an access code.

Correctness:

The concept of correct handoff is subjective and therefore it may have different interpretations, e.g. Wong [5] and Saleh [63]. To us, a correct handoff produces the greater benefits to the lower costs. In particular, it keeps the user always connected to the best available network with the smaller number of handoffs. This is similar to the Gustaffson's vision of ABC defined in [40]. We consider the best network is the one that is sufficiently better and consistently better. Furthermore, we believe correctness can bring other additional features to the handoff process. A correct handoff is *beneficial* if quality of communications, user expectations, or power conditions get improved after handoff. A correct handoff is *timely* if it is executed just in time; i.e., right after target is properly selected and before degradations or interruptions occur. A correct handoff is *selective* if it properly chooses the best network among all the available networks. A correct handoff is *necessary* if it is initiated because of one imperative or opportunist reason. Finally, a correct handoff is *efficient* if it selects the most appropriate method, protocol, or strategy, according to the type of handoff in progress, user location, user mobility style, and type of application. These handoff attributes, derived from correctness, take special relevance during the decision-making phase, where it must be decided why, where, how, who, and when to trigger a handoff.

Adaptability:

An adaptable handoff should be successful across any handoff scenario. A handoff is successful if it simultaneously achieves multiple desirable features or handoff purposes at a minimum level of user satisfaction or accomplishment. A handoff scenario that performs a successful handoff is a *successful scenario*. The adaptable handoff seeks to maximize the number of successful scenarios. Therefore, an adaptable handoff should know the handoff context information and the taxonomy of handoff scenarios.

3.1.3 Structure of Handoff Context Information

From the external and internal vision of the handoff environment, we identified five external sources of context information and one internal source which is the handoff process itself. All the handoff context information originates in one of these six context sources or context domains (user, terminal, application, network, provider, and handoff). The context information is the base that supports the entire handoff process and the achievement of multiple desirable features. Therefore, such information should be arranged in a clear structure. We organize the handoff context according to the source where it originates and according to the class of information it represents. Table 3-1 and Table 3-2 show these arrangements.

Table 3-1. Handoff context information structured by sources.

Sources of Context	Context Information Description
User	Allows users to customize the handoff process according to their own needs, habits, and preferences. It contains the user preferences, user priorities, user profiles, and user history.
Provider	Includes connection fees, billing models, roaming agreements, coverage area maps, security management (AAAC), types of services (data, voice, video), provider preferences, and provider priorities. Negotiation models may be required to equate differences between service providers, network operators, and mobile users [64].
Application	Includes the QoS requirements of running applications. The QoS parameters are composed by the rate of lost packets (rLP), delayed packets (rDP), corrupted packets (rCP), duplicated packets (rDuP), jittered packets (rJP), goodput or data transfer rate (DTR), out-of-order delivered packets (rOOD), application type (AppT), etc. These parameters help to develop QoS-aware handoffs [43].
Terminal	Contains parameters for evaluating: the link quality, the power management, and the geographic mobility. These conditions allow the deployment of traditional (single-criterion) handoffs [32], power-based handoffs [44], and location-aided handoffs [63]. • Link quality: RSS, SNR, SIR, SNIR, BER, BLER, CCI, CIR. • Power management: battery types (BT), battery load (BL), energy-consumption rate (ECR), current network transmit power (TPC), target network transmit power (TPT), etc. • Geo-mobility: velocity, distance, location, direction, etc.
Network	The network performance context includes parameters such as bandwidth (NBW), load (NL), delay (ND), jitter (NJ), throughput (NT), MTU, etc. These parameters are needed to avoid selecting congested networks (before handoff), to monitor service continuity (during handoff), and to assess the handoff success by measuring network conditions (after handoff).

Handoff	The handoff performance context includes parameters such as Call Blocking (CB), Call Dropping (CD), Handoff Blocking (HOB), Handoff Rate (HOR), Handoff Latency (HOL), Decisions Latency (DLat), Execution Latency (ExLat), Evaluation Latency (EvLat), Handoff Type (HOType), Elapsed Time Since Last Handoff (ETSLH), Interruption Rate (IR), Interruption Latency (IL), Degradation Rate (DR), Degradation Latency (DL), Degradation Intensity (DI), Utility Function (UF), Signaling Overload (HOSO), Security Signaling Overload (SSO), Improvement Rate (ImpR), Application Improvement Rate (AppImpR), User Improvement Rate (UsrImpR), Terminal Improvement Rate (TermImpR), Successful Handoff Rate (SHOR), Imperative Handoff Rate (IHOR), Opportunist Handoff Rate (OHOR), Dwell-Time in the Best (DTiB), Authentication Latency (AL), Detected Attacks Rate (DAR), Online User Interventions Rate (OUIR), Tardy Handoff Rate (THOR), Premature Handoff Rate (PHOR), etc. This information may be used to keep up historic data about the handoff and to evaluate the handoff performance.

The handoff desirable features determine the context information the handoff process will need, but also, the context that is available to a handoff control entity (HCE) determines the purposes that such handoff will be able to achieve; i.e., handoff desired features and handoff context are correlated. In general, we expect a multi-purpose handoff not only makes use of multiple criteria during its operation, but multiple criteria coming from all context domains. Now, we organize the handoff context information according to different roles the context takes to support the handoff control process.

Table 3-2. Handoff context information structured by classes.

Class of Information	Context Information Description
Handoff Criteria	Context data or variables from the external or internal environment, which are commonly used as input to handoff algorithms. Handoff algorithms use different criteria to support different tasks, e.g., network discovery, decision-making, and

	performance evaluation. Some examples of handoff criteria include RSS, NL, BL, rLP, maximum HOL, terminal velocity, connection price. Handoff criteria are characterized to be dynamic, distributed, extensive, and heterogeneous, therefore they have to be periodically collected and normalized so that they can be combined within a single utility function. It is important to have a broad set of handoff criteria to achieve a broad spectrum of handoff objectives.
Handoff Metrics	Mathematical models that combine a variety of handoff criteria into a single utility function to help the handoff algorithm to make optimal decisions. Utility is a measure of relative satisfaction that can be helpful in deciding why, where, how, who, and when to initiate a handoff. HO metrics can be used to measure several properties along the handoff process; e.g., the quality of links, the quality of communications, the quality of networks, the quality and quantity of handoffs, the quality of providers, the achievement of user preferences, the power budget of a mobile terminal, the geographic mobility of a user, etc. HO metrics may be formed by a single criterion, thus handoff criteria are also handoff metrics.
Performance Measures	Parameters used individually or within a metric to quantify the performance of applications (QoS parameters), networks (NBW, NL, NT, etc.), handoffs (e.g., HOR, HOL, ETSLH, etc.), and achievement of particular handoff objectives (e.g., DTiB, IR, OUIR, ImpR, SHOR, etc.)
Handoff Policies	Users and providers define *rules* for controlling the handoff operation; e.g., what to do if link quality drops below a threshold, how to choose the best target network, when to trigger a handoff to the best available network, who should trigger it, etc. Handoff policies from users may be in conflict with those from providers; e.g., providers might be more interested in providing QoS, while users might be more interested in using the cheapest available connection. Therefore, a handoff policy manager should consider this type of conflicts.

Handoff Constraints	Conditions that must be satisfied in a particular handoff scenario. They control the handoff operation by keeping performance parameters within specific tolerance ranges. For instance, for a seamless handoff process, delay has to be kept within certain boundaries; for real-time applications a delay of 50 ms could be acceptable, whereas non-real-time applications might accept delays as long as 3-10 sec [14]. Thus, in the situation where a terminal operates both with real-time and non-real-time applications, the delay bounds are naturally dictated by the real-time traffic.
Handoff Configuration	Handoff algorithms use a variety of configuration parameters such as thresholds, timers, hysteresis margins, weights associated to factors, etc. The handoff configuration process should be performed offline to avoid user distractions. Typically, the configuration information is organized in a handoff profile linked to a particular user, provider, and terminal. A handoff profile defines user/provider preferences, priorities, and other initialization parameters required to customize the handoff operation. The handoff profile may be set up by the user, the provider, or self-configured.

Structures in both tables are useful in the process of creating a cognitive handoff functional architecture. We have identified sources of context, the kind of information each source produces, and the different functions the handoff context takes to support the cognitive handoff process. Now, it is time to discuss the variety of handoff scenarios.

3.1.4 Taxonomy of Handoff Mobility Scenarios

Using a holistic approach we created a new taxonomy of handoff mobility scenarios derived from combining all the possible transition elements involved in handoffs. Such elements are radio channels, base stations, IP networks, service providers, and end-user terminals. This taxonomy depicts all different kinds of handoffs that are possible to be found in real networks. It is important to make a classification of handoffs according to the elements involved during the transition because its complexity and treatment depend on the type of handoff that is occurring.

A handoff will require of services from distinct OSI model layers depending on the elements involved in the transition. For example, a handoff between channels of the same cell is a layer 1 handoff; a handoff between cells (base stations) is a layer 2 handoff, it is homogeneous if cells use the same wireless technology, otherwise is heterogeneous; a handoff between IP networks is a layer 3 handoff; a handoff from one provider to another or between user terminals will demand the services of layers 4-7. Figure 3-3 depicts the hierarchical structure of a mobile Internet in a four-layer design (core, distribution, access, and mobile). Different overlay sizes are shown for macro, micro, pico, and femto cells. We use this figure to explain a handoff hierarchy that involves channels, cells, networks, providers, and terminals.

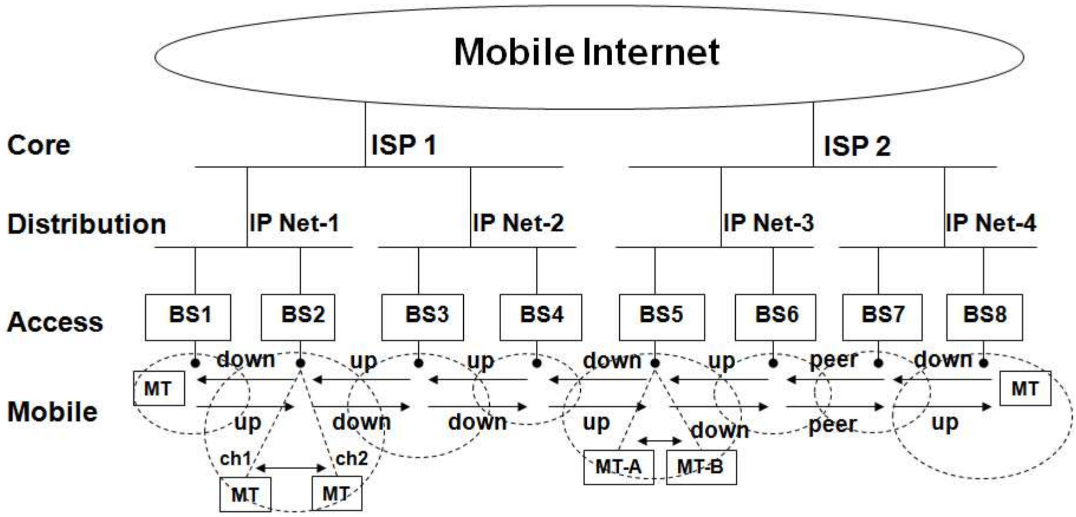


Figure 3-3. Hierarchy of handoff mobility scenarios.

The mobile Internet is divided into independent administrative units called Autonomous Systems (AS). An AS is a network administrated by a single organization or person. The Internet is a network of autonomous systems. Figure 3-3 depicts two autonomous systems called ISP1 and ISP2 for two distinct service providers. Every ISP uses a very high-speed core network where main servers are located. Providers divide their distribution networks, physically and logically, into a number of IP networks, subnets, or VLANs (Virtual LANs), where the types of services and users are separated. Each IP Net includes a group of base stations or access points with the same or different wireless access technology. Base stations get distributed across a geographic area to offer mobile communication services. Each base station controls a cell that may have a group of channels to distribute among the associated terminals or a single channel that is shared among several associated terminals.

In figure 3-3, BS2 illustrates a layer 1 handoff when the mobile terminal (MT) changes its connection between channels ch1 and ch2 without changing of BS, IP Net, ISP, or MT. A layer 2 handoff is illustrated between BS1-BS2, BS3-BS4, BS5-BS6, and BS7-BS8. A layer 2 handoff changes from one channel to another and from one base station to another, but keeps the same IP Net, ISP, and MT; however, if the cells involved are heterogeneous, then the handoff is *vertical*, otherwise is *horizontal*. A layer 3 handoff is depicted in BS2-BS3 and BS6-BS7. A layer 3 handoff changes from one channel to another, from one cell to another, and from one IP network to another, but preserves the same provider and the same terminal; the layer 3 handoff may be heterogeneous, like in BS2-BS3, or homogeneous, like in BS6-BS7. We represent a layer 4-7 handoff, in BS4-BS5, when MT changes its communications from on channel to another, from one cell to another, from one IP Net to another, and from one ISP to another, but the user keeps the same terminal. The encryption schemes and data representation formats change from one provider to another, thus higher layer services are required. Inside the cell for BS5 we depict a handoff between terminals where the user transfers the whole session (current state of running applications) from terminal MT-A to terminal MT-B. Handoffs between terminals can be done for terminals within the same cell or different cells, within the same IP network or different IP networks, within the same provider or different providers. The terminal handoff depicted in BS5 keeps the same cell, same IP Net, and same ISP.

Figure 3-4 presents a process diagram that generates the complete taxonomy of handoffs by following the different paths from the upper node to the lower nodes. Every handoff type in this taxonomy should be complemented or further classified according to many other criteria by using the handoff classification tree of Nasser in [7]. There are 15 types of feasible handoffs that can be implemented in real wireless overlay networks. The 1Fh is not a handoff.

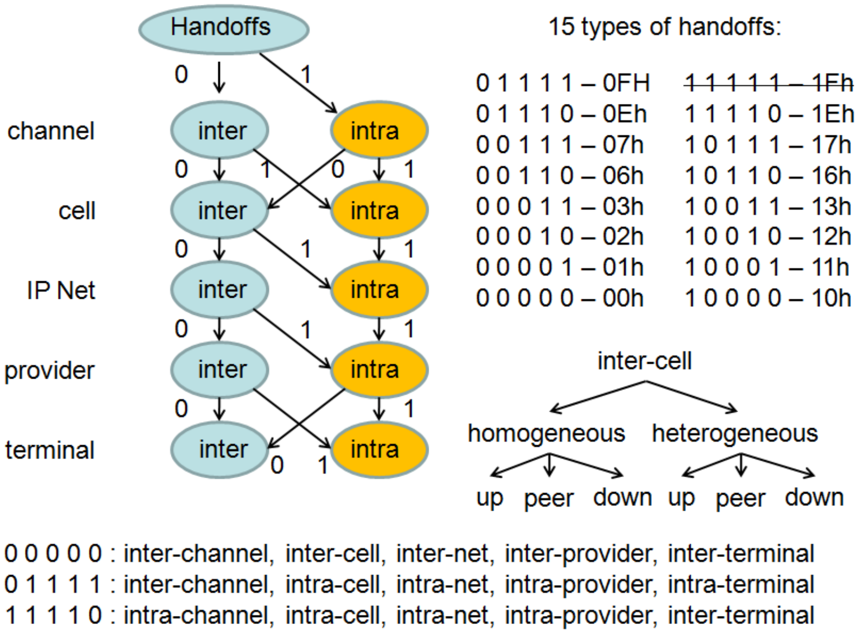


Figure 3-4. Generation process for handoff taxonomy.

3.2 Methodology for Developing Cognitive Handoffs

Once we have given a holistic vision about cognitive handoffs, we will provide a model-driven methodology for the systematic development of cognitive handoffs. We start by discussing some of the existing difficulties for developing cognitive handoffs; then, we describe a top-down procedure that will systematically lead us to the development of cognitive handoffs.

3.2.1 Difficulties for Developing Cognitive Handoffs

The simple idea of achieving multiple purposes simultaneously is challenging even for humans. Moreover, if the intended purposes represent opposing situations which all of them are desired, then even humans need a way to balance the different purposes in conflict; e.g., the conflict between doing the job accurately and doing it quickly. In optimization theory, multi-objective optimization states that improvements to a single purpose can be made as long as the change that made that purpose better off does not make any other purpose worse off. This is called a *Pareto improvement*. When no further Pareto improvements can be made, then the solution is called Pareto optimal [60]. Therefore, the first difficulty in developing cognitive handoffs arises because there are many handoff purposes, objectives, and goals in conflict that need to be tradeoff. A second significant difficulty emerges because numerous sources of environment information need to be considered to achieve the desired multiple purposes. Such sources produce context data that need to be collected, transformed, and distributed to different handoff control entities (HCEs). The challenge is how to manage large amounts of unsorted high-dimensional data that have very complicated structures and at the same time reducing the signaling traffic overload produced by this task. The last significant difficulty is originated by the diversity of transition elements involved in the handoff process. Such variety of transition elements produces a large amount of handoff scenarios that need to be considered for an adaptive handoff scheme.

3.2.2 Design and Development Procedure

Adapting the model-driven paradigm and following a form of top-down procedure, we list key steps needed for developing cognitive handoffs. Figure 3-5 depicts the general steps that are followed by the proposed methodology.

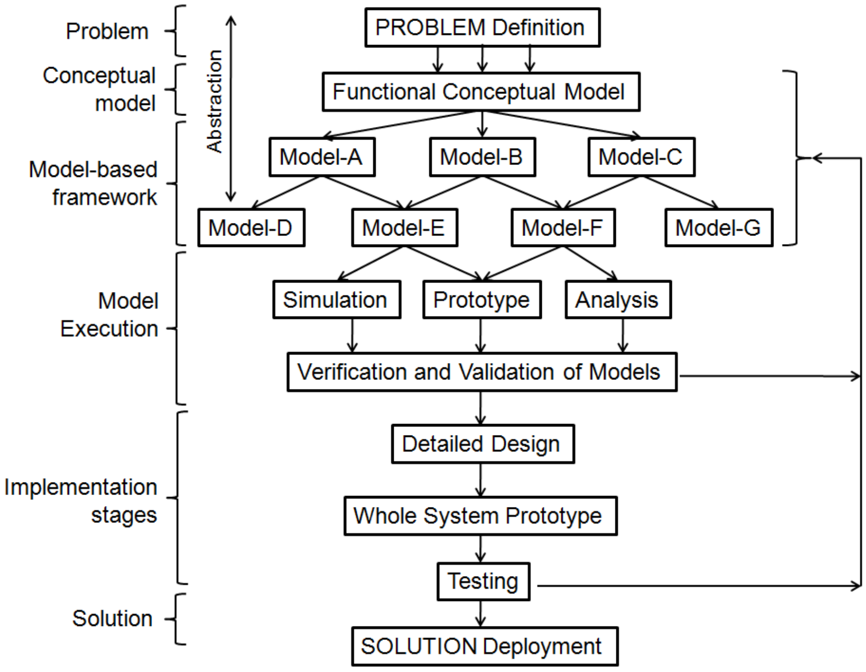


Figure 3-5. Model-driven methodology for developing cognitive handoffs.

1) Describe the problem: An initial step is to define and understand the problem. In simple words, our problem is to develop a handoff procedure that can optimally achieve multiple desirable features simultaneously. The handoff procedure should be implemented for operating in real scenarios with multiple dimensions of heterogeneity; i.e., it should be aware of its entire environment.

2) Define a Cognitive Handoff Conceptual Model: A functional conceptual model is the more abstract representation of the cognitive handoff operation. The following two steps comprise the construction of the conceptual model: a) Identify and analyze the required system functions (or desirable features to achieve). Study the desirable handoff features that are going to be implemented and determine the purpose, objectives, and goals associated to every attractive feature. Associate a general purpose to every desirable feature. Decompose each purpose into one or more objectives by identifying the performance parameters that help to quantify the achievement of every purpose. In the same way, divide every objective into more specific handoff goals using optimization values and handoff context data. b) Determine the required handoff context information. Establish what handoff criteria, handoff metrics, performance measures, handoff policies, handoff constraints, and handoff scenarios are needed by each desired purpose. Study the availability, locality, dynamicity, structure, and complexity of variables, policies, and constraints to use. This conceptual model helps to identify correlations between context data and desirable handoff features.

3) Design a subsystem structure or model-based framework: Using functional decomposition, divide up the conceptual model into a number of sub-models. Every sub-model corresponds to a particular subsystem that functionally is part of the whole handoff problem. The structure of the system may be represented through a *hierarchy* of models or framework enclosing the parts of the whole system organized by functional relations. Models in this framework describe the system behavior in an accurate and unambiguous way if one uses a finite set of states and a set of transition functions; thus, to ease this part, you should identify the associated system states and phases. These dynamic models can be formally represented using finite automata, Petri nets, timed automata, etc. [57]. The states or phases of the handoff process should describe a general behavior rather than specific details of particular sub-models.

4) Execute the models: Execution of models allows verification and validation of such models. This is the difference between just drawing pictures and making pictures “live” as it was pointed out by Hoffmann in [53]. However, verification and validation should not be confused. Model verification means to test if the model satisfies its intended purposes or specifications. Model validation tests if the model provides consistent outcomes that are accurate representations of the real world. We use three strategies for these tasks: simulation, prototyping, and analysis. Whatever the strategy we choose, model testing or model checking [65] requires the use of a formal notation; e.g., modeling languages for simulation, mathematic and logic for analysis, and programming languages or middleware for model prototype implementation. If a model cannot be properly validated or verified, then it must be redesigned within the framework.

5) Implementation stages: Once all the models in the framework have been individually tested, the design problem now reflects a well-structured solution. A detailed design can now be generated considering the entire framework of models. This whole system design should be implemented in a whole system prototype. The final prototype is ready to be tested in-situ; if any failure occurs during testing, then the conceptual model or any sub-model in the framework should be reviewed.

6) Solution deployment: The cognitive handoff solution is ready to operate on a real handoff environment. The solution system (cognitive handoff) provides a simultaneous accomplishment of the multiple purposes defined by the handoff problem. Each purpose should be associated to quantitative objective functions to measure the degree in which every handoff purpose was achieved.

3.3 The Cognitive Handoff Functional Architecture

Following the indications of step 2, we start by creating a cognitive handoff conceptual model. This model is initially set up by interconnecting the intended desirable handoff features to implement with multiple context domains. Figure 3-6 depicts a high abstraction model representing this idea.

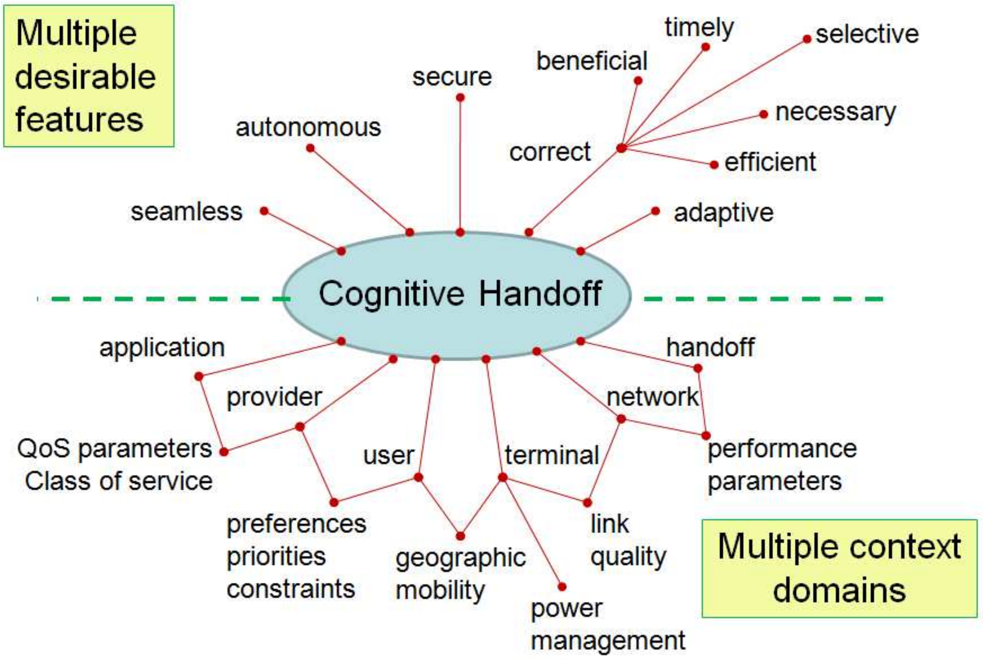


Figure 3-6. The cognitive handoff conceptual model.

This model is intended to understanding and explaining the complexities of developing cognitive handoffs. Models like the one we present here are validated by credibility, and credibility comes from the way in which the cognitive maps are built and the clarity it represents most of the experts' opinions [66]. Now, but as part of this conceptual model, we assign a qualitative purpose to every desired feature, and a set of quantitative objectives and goals to every handoff purpose. Table 3-3 outlines such associations.

Table 3-3. Desired features, purposes, objectives, and goals.

Desired Handoff Features	Qualitative	Quantitative	
	Purposes	Objectives	Goals
Seamless	Maintain the continuity of services	• Reduce the number, latency, and intensity of service degradations (DR, DL, DI) • Reduce the number and latency of service interruptions (IR, IL)	• Minimize (BER, CCI, BLER, NL, ND, NJ, rLP, rDP, rCP, rDuP, rJP, TPC, TPT, ECR, CB, CD, HOB, HOL) • Maximize (RSS, SNR, SNIR, SIR, CIR, NBW, NT, MTU, DTR, BL, ETSLH)
Autonomous	Preserve the handoff operation independent of users	• Reduce the number OUIR	• Maintain (IL < app.Timeout)
Secure	Maintain a constant level of security along the handoff	• Reduce SSO • Reduce DAR	• Minimize (AL, HOSO, HOL) • Maintain (High Encryption)
Correct	Keep the user always best connected with minimal handoffs	• Reduce HOR • Increase DTiB	• Minimize (HOR) • Maximize (DTiB)
Adaptive	Keep success of all handoff objectives across any scenario	• Increase SHOR • Multi-objective optimal balance	• Keep every desirable feature within its success range • Maximize (SHOR)
Necessary	Prevent unnecessary handoffs	• Start HO only if it is imperative or opportunist • Maintain HOR = IHOR + OHOR	• Imperative if UFcurr < Thinf • Opportunist if UFcurr > Thsup • UFtraget is SuffB & ConB
Selective	Avoid selecting the wrong target	• Verify UFtarget is suffB and conB	• SuffB: UFtarget > (UFcurr+Δ) • ConB: SuffB is maintained by SP time
Efficient	Operate quickly and well-organized to decide how to perform the HO	• Select the best method, protocol, or strategy according to HOType, AppType, mobility state • Reduce DLat, ExLat, EvLat	• Choose MIP protocol if … • Choose SIP protocol if … • Choose MAHO if … • Choose NAHO if …
Beneficial	Augment benefits to applications, users, and terminals after handoff	• Have a better UF after HO or a maximum improvement rate (UFnew/UFold)	• Maximize (ImpR) • Maximize (ApplmpR, UsrImpR, TermImpR)
Timely	Initiate a HO not tardy and not prematurely	• Reduce THOR, PHOR	• Maintain DLat within its tolerance range

This table represents a relevant preliminary result of the applicability of cognitive handoff methodology. On one hand, they help to reduce the ambiguity and confusion on the usability of similar handoff features because every desirable handoff feature is defined in qualitative terms (purpose) and quantitative terms (objectives and goals). On the other hand, they help to correlate context data with desirable features. For instance, from Table 3-3, we observe that RSS is correlated with seamlessness, IL with autonomy, AL with security, etc. This correlation is intended to select the context data that is needed to support every handoff purpose.

Now, going forward to step 3, we use the functional decomposition approach [52] to expand the oval in the middle of figure 3-6 into several subsystems. Figure 3-7 shows the main functional subsystems for cognitive handoffs represented in ovals: handoff control algorithm, network discovery, handoff decisions, handoff execution, handoff evaluation, and handoff context information management. The desired features provide purposes, objectives, and goals to achieve, while context domains provide the information needed to attain such goals. We briefly describe these functional components:

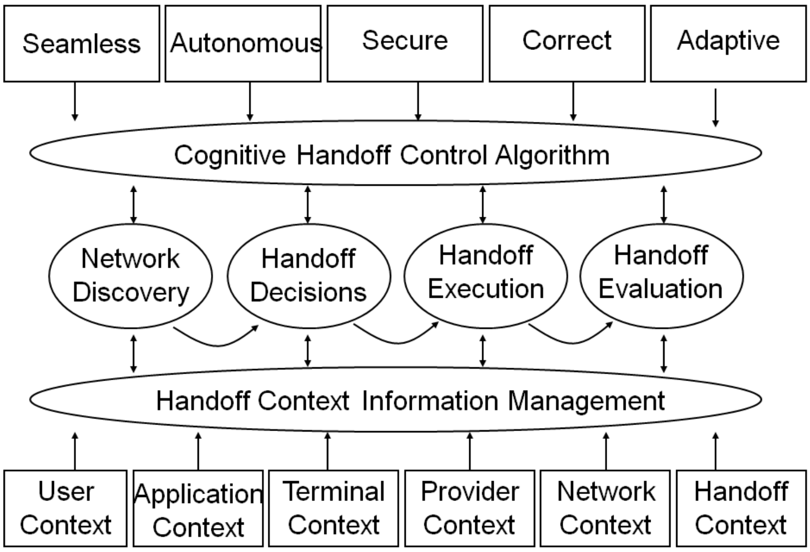


Figure 3-7. First-level functional decomposition model for cognitive handoffs.

Cognitive Handoff Control Algorithm

This is the main director of the handoff procedure. The entity which implements the control algorithm is called HCE. There should be one HCE in every user terminal and also there may be many others distributed across the network infrastructure. HCEs are agents that cooperate and compete to take a particular handoff to succeed. Thus, the cognitive handoff system is expected to be implemented through multi-agent systems.

Network Discovery

This is the system for detecting and discovering available access networks. An available access network is a reachable and authorized network that is considered for an eventual handoff. Thus, available networks are pre-authenticated networks.

Handoff Decisions

The handoff decisions system is intended to answer the questions of why, when, where, how, and who should trigger the handoff. To answer these questions correctly is a significant challenge because the consequences of giving a bad answer will impact directly in the performance of the whole handoff system. Many authors have focused only in answering where and when to handoff (e.g., [45]); however, our handoff holistic vision extends the scope of handoff decisions.

Handoff Execution

This system is intended to change the physical and logical connection from one network to another, from one provider to another, or form one terminal to another. This change requires the most effective method, protocol, or strategy according to the current handoff scenario. The MIPSHOP group at IETF and the 802.21 workgroup at IEEE are creating tools for implementing media independent handoffs since 2003.

Handoff Evaluation

This system measures the achievement of every desirable handoff feature and determines whether the executed handoff was successful or not. The evaluation results should be delivered after the handoff execution, but within strict time constraints. Thus, this task is better to be proactively distributed along the handoff process.

Handoff Context Information Management

This system is intended to collect the distributed handoff context data, transform the data into information, and redistribute this information to the HCEs which are responsible for making handoff decisions and control.

Discovery, decisions, execution, and evaluation systems can be viewed as sequential stages of the handoff process; however, the context manager is a background process which permanently supplies the handoff control entities with fresh information about the handoff environment.

The subsystem structure depicted in Figure 3-7 can be further decomposed into more detailed functional subsystems, which begin to form what we call the cognitive handoff model based framework. So, going deeper into the structure of a major component of the handoff system, we focus on the cognitive handoff control system. At this stage, we designed a *state-based model* whose purpose is to understand the general functionality that should have the handoff control system. Thus, this model represents a significant outcome from applying the third step of the proposed methodology.

Figure 3-8 shows a five-state diagram modeling a general control handoff process. This state diagram shows a reactive and deterministic behavior of cognitive handoffs. The states are: (1) Disconnection, (2) Initiation, (3) Preparation, (4) Execution, and (5) Evaluation. This model describes a generic control handoff system coordinating the stages before, during, and after the handoff. We describe each state briefly:

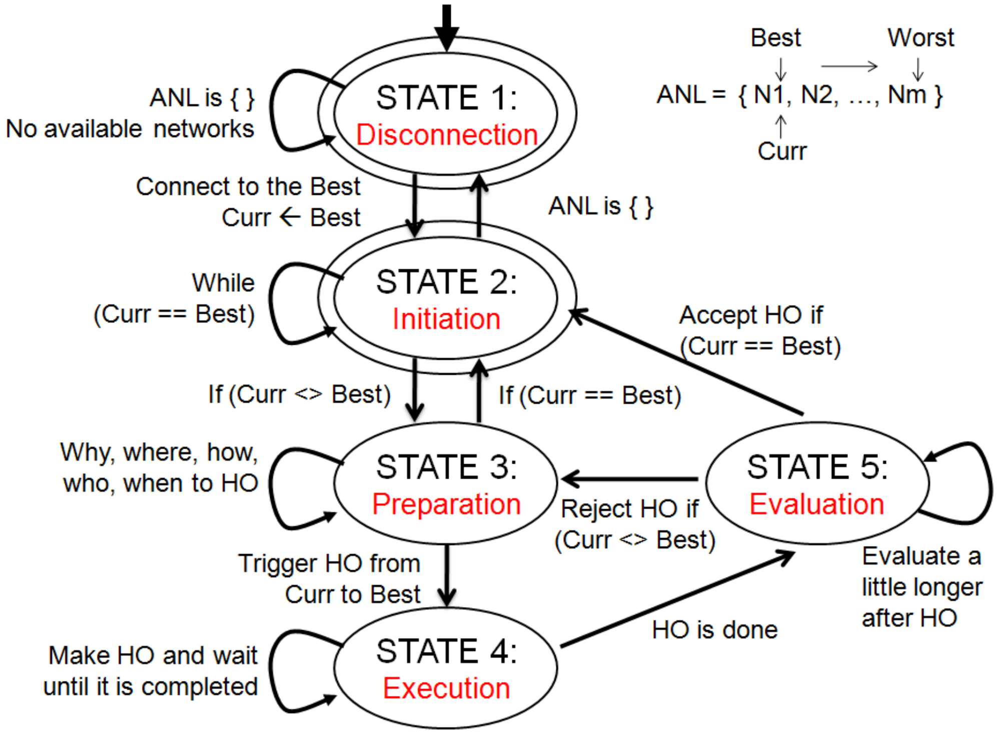


Figure 3-8. A handoff control state-based model.

State 1 - Disconnection: is the initial state and one of the two final states. Here, the terminal is disconnected but discovering available networks. As new available networks are discovered, they are arranged into an ordered and dynamic list named ANL. The process will stay here while there are no available networks.

State 2 - Initiation: In this state, the terminal is connected to the best available network and communications flow normally. This is another final state. The process stays here while there are no reasons (imperative or opportunistic [67]) to prepare for a handoff. If current connection breaks and no other networks are available, then the process goes back to disconnection state.

State 3 - Preparation: As soon as a better network appears, the process changes to the preparation state. Here is where properly the handoff begins. This state decides why, where, how, who, and when to trigger the handoff. The handoff in progress can be rolled back to initiation if current link becomes again the best one.

State 4 - Execution: Once a control entity decides to trigger a handoff, there is no way to rollback; the handoff will be performed. This state knows the current and destination networks, the active application to be affected, and the strategy or method to use.

State 5 - Evaluation: Once the link switch is made, the control entity enters the evaluation state. This state combines the measures of every *objective function* taken before and during the handoff, with new samples taken after the handoff to determine its successfulness. The evaluation latency is adjusted according to a stabilization period [44].

Following the functional decomposition scheme described in the step 3 of the proposed methodology, we now turn our attention towards another important component of the functional subsystem structure, the handoff context information management. In fact, this subsystem works in closely cooperation with the control handoff subsystem. We explain this relationship through a Hierarchical Context Management Model (HiCOM) illustrated in figure 3-9 and presented originally in [48].

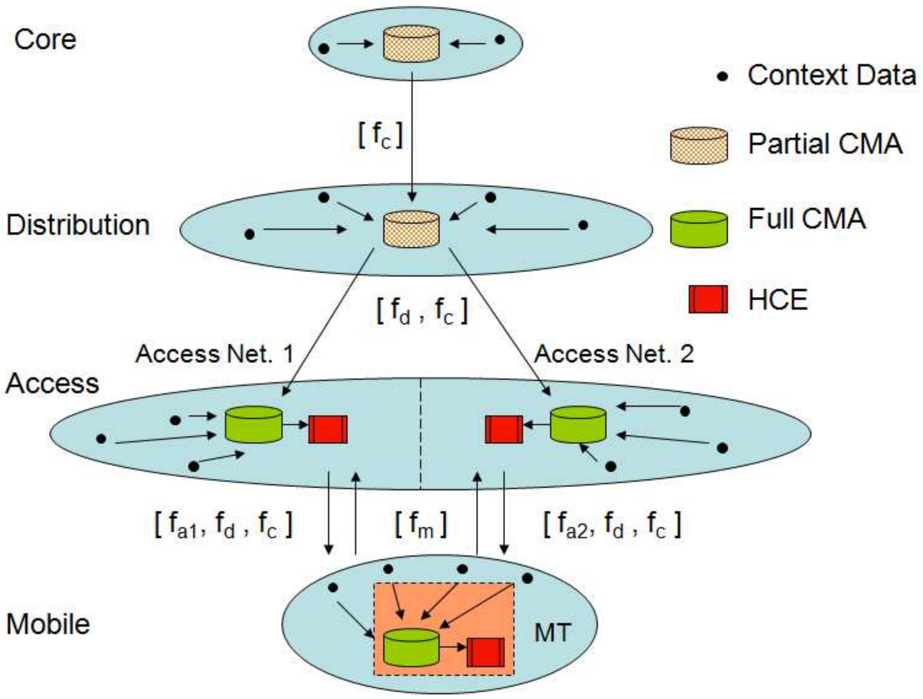


Figure 3-9. Hierarchical context management model (HiCOM).

First, we distinguish between agents for controlling the handoff process (HCEs) and agents for managing the handoff context data (CMAs); also notice that context data is distributed across all the network layers. The CMAs are responsible for collecting context data, transforming data into information, and distributing context information to the HCEs or to another CMA. CMAs are located in user terminals and distributed in all different layers of the network infrastructure. On the contrary, HCEs are located in every user terminal and access network. These control entities share the task of attaining the handoff process in every stage: discovery, decisions, execution, and evaluation. CMAs linked to HCEs are called full CMAs. CMAs linked to other CMAs are called partial CMAs. The collecting method we propose is based on the paradigm "collect only the closest data and distribute summarized information". This way, a partial CMA in the core acts as a collection point of context data "living" in the core. The partial CMA in the core collects only nearby context elements (c_1, c_2, …, c_N) and converts such context data into context information [f_c] by applying a utility function *f* to context data; i.e., $f_c = f(c_1, c_2, \ldots, c_N)$. The utility function *f* may represent a high level handoff metric like desirability, benefit, or cost.

Next, the core partial agent sends downward the core information to the partial CMA in the distribution layer. By distributing only [f_c] and not all the core context elements, we reduce the handoff context management traffic. The metric f_c effectively represents a summarization of all the core context data. Similarly, the partial CMA in the distribution layer collects only nearby context elements (d_1, d_2, …, d_M) from distribution layer, and transforms distribution context data into distribution context information by making $f_d = f(d_1, d_2, \ldots, d_M)$. Now, the distribution layer counts with f_c and f_d. Now, the partial CMA in the distribution layer updates [f_c, f_d] into the full CMA of each access network. Likewise, each full CMA in the access networks collects context data located on the same access network and creates f_{a1} for access network one, f_{a2} for access network two, etc. Equally, the full context agent in the mobile terminal performs context data collection within the mobile environment and converts the mobile context data into mobile context information f_m. We say that all the full CMAs converge when they have the same information at a given time. Figure 3-10 shows the message exchange sequence that will make the full CMAs converge after Δt. The mobile terminal is able to acquire context information from any other access network by using only its current access network. This facility allows the HCE has updated context information before and after handoff.

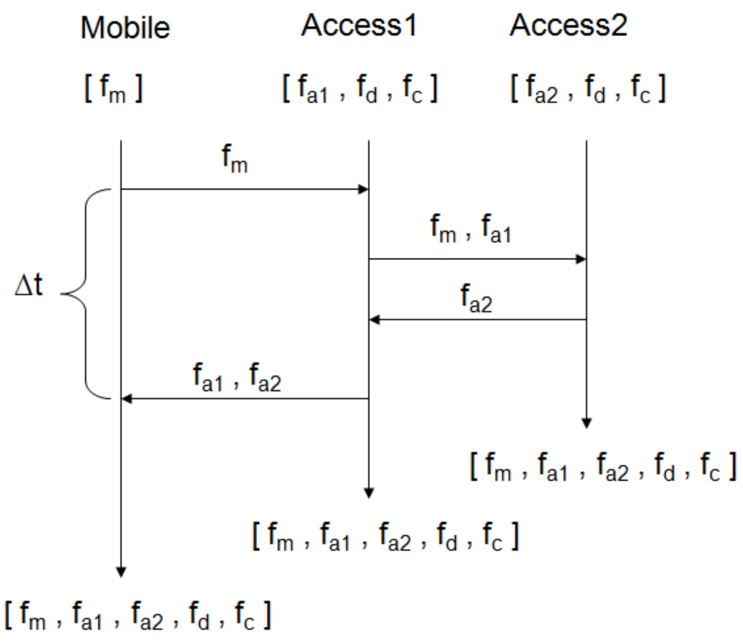


Figure 3-10. Message exchange sequence in HiCOM.

So far, we have applied the first steps of the cognitive handoff methodology and it starts to appear a hierarchy of sub-models exhibiting more details as we proceed. This set of models defines our cognitive handoff conceptual architecture.

3.4 Evaluating Cognitive Handoffs

The performance evaluation of cognitive handoffs requires a performance metric for each handoff purpose and a graphical representation to visualize multivariate data [68]. These metrics combine mathematically several performance measures that are associated to every handoff purpose. It is possible that metrics can normalize heterogeneous data into a single value representing the performance of each handoff purpose. Moreover, metrics can also be designed as utility functions so that greater values are better and all values are on the same scale. Figure 3-11 exemplifies a radar graph comparing the performance of multiple handoff purposes simultaneously. We say that if all measures range within a boundary circle of acceptable quality, then the cognitive handoff is successful, otherwise the handoff is defective and outliers should be corrected.

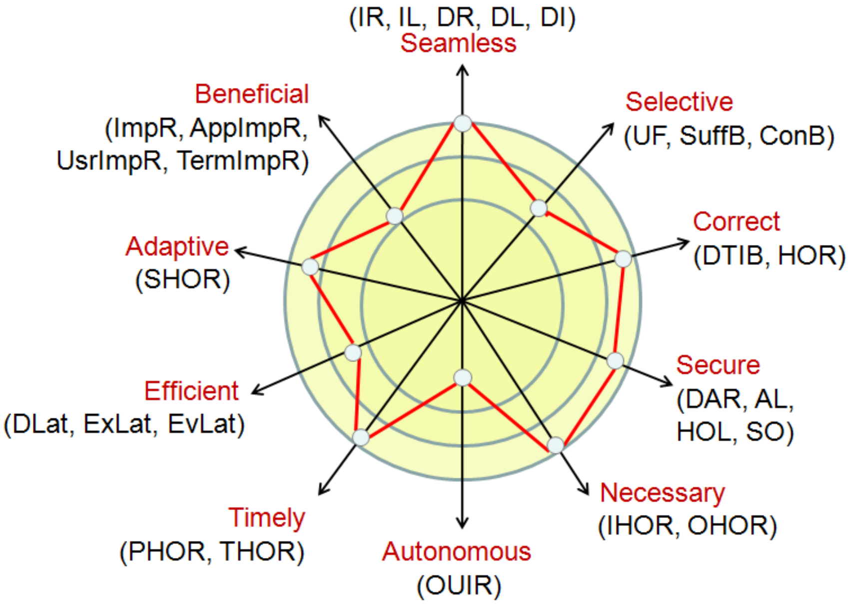


Figure 3-11. Radar graph comparing multiple objective functions.

3.4.1 Cognitive Handoff Performance Measures

The following performance measures can be used to evaluate the success of each handoff purpose:

- **Interruption Rate (IR)** is the number of network disconnections the terminal exhibits per unit of time. Higher interruption rates leads to service discontinuities, which can have a detrimental effect on the performance of seamless handoffs.

- **Interruption Latency (IL)** is the time duration for which communication services or data flows have been interrupted. Manual resets of terminals or applications might be necessary if interruption latency is excessive.

- **Degradation Rate (DR)** is the number of degradations per unit of time. Degradation is a reduction of the quality of communications that occurs when some context parameters fall out of its tolerance range. Service degradations normally arise before interruptions.

- **Degradation Latency (DL)** is the time duration for which the context parameters have exceeded the bounds of their tolerance ranges.

- **Degradation Intensity (DI)** is a metric that combines the number context parameters involved in the degradation and the difference between their exceeded values and their acceptance bounds. It measures how many and how far the context parameters have gone beyond their limits.

- **Utility Function (UF)** is a metric that combines different context parameters to measure relative desirability or satisfaction of various goods or services. For instance, a UF for link quality may combine RSS, SNR, and BER; a UF for network quality may use NBW, NL, ND, and NT; but, a UF for link and network quality might include RSS, SNR, ND, and NT. A UF can be obtained for every available network, terminal, or provider involved in a handoff.

- **Sufficiently Better (SuffB)** is a handoff constraint. We say target is better than current if UFtarget > UFcurr, but target is sufficiently better than current if [UFtarget > UFcurr + Δ], where Δ is a margin of goodness (configuration parameter).

- **Consistently Better (ConB)** is a handoff constraint. We say target is consistently better than current if [UFtarget(t) > UFcurr(t) + Δ] for Tmin ≤ t ≤ Tmax, where Tmin and Tmax are configuration parameters. The best network is both SuffB and ConB.

- **Dwell Time in the Best (DTiB)** is the time duration for which a terminal stays connected to the best network.

- **Handoff Rate (HOR)** is the number of handoffs per unit of time. Every handoff introduces signaling traffic and consumes network bandwidth and other resources. High handoff rates may lead to service degradations or service interruptions.

- **Detected Attacks Rate (DAR)** is the number of attacks or vulnerabilities detected along the handoff process. This task could be overwhelming for the handoff process because there are many methods of attack or intrinsic vulnerabilities that may not be easy to detect. Therefore, reducing handoff rate, handoff latency, and authentication latency are preventing measures that could in consequence reduce DAR.

- **Authentication Latency (AL)** is the time interval between an authentication request and an authentication response. In pre-authentication schemes this parameter is zero.

- **Handoff Latency (HOL)** is the global time that takes the handoff process to switch data flows from current to target. It initiates when a valid reason to prepare for a handoff emerges and the moment when communications have been switched and evaluated (HOL = DLat + ExLat + EvLat).

- **Signaling Overload (SO)** is the traffic load introduced to the network by the handoff algorithms and handoff protocols.

- **Imperative Handoff Rate (IHOR)** is the number of imperative handoffs performed per unit of time. An imperative handoff is performed if [UFcurr < Thinf] where Thinf is a lower degradation threshold (configuration parameter) and another UFtarget is the best available.

- **Opportunist Handoff Rate (OHOR)** is the number of opportunist handoffs performed per unit of time. An opportunist handoff is performed when [UFcurr > Thsup] where Thsup is the higher desirability threshold (configuration parameter) but UFtarget is the best available network.

- **Online User Intervention Rate (OUIR)** is the ratio of online user interventions to service interruptions.

- **Premature Handoff Rate (PHOR)** is the number of premature handoffs per executed handoffs. A premature handoff initiates before target is properly selected, i.e., when UFtarget is better but not consistently better.

- **Tardy Handoff Rate (THOR)** is the number of tardy handoffs per executed handoffs. A tardy handoff initiates after service degradations or interruptions have occurred.

- **Decisions Latency (DLat)** is the time interval between the initiation of a handoff request and the execution of the handoff request. All handoff decisions are made in this interval.
- **Execution Latency (ExLat)** is the time the control handoff algorithm takes to switch the physical and logical connectivity from current to target.
- **Evaluation Latency (EvLat)** is the time the control handoff algorithm takes to issue the handoff evaluation results after handoff execution.
- **Successful Handoff Rate (SHOR)** is the ratio of successful handoffs to the total number of performed handoffs.
- **Improvement Rate (ImpR)** is the total ratio of UFnew to UFold for measuring the improvement according to the quality of applications, terminals, and user preferences.
- **Application Improvement Rate (AppImpR)** is the ratio of UFnew to UFold but just for measuring the improvement on application quality.
- **User Improvement Rate (UsrImpR)** is the improvement rate for measuring the accomplishments of user preferences.
- **Terminal Improvement Rate (TermImpR)** is the improvement rate for measuring the improvement on terminal quality.

3.4.2 Formulating the Cognitive Handoff as a MOP

The evaluation of a cognitive handoff can be defined as a multi-objective optimization problem (MOP). This problem can be formulated as follows.

Let F be the set of desirable handoff features and C be the set of context data. We say that a context variable $V_i \in C$ is *correlated* with a desired feature $f \in F$ if and only if a change on the value of V_i impacts on the purpose of *f*. For instance, some changes on the value of SNR may degrade or improve the link quality and impact on the purpose of seamlessness; thus, we say that SNR is correlated with seamlessness.

Let V_f be the set of correlated variables with *f*, where $V_i \in V_f \subseteq C$. We say that V_i is *positively correlated* with *f* if and only if increments on the value of V_i produce improvements on the purpose of *f* and decrements on V_i produce degradations on the purpose of *f*. For instance, increments on SNR improve the link quality, which improves the service continuity of seamlessness, and conversely, decrements on SNR degrade the link quality, which degrades the service continuity of seamlessness. Therefore, SNR is positively correlated with seamlessness.

↑SNR → ↑LINKQUALITY → ↑SEAMLESSNESS
↓SNR → ↓LINKQUALITY → ↓SEAMLESSNESS

We say that V_i is *negatively correlated* with *f* if and only if increments on the value of V_i produce degradations on the purpose of *f* and decrements on V_i produce improvements on the purpose of *f*. For example, increments on BER degrade the link quality, which degrades the service continuity of seamlessness, and conversely, decrements on BER improve the link quality, which improves the service continuity of seamlessness. Therefore, BER is negatively correlated with seamlessness.

↑BER → ↓LINKQUALITY → ↓SEAMLESSNESS
↓BER → ↑LINKQUALITY → ↑SEAMLESSNESS

Hence, the set V_f is partitioned in two subsets V_f^+ and V_f^- where V_f^+ is the set of variables positively correlated with *f* and V_f^- is the set of variables negatively correlated with *f*. Every V_i has a weight W_i associated to its priority where $W_i \in \Re[0,1]$ and $\Sigma W_i = 1$. Let **v** represent the vector of variables $\mathbf{v} = (V_1, V_2, \ldots, V_m)$, then the *objective function* for the desired handoff feature *f* is defined by

$$f(\mathbf{v}) = \Sigma(K+W_i)\log(V_i^+) - \Sigma(K+W_i)\log(V_i^-) ,$$

where K is a scaling factor so that small changes on the context variables reflect big changes on $f(\mathbf{v})$. In this general objective function, V_i^+ and V_i^- are positively and negatively correlated variables of f. The objective function $f(\mathbf{v}) : \Re^m \rightarrow \Re$ is a utility function that we want to maximize because in desirable features the higher the value the better. Considering k different objective functions f_i that we want to maximize simultaneously, where some of them may be in conflict, then the multi-objective optimization problem can be stated as,

Maximize $\{f_1(\mathbf{v}), f_2(\mathbf{v}), \ldots, f_k(\mathbf{v})\}$

Subject to $\mathbf{v}_l \le \mathbf{v} \le \mathbf{v}_u$, where $\mathbf{v}_l$ and $\mathbf{v}_u$ represent bounds of the tolerance range.

3.4.3 Tradeoffs between Conflicting Objectives

A cognitive handoff is designed to achieve multiple objectives simultaneously. We can distinguish between objectives with complementary nature and those with competitive nature. Complementary objectives can be simultaneously optimized without any conflict between them, but competing objectives cannot be simultaneously optimized, unless we find compromised solutions, largely known as Pareto-optimal solutions or non-dominated solutions [60]. We describe several tradeoffs to consider in multi-objective handoffs:

a) *(Max. DTIB and Min. HOR)*: There is a tradeoff between maximizing the time to stay always best connected (DTIB) and minimizing the number of handoffs (HOR). The conflict arises because in a dynamic environment the best network is changing frequently and stochastically; thus, to maximize

DTIB is necessary to make frequent handoffs as soon as a new best is available. This increase in the number of handoffs creates a conflict with minimizing HOR.

b) *(Min. DLat and Max. SHOR)*: This tradeoff is between minimizing the handoff decisions latency (DLat) and maximizing the number of successful handoffs (SHOR). The conflict emerges because the less time elapsed to make decisions will necessary lead to reduce the number of successful handoffs; e.g., in case of imperative handoffs, DLat is reduced but this may lead to select an incorrect target because the selection time is also reduced.

c) *(Max. Size-of-Context-Info and Min SO)*: This is a tradeoff between minimizing the handoff signaling overload (SO) and maximizing the amount of handoff context information to be managed by the handoff control entities. The conflict arises because broad handoff information is required to attain multiple desirable features, but this will increase the amount of signaling traffic in the network.

d) *(User and Provider Preferences)*: Several conflicts may appear due to differences between provider and user preferences. For instance, providers may prefer networks within their own administrative domain while users may prefer networks with lower charges even if they are owned by other service providers. Users may prefer a Mobile Controlled Handoff (MCHO) while providers may prefer Network Controlled Handoffs (NCHO). Conflicts like these require a balance between different interests. Handoff protocols like Mobile Assisted Handoff (MAHO) and Network Assisted Handoff (NAHO) try to balance the handoff control [9].

Chapter 4

Case Study: A Correct Handoff Algorithm

This chapter presents the development of a case study about a specific kind of multi-objective handoff named correct handoff. For this purpose, the discussion is divided into four parts. The first part describes the correct handoff problem. The second part shows the correct handoff algorithm: description, pseudocode, and flowchart. The third part illustrates the development (specification, design, implementation, and testing) of a handoff simulation instrument addressed to evaluate the performance of the correct handoff algorithm. The fourth and last part presents the main results obtained.

4.1 The Correct Handoff Problem

Now, focused on the verification and validation of models, we create special case study following a reductionist approach and applying the step 4 of the proposed methodology. This case study is based on the conceptual models described in chapter 3, in particular, in the handoff control state-based model depicted in figure 3-8.

4.1.1 Problem Definition and Background

Let us initially define the correct handoff problem as follows:

"Design a handoff algorithm that performs the best balance between maximizing the dwelling-time in the best network and minimizing the rate of executed handoffs at every handoff scenario."

Networks are changing entities that may have sudden performance improvements or degradations depending on different factors; e.g., the current network operating conditions, the time of the day, the user geographic environment, the user mobility situation, etc. This implies that *the best network is changing in time*, perhaps abruptly and stochastically or perhaps smoothly and deterministically. Such behavior can be illustrated by considering the next scenario: A passenger with a handheld computer is surfing the web while he travels around the city in a bus. When the bus is stopped before a traffic light, normally no new networks appear in the scene and thus the best network may vary smoothly and deterministically, but, as the bus accelerates and moves, new networks may suddenly appear or disappear and thus the best network may change abruptly and stochastically. Therefore, the best network behavior cannot be easily classified as deterministic or non-deterministic because it may show both behaviors at different times.

The dynamic behavior of the best network condition requires a *handoff mechanism* that smartly switches the connectivity from one network to another. A major handoff purpose is to maintain the communications through the best network most of the time. This means to increase the dwelling-time in the best network (DTiB). However, every handoff places signaling traffic in the network which delays or redirects the normal packet delivery service. Signaling traffic overload may degrade or disrupt the user communications during transitions. Therefore, the number of executed handoffs (nEHO) should be reduced; but, minimizing nEHO and maximizing DTiB are objectives in conflict. This conflict emerges because if we want to increase DTiB, then every time a new best network appears in the *handoff scenario*, a transition from current to best should be quickly performed, but the cost of doing this is increasing nEHO. On the other hand, if we want to reduce nEHO, then we should avoid performing handoffs as soon as a new and better network appears in the scenario; but, this would imply to decrease DTiB. Thus, in general, increasing DTiB implies increasing nEHO, and, reducing nEHO implies reducing DTiB. This situation produces the necessity of designing a handoff algorithm that achieves the *best balance* between these conflicting objectives on *every* handoff scenario.

4.1.2 Problem Modeling

Desirability Function

The first aspect of the problem that we are going to model is the concept of *best network*. For this purpose we define the notion of *network desirability*. The desirability of a network is a measure of how attractive a network is in a given time. The desirability metric is a utility function that combines multiple network variables to produce a single numerical value for one specific network at one specific time. Weights are associated to each variable and assigned by the user or the service provider in order to rise or decrease the relevance of each variable within the function. Thus, *the best network is the one with the highest desirability value*.

Let $D_n(\mathbf{v}; t_k)$ be the desirability for the *n*th network at t_k time, where $\mathbf{v} = (v_1, v_2, \ldots, v_m)$ is the vector of *m* network variables considered to evaluate the network desirability. The set of variables is partitioned into two subsets $\mathbf{v}^+$ and $\mathbf{v}^-$, where $\mathbf{v}^+$ is the set of variables that are positively correlated to desirability (e.g., NBW, NT) and $\mathbf{v}^-$ is the set of negatively correlated variables (e.g., NL, ND). Thus, the network desirability function can be expressed as a balance between desirability and undesirability:

$$D_n(\mathbf{v}; t_k) = \Sigma(E + W_i)\mathit{log}(v_i^+[t_k]) - \Sigma(E + W_j)\mathit{log}(v_j^-[t_k]) \qquad (1)$$

Where W_i and W_j are weights associated to each variable such as W_i and $W_j \in \Re[0, 1]$ and $\Sigma W_i = \Sigma W_j = 1$ and E is a scaling factor so that “small” changes in variables reflect “big” changes in desirability. Variables $v_i^+[t_k]$ and $v_i^-[t_k]$ are the positively and negatively correlated variables evaluated in time t_k.

In fact, such function $D_n(\mathbf{v}; t_k) : \Re^{m+1} \rightarrow \Re$ represents a mapping from *m* network variables plus one parameter control (time), to a single real number representing the desirability of the *n*th network. The logarithm is used, as a normalization function, to allow homogeneous operations with heterogeneous variables. It is worth to note that the desirability real number is obtained by subtracting the contributions to desirability from the contributions to undesirability. For notation simplicity, let us make $D_n(\mathbf{v}; t_k) = D_n(t_k)$ whose domain is the time discrete interval $t_0 \leq t_k \leq t_p$ such that $t_k = t_0 + k\delta$ and $0 \leq k \leq p$ where the step δ represents the time increment at which the desirability function is evaluated and the total sampling time is $(t_p - t_0)$. Thus, the range of desirability is $[-\infty,+\infty]$ but, we can specify the existence of desirability thresholds.

Lower and Upper Thresholds

Desirability values below a lower threshold *L* are considered extremely undesirable to the degree that a network in this situation is unable to carry on communications, and therefore, it is not available any more or it is disconnected. On the contrary, the higher the desirability is above the lower threshold, the better is the network. This condition may be sustained without any upper desirability limit or until desirability values reach an upper threshold *U*. If an upper threshold is defined, then desirability values above *U* are considered extremely desirable, such that any network in this situation is considered the best available network. These regions of desirability are defined in Table 4-1. Therefore, below the lower threshold (*red region*) and above the upper threshold (*green region*) there is no way to say that one network is better than another. All networks in the red region are considered the worst network and all networks in the green region are considered the best network. Only in the *handoff region*, the region between thresholds or the region above the lower threshold, in case no upper threshold is defined, is that it is possible to compare network desirability values to decide which network is better. Thus, handoffs are performed only in the handoff region.

Table 4-1. Regions of desirability formed with two thresholds.

Region	Condition
Red or worst network	$D_n(t_k) < L$, for any t_k and L
Green or best network	$D_n(t_k) > U$, for any t_k, if U is defined
Handoff or region of HO execution	$L < D_n(t_k) < U$, for any t_k, if U is defined $L < D_n(t_k) \leq \infty$, for any t_k, if U is undefined

Desirability Graphics

The network desirability graphs can be constructed from a series of data points obtained when the network variables are evaluated by the utility function $D_n(t_k)$ at a given time. Any type of desirability graphic may appear in a handoff scenario; i.e., any of the following possibilities may occur: deterministic behavior or random behavior, discontinuous or continuous functions, smooth changes in desirability or abrupt changes. Due to these conditions, the graph of a network desirability function may contain breaks, bends, cusps, or points with a vertical tangent; therefore, we cannot assume that the network desirability function is a *differentiable function* along each point in its domain. Although the desirability function $D_n(t_k)$ may be step-wise differentiable in a sub-domain of the function, we prefer not to use the properties of derivatives in our handoff algorithm design because, in general, we do not know when the function will become non-differentiable.

A network desirability fitted curved can be used as an aid for data visualization, to infer values of the function where no data are available, and to visualize the variability of network desirability with time. We assume that after constructing a desirability fitted curve $d_n(t)$ for each available network, we can model it with polynomial functions (including roots or quotients of polynomials), transcendental functions (including trigonometric, logarithmic, and exponential functions), or a combination of both.

Handoff Scenarios

A handoff scenario can be considered as an instance of the running environment where the handoff algorithm will operate. In this way, a handoff scenario *s* is a data structure that is part of the *input* to the handoff algorithm. Although we are going to give more details on the inputs to our handoff algorithm in Section 4.2.1, by now, we are only interested in providing an overview of the data contained in a handoff scenario, this will allow to give reasons that show how the universal set *S* of handoff scenarios is countably infinite. A handoff scenario $s \in S$ is a tuple (N, D, W, L, U, δ) where

- *N* is the number of network desirability curves considered by the scenario.
- *D* is a set of mathematical expressions $d_1,\ldots,d_N$ where each d_k is a desirability curve.
- *W* is the rectangular window bounding the display and analysis of desirability curves; this area is determined by the initial and final coordinates (x1, y1) and (x2, y2), respectively.
- *L* is the lower desirability threshold.
- *U* is the upper desirability threshold.
- δ is the step time or dot time defined to plot desirability data points on the curve.

Now, let's discuss about the amount of different handoff scenarios that can be created. This discussion is relevant for a handoff algorithm intended to get the *best balance* between *nEHO* and *DTiB* at *every* handoff scenario.

First, the number of desirability curves in a handoff scenario is countable and perhaps infinite in theory. Second, the number of different mathematical expressions that can be used for modeling a desirability curve is uncountable; we can create desirability curves practically in an infinite number of ways, and this infinite is uncountable. Third, the number of rectangular windows for setting the boundaries of the handoff scenario is also uncountably infinite as long as the coordinates are expressed as pairs of real numbers. Fourth and final, the different ways for setting the upper and lower thresholds and the dot time is infinite and again uncountable if they are real numbers. However, we cannot have a half of scenario or any fraction of scenario as input to the handoff algorithm, therefore, we can count the number of input scenarios by mapping scenarios to natural numbers, and thus, we say that the space, S, of handoff scenarios is discrete but infinite. This conclusion raises the question: Is it possible to create a handoff algorithm that performs the **best balance** between maximizing *DTiB* and minimizing *nEHO* on **every handoff scenario**? We provide insights into this question in the next paragraphs.

Handoff Performance Parameters

In Section 3.4.1, we showed that there are many parameters that can be used to measure the performance of a handoff algorithm; however, for the purpose of the problem we stated in section 4.1.1, we will concentrate only in two handoff performance measures: DTiB and nEHO. These parameters take real values and integer values in the interval $[0, \infty)$, respectively. However, as such heterogeneous performance parameters need to be compared, thus they need to be *normalized*.

We define the *rate of Time in the Best* (rTiB) as the ratio DTiB/TST, where TST is the Total Simulation Time. TST is a user parameter defined through the coordinates of the visualization window in a handoff scenario. Clearly, DTiB cannot exceed TST; thus, DTiB varies in the interval 0 ≤ DTiB ≤ TST and therefore 0 ≤ rTiB ≤ 1. Similarly, we define the *rate of Executed Handoffs* (rEHO) as the ratio nEHO/ToX, where ToX is the number of *instantaneous handoffs* needed to stay *always* connected in the best network. It is important to notice that ToX counts only the crossing points occurring in the handoff region. In a *crossing* point, the slopes from the left and from the right are different. A handoff algorithm should not make more handoffs than ToX, thus, 0 ≤ nEHO ≤ ToX, and therefore 0 ≤ rEHO ≤ 1.

Best Balance, Worst Balance, and Fair Balance

Once we normalized the two performance parameters of interest, 0 ≤ rTiB, rEHO ≤ 1, and restate the objectives as maximizing rTiB and minimizing rEHO, we can define the concepts of best balance, worst balance, and fair balance. Figure 4-1 shows the solution space (rTiB, rEHO) defined by the square bounded by the coordinates (0, 0), (0, 1), (1, 0), (1, 1). The best balance occurs at rTiB = 1 and rEHO = 0 and the worst balance occurs at rTiB = 0 and rEHO = 1. The diagonal black dash line going between the best and the worst balance represents the fair balance which depicts the line of equilibrium between these two performance parameters. Results on the line balance meet the relation rTiB + rEHO = 1; it indicates that the proportion that maximizes rTiB is the same proportion that minimizes rEHO.

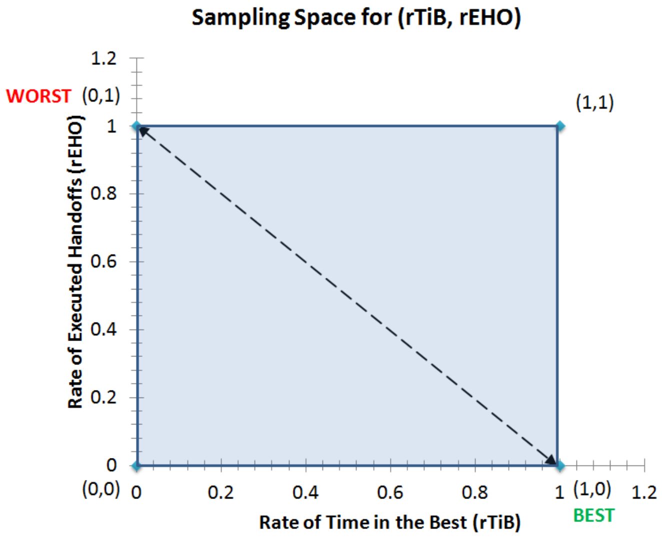


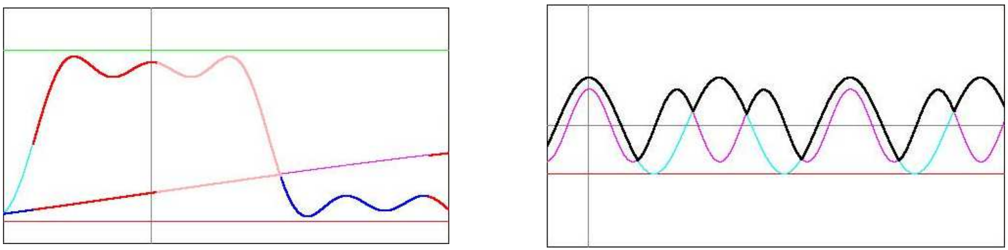
Figure 4-1. Sampling space for all possible results in the tuple (rTiB, rEHO).

The best balance means being always in the best network without executing handoffs; however, this is possible only if the best network is always the best network. Many handoff scenarios can be designed to meet this condition; but, in these cases there would not be any need for creating a handoff algorithm.

It is not very common that one single network be always the best network. Network desirability depends on many dynamic factors which contribute to have a variable desirability. Therefore, there are also many other handoff scenarios where the best network is dynamically changing among various networks. For this kind of scenarios is that a handoff procedure is required. The optimum balance cannot be reached if handoffs are executed (i.e., rEHO > 0). Every time a handoff is performed, the rate rEHO increases and gets apart from the optimal condition rEHO = 0. In other words, we are saying that the achievement of the best balance depends only on the handoff scenario and not on the handoff algorithm. The best balance can be reached only if the handoff scenario allows it.

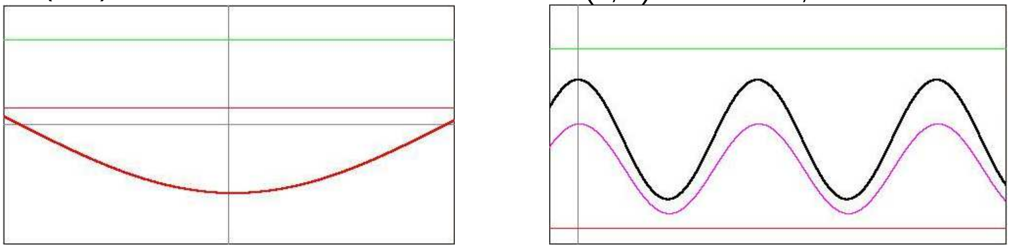
Sample Handoff Scenarios for each Vertex of the Unit Square

Figure 4-2 depicts instances of handoff scenarios corresponding to each vertex of the space of handoff performance results.



(0, 1) – Worst rTiB and rEHO

(1, 1) – Best rTiB, Worst rEHO



(0, 0) – Worst rTiB, Best rEHO

(1, 0) – Best rTiB and rEHO

Figure 4-2. Handoff scenarios at each vertex of the unit square.

Scenario (1, 0), defined by the tuple: (2, {3*S(x+1.5)+4; 4*C(x)+6}, [(-1,-1), (15,15)], 0, 12, 0.0001), depicts a best balance scenario, both rTiB and rEHO are optimized. Notice that in this scenario the best network is always the best network, hence, the best balance is reached without handoffs.

Scenario (1, 1), defined by the tuple: (2, {3*S(3*x+1.5); 4*C(2*x)}, [(-1, -10), (10, 10)], -4, ∞, 0.001), depicts an always best connected scenario performing *very fast* handoffs at each cross point. This scenario is unbalanced because it optimizes the rate of time in the best (rTiB = 1), but with the worst handoff rate (rEHO = 1). We simulate a very fast handoff, but not instantaneous, by making the latencies of preparation, execution, and evaluation, near to zero or smaller than the dot time (0.001) but greater than 0.

Scenario (0, 1), defined by the tuple: (2, {3*S(x/3) + 1.3656; 4*(C(2*x) - (1/3)*C(6*x) + (1/5)*C(10*x)) + 4 }, [(-1, -1), (2, 10)], 0, 8, 0.0001), depicts a worst balance scenario. In this scenario, neither rTiB nor rEHO are optimized; moreover, they take their worst values rTiB = 0 and rEHO = 1. In this scenario, the algorithm performs all the possible handoffs (nEHO = ToX = 2) but despite of this, the terminal never stays in the best network (i.e., DTiB = 0). This situation occurs when total handoff latency (i.e., preparation latency (blue = 0.2) + execution latency (red = 0.835) + evaluation latency (pink = 0.835)) is such that when the handoff is completed, the new network is not any more the best network, producing a *rollback* handoff to the original network. This is the famous ping-pong effect that handoff algorithms always try to prevent [41], but not always is easy to avoid.

Finally, scenario (0, 0) is another unbalanced scenario. It only optimizes the rate of handoffs (rEHO = 0) while rTiB takes its worst value (0). Any handoff scenario with network curves defined under the lower threshold, for all the simulation time, produces this result.

Redefining the Correct Handoff Problem

Previous discussions showed that the best balance cannot be reached by any handoff algorithm because this optimal result is reachable only for certain kind of handoff scenarios, independently of the handoff algorithm. It was also discussed that the sampling space representing all handoff scenarios is discrete and infinite; which implicates that it is not possible to test the performance on every handoff scenario. Therefore, the problem statement, as it was defined in the first section, needs to adjust the concepts of “best balance” and “every” handoff scenario, which are not possible to achieve. In fact, what we are arguing is that it is not possible to create a handoff algorithm that simultaneously obtain the best balance between rTiB and rEHO, and, get this optimum result on every handoff scenario. So, we restate the problem as follows:

"Design a handoff algorithm that performs a *good* balance between maximizing rTiB and minimizing rEHO and achieve this result on at least 90% of a series of random sampled scenarios."

Defining a Template with Levels between Worst and Best

Using the concepts of worst balance, best balance, and fair balance, we now define a template for grading the sampling space of (rTiB, rEHO). The template on Figure 4-3 defines different levels for “good” and “bad” results that may be produced by the handoff algorithm. Intuitively, we use the proximity to the best balance point (1, 0) to indicate how good a result is, and the closeness to the line of equilibrium to indicate how balanced a result is.

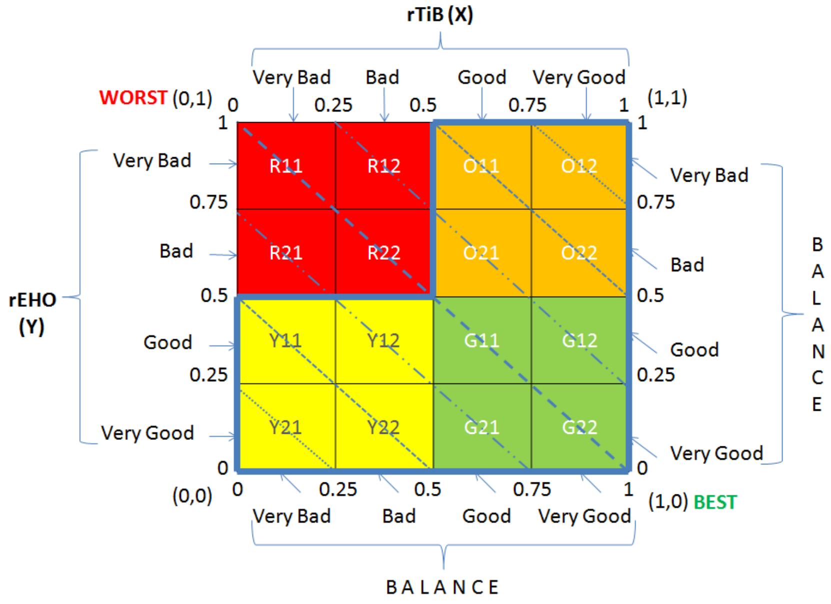


Figure 4-3. Template splitting the space of outcomes into different levels of results and balances.

We first are going to define what an unacceptable result is. Let X = {x | 0 ≤ x ≤ 1} be the domain of rTiB and let Y = {y | 0 ≤ y ≤ 1} be the domain of rEHO. A fair choice is to split the *domain* of each variable into two segments of equal size; i.e., 0 ≤ x ≤ 0.5, 0.5 ≤ x ≤ 1, 0 ≤ y ≤ 0.5, and 0.5 ≤ y ≤ 1. We say that rTiB is improved if rTiB ≥ 50%, otherwise it is worsened. Similarly, we say that rEHO is improved if rEHO ≤ 50%, otherwise it is worsened. An *unacceptable* or bad result (x, y) is one where both variables are worsened. On the contrary, an *acceptable* or good result (x, y) is that where at least one variable is improved. This initial division of the sampling space is depicted in figure 4-3 through a red (R), yellow (Y), orange (O), and green (G) square. R is the subspace of unacceptable results, while Y, O, and G represent the subspace of acceptable results. Table 4-2 shows a formal definition for acceptable and unacceptable results and boundaries between subspaces.

Table 4-2. Different types of acceptable and unacceptable results.

Result type	Improves	Subspace name	Subspace definition
Unacceptable	None	Red (R)	$\{ (x, y) \mid 0 \leq x < 0.5, 0.5 \leq y \leq 1 \}$
Acceptable	rEHO	Yellow (Y)	$\{ (x, y) \mid 0 \leq x < 0.5, 0 \leq y < 0.5 \}$
Acceptable	rTiB	Orange (O)	$\{ (x, y) \mid 0.5 \leq x \leq 1, 0.5 \leq y \leq 1 \}$
Acceptable	Both	Green (G)	$\{ (x, y) \mid 0.5 \leq x \leq 1, 0 \leq y < 0.5 \}$

Now, in order to get a finer scale, we make another fair choice by dividing the domain of each variable into four segments of equal size. This partition allows having four levels for each variable: very bad, bad, good, and very good. As depicted in figure 4-3, a total of 16 squares are created. Table 4-3, provides a formal definition for each subspace of results.

Table 4-3. Definition of 16 types of results for how good or bad a result is.

Result type	Space name	Subspace definition
Very Bad rTiB, Very Bad rEHO	R11	$\{ (x, y) \mid 0 \leq x < 0.25, 0.75 \leq y \leq 1 \}$
Very Bad rTiB, Bad rEHO	R21	$\{ (x, y) \mid 0 \leq x < 0.25, 0.5 \leq y < 0.75 \}$

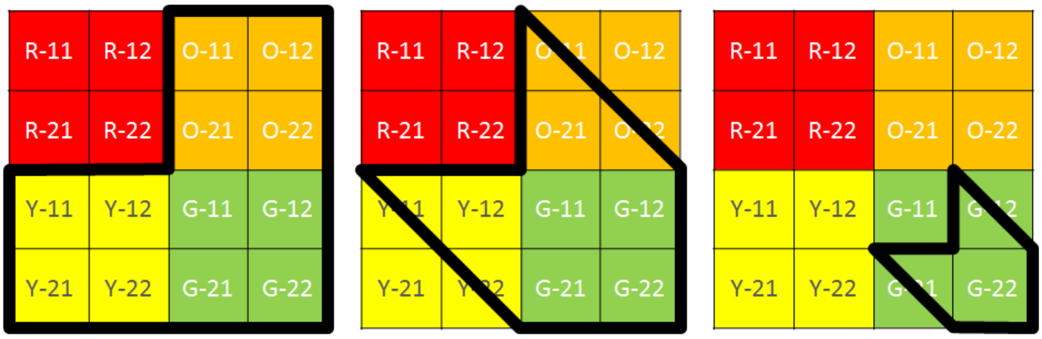
Bad rTiB, Very Bad rEHO	R12	$\{ (x, y) \mid 0.25 \leq x < 0.5, 0.75 \leq y \leq 1 \}$
Bad rTiB, Bad rEHO	R22	$\{ (x, y) \mid 0.25 \leq x < 0.5, 0.5 \leq y < 0.75 \}$
Very Bad rTiB, Good rEHO	Y11	$\{ (x, y) \mid 0 \leq x < 0.25, 0.25 \leq y < 0.5 \}$
Very Bad rTiB, Very Good rEHO	Y21	$\{ (x, y) \mid 0 \leq x < 0.25, 0 \leq y < 0.25 \}$
Bad rTiB, Good rEHO	Y12	$\{ (x, y) \mid 0.25 \leq x < 0.5, 0.25 \leq y < 0.5 \}$
Bad rTiB, Very Good rEHO	Y22	$\{ (x, y) \mid 0.25 \leq x < 0.5, 0 \leq y < 0.25 \}$
Good rTiB, Very Bad rEHO	O11	$\{ (x, y) \mid 0.5 \leq x < 0.75, 0.75 \leq y \leq 1 \}$
Good rTiB, Bad rEHO	O21	$\{ (x, y) \mid 0.5 \leq x < 0.75, 0.5 \leq y < 0.75 \}$
Very Good rTiB, Very Bad rEHO	O12	$\{ (x, y) \mid 0.75 \leq x \leq 1, 0.75 \leq y \leq 1 \}$
Very Good rTiB, Bad rEHO	O22	$\{ (x, y) \mid 0.75 \leq x \leq 1, 0.5 \leq y < 0.75 \}$
Good rTiB, Good rEHO	G11	$\{ (x, y) \mid 0.5 \leq x < 0.75, 0.25 \leq y < 0.5 \}$
Good rTiB, Very Good rEHO	G21	$\{ (x, y) \mid 0.5 \leq x < 0.75, 0 \leq y < 0.25 \}$
Very Good rTiB, Good rEHO	G12	$\{ (x, y) \mid 0.75 \leq x \leq 1, 0.25 \leq y < 0.5 \}$
Very Good rTiB, Very Good rEHO	G22	$\{ (x, y) \mid 0.75 \leq x \leq 1, 0 \leq y < 0.25 \}$

We have 16 levels for measuring how good or bad a result is, now we need some levels for measuring how balanced a result is. For this purpose, we further divide the space $X \times Y$ into four levels of balance: very good, good, bad, and very bad balance, as indicated in figure 4-3. These grades of balance are formally defined in table 4-4.

Table 4-4. Definition of 4 types of results for how balanced a result is.

Result type	Subspace definition
Very Good Balance	$\{ (x, y) \mid -x + 0.75 \leq y \leq -x + 1.25 \}$
Good Balance	$\{ (x, y) \mid -x + 0.5 \leq y \leq -x + 1.5 \}$
Bad Balance	$\{ (x, y) \mid -x + 1.5 < y < -x + 0.5 \}$
Very Bad Balance	$\{ (x, y) \mid -x + 1.75 < y < -x + 0.25 \}$

As we mentioned in redefining the correct handoff problem, our design goal is to create a handoff algorithm that achieves at least 90% of good results. However, considering that having a good balance is as important as having a good result, another performance specification for our algorithm is that it attains at least 50% of good results with good balance. Finally, the closest metric to the optimum result and optimum balance is to have very good results with very good balance with a hit rate of at least 10%. These percentages are with respect to a total of random sampled scenarios, where sample size is above 32 samples. Figure 4-4 summarizes these performance goals and depicts the spaces for different types of hits.



Space for
Good Results

Min. 90%

Space for
Good Results &
Good Balance

Min. 50%

Space for
Very Good Results &
Very Good Balance

Min. 10%

Figure 4-4. Three performance goals for the correct handoff algorithm.

4.2 The Correct Handoff Algorithm

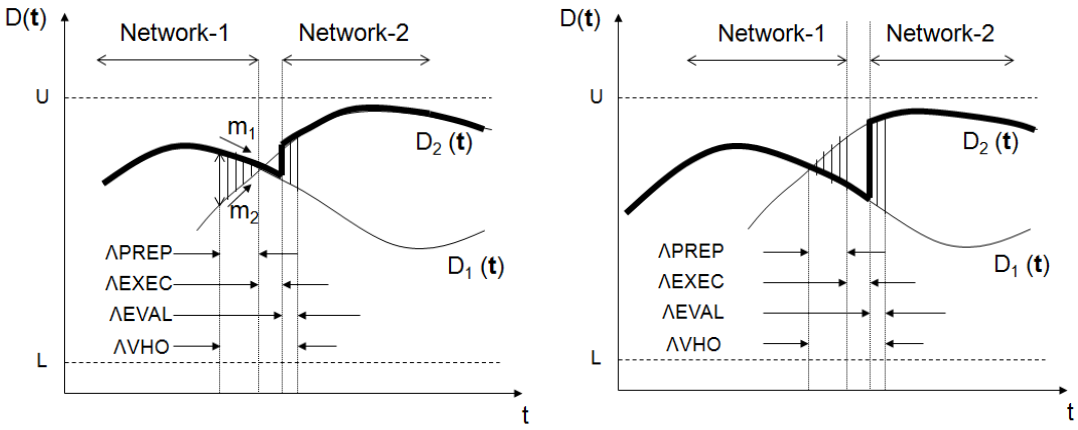
Once we have defined and specified the correct handoff problem, we now focus on describing and presenting a computational model that will provide a heuristic solution to this problem.

4.2.1 Algorithm Description

When we redefined the handoff problem in section 4.1.2, we mentioned that the optimum result (rTiB=1, rEHO=0) cannot be obtained for all handoff scenarios, therefore, the best a handoff algorithm can do is to find solutions that approximate to some extent of this optimum point. Despite this limitation, we created a handoff algorithm characterized as *deterministic*, *reactive*, *heuristic*, *autonomous*, *adaptive*, and *successful*. This algorithm, called, Relative Desirability Handoff Algorithm with hysteresis, dwell-timers, and two thresholds, or algorithm R for simplicity, is a procedure to make a terminal stay most of the time on the best network, while it performs the fewer number of handoffs, and achieves good results on most handoff scenarios.

Determinism is a desirable feature of handoff algorithms which allows a handoff to have a predictable behavior; this is particularly important for algorithms that pursue to control a complex process. Determinism makes an algorithm always produce the same output for the same input, and makes its underlying machine always pass through the same sequence of states. Our algorithm came out from the deterministic state machine of the global handoff process that we proposed in Figure 3-8. The state machine is deterministic because it is always in exactly one state at any given time. However, transitions between states depend on the answers we provide to the several questions: Why to initiate a handoff preparation? Where to hand off? When to initiate a handoff execution? How to evaluate its performance? Etc. Different handoff algorithms may be created according to the answers given to those questions.

The algorithm we propose follows a *reactive* strategy. A reactive handoff starts the handoff preparation (ΛPREP) immediately after a new and better network is detected. Although a proactive strategy could be considered a better approach, we believe a reactive strategy is more suitable for random desirability curves, whereas a proactive strategy works better for deterministic curves. A proactive handoff starts a handoff preparation before a crossing point occur, based on the growing slope (m_2) of an approaching better network. However, the fact that we do not know the moment when a deterministic curve may become random, makes the curve random, and thus, we prefer to implement the case of random desirability curves, which indeed would be a worst case. Remember that desirability curves are created at random and although they can be described as polynomials or transcendental functions, the algorithm pursuing a reactive strategy should never make use of properties of derivatives (m_1, m_2) to make handoff decisions. Figure 4-5 depicts both, a proactive and a reactive handoff strategy. Handoff latency (ΛVHO) can be estimated as the sum of latencies in the phases of preparation (ΛPREP), execution (ΛEXEC), and evaluation (ΛEVAL).



Proactive Handoff

Reactive Handoff

Figure 4-5. Two main types of handoff strategies are proactive and reactive.

Since it is too difficult or perhaps impossible to obtain optimal results on every handoff scenario, we consider the choice of *heuristic* programming [59], which may be used to find approximate solutions to optimization problems. The algorithm we propose is *heuristic* because it is based on three simple rules or strategies. These heuristic rules are used to make two key handoff decisions: where to hand off and when to initiate a handoff execution? A candidate network to handoff is any network with higher desirability than the current network. A candidate network is selected as the *best candidate* if it becomes *consistently better* and *sufficiently better*. The first candidate that meets both conditions becomes the best candidate. As soon as a best candidate network is selected, the algorithm is ready to trigger a handoff execution from the current network to the best candidate network. The three heuristic rules are:

1. A candidate network is *sufficiently better* (suffB) if the relative desirability ΔR, which is a comparison between the candidate and current networks, is greater than a configuration parameter named Δ or hysteresis margin; i.e., if $\exists t_k$ such that $\Delta R = [D_{candidate}(t_k) - D_{current}(t_k)] > \Delta$.
2. A candidate network is *consistently better* (consB) if $\Delta R > 0$ during a period of time or dwell-timer SP; i.e., if $\Delta R = [D_{candidate}(t) - D_{current}(t)] > 0$, for $t = t_1, t_2, \ldots, t_k$; and $t_k - t_1 \geq SP$. The dwell-timer is also a configuration parameter.
3. A candidate network is the *best candidate* network if it is both, sufficiently better and consistently better; i.e., if $\Delta R = [D_{candidate}(t) - D_{current}(t)] > \Delta$, for $t = t_1, t_2, \ldots, t_k$; and $t_k - t_1 \geq SP$.

A heuristic handoff algorithm produces good and fast solutions for most of the handoff scenarios at the cost of optimum results as long as they meet certain minimal performance measures. Thus, our heuristic algorithm cannot guarantee to produce always good solutions, but it may guarantee statistically good results or results that fall within specific margins of performance.

The algorithm of relative desirability is *autonomous* because it does not demand the user intervention during the online handoff process. Certainly, there are configuration parameters that can be established by the user offline, but once they are fixed to set up an initial tuning performance, no more user interventions are required.

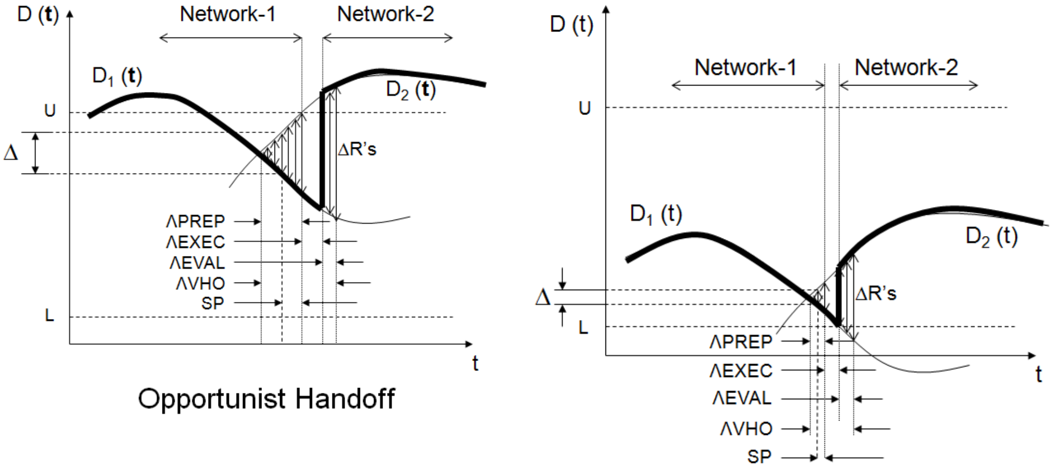
The algorithm is *adaptive* because it changes its behavior automatically according to two types of handoff that may be in progress: *imperative* or *opportunist*.

An opportunist handoff is a relaxed handoff because current network is “far” above the lower threshold, which implies that current network has a high desirability and thus, there is no an urgent need for making a handoff; however, the presence of another network that has proved to be a consistently better candidate, offers an opportunity to the current network for improving its communications. Conversely, an imperative handoff is a hassled handoff because current network is “close” above the lower threshold, which implies that current network is getting lost and therefore, a handoff to any better network is imperious.

Adaptability, in this case, means that the algorithm should automatically increase the configuration parameters Δ and SP according to a distance above the lower threshold. A minimum Δ (mΔ) and minimum SP (mSP) are inputs to the algorithm. In this way, the handoff preparation latency gets shorter as the current network desirability approaches to L, and gets larger as the current network desirability gets away from L, or until it reaches the top of the handoff region. Imperative or opportunist handoffs are dependent on the handoff scenario; thus, the handoff algorithm is adaptive to different handoff scenarios. Figure 4-6 depicts both types of handoffs: opportunist and imperative. This figure shows how the control parameters Δ and SP are adaptable to different handoff scenarios. Opportunist and imperative handoffs depend on where the crossing point occurs.

In order to make Δ and SP adaptable, we divide the handoff region in *adaptability levels* of equal size 0.5. This value defines the granularity or amount of levels we want in the handoff region, i.e., there are (U – L)/0.5

levels in the handoff region. The crossing point of the current network with another network occurs at the *level* = $\lceil(D_{curr}(t) - L)/0.5\rceil$ and thus, the values for Δ and SP are (*level* × mΔ) and (*level* × mSP) respectively.



Opportunist Handoff

Imperative Handoff

Figure 4-6. Adaptability characteristics of opportunist and imperative handoffs.

Finally, the relative desirability handoff algorithm is *successful* because it globally achieves all the performance goals that we specified at the end of section 4.1. To measure successfulness the algorithm assesses every executed handoff individually. The algorithm takes some time after the execution phase to determine the success or failure of the performed handoff and react accordingly. A handoff succeeds (it is *beneficial*) if the new network is consistently better than the old network; otherwise, it fails. The amount of successes is a figure of correctness.

If the handoff succeeds then it goes back to the normal initiation state. If the handoff fails then it goes back to the preparation state. The algorithm also provides a third performance measure named rate of beneficial handoffs (rBHO), where rBHO = nBHO/nEHO, the number of beneficial handoffs over the number of executed handoffs. The algorithm should also attain a maximum rBHO above 90% of the sampled scenarios.

Algorithm Inputs

The inputs are of two kinds: handoff scenario parameters and control parameters. Parameters of the handoff scenario were defined in section 4.1.2, but now we give some other terms to be more precise:

- N: the number of networks included in the handoff scenario, $N \geq 2$.
- $x1$, $x2$: the boundaries of time, where $x1$, $x2$ are integers such that $x1 < x2$.
- $D_i(t)$: A set of N network desirability curves defined for $1 \leq i \leq N$ and $x1 \leq t \leq x2$. We use the notation $D[i, t]$ in preference to the subscripted notation $D_i(t)$. We consider that $D[i, t]$ is a real number representing the desirability for the ith network at time t. The domain of t is given by specific real numbers between $x1$ and $x2$.
- L: The lower threshold for desirability. A network with desirability lower than L is considered disconnected or not available. We assume L is an integer.
- U: The upper threshold for desirability. Any network with desirability greater than U is considered the best available network. We assume U is an integer and $U > L$.
- δ: The step time, the constant time between samples of desirability. It is a real value in the interval (0, 1) such that $\delta = (x2 - x1)/n$, where $n+1$ is the number of samples of $D[i, t]$ in the time domain $[x1, x2]$. D is the matrix of desirability of size $N \times (n+1)$.

$D[1, x1]$	$D[1, x1+\delta]$	$D[1, x1+2\delta]$	…	$D[1, x1+n\delta]$
$D[2, x1]$	$D[2, x1+\delta]$	$D[2, x1+2\delta]$	…	$D[2, x1+n\delta]$
⋮	⋮	⋮	⋮	⋮
$D[N, x1]$	$D[N, x1+\delta]$	$D[N, x1+2\delta]$	…	$D[N, x1+n\delta]$

Parameters of control:

- *mSP*: The minimum value of time (dwell-timer) required to test if a candidate network is consistently better. It is required that $mSP \geq \delta$ in order to test consistency for at least one step time.
- *m*Δ: The minimum value of relative desirability (ΔR) required to test if a candidate network is sufficiently better. It is required that $m\Delta > 0$ so that the sufficiency condition can be tested.
- Λ*EXEC*: The average latency of handoff execution. Although we may consider ideal instantaneous handoff making $\Lambda EXEC = 0$, in real scenarios, the latency of handoff execution is a random variable that is hard to be predicted for a general handoff scenario. We assume this input is a real positive number such that $\Lambda EXEC \geq \delta$.
- Λ*EVAL*: The average latency of handoff evaluation. This parameter represents the time the algorithm spends evaluating the performed handoff. Although this parameter could also be adaptable according to the level of desirability where the cross point occurred, we preferred to consider a constant average evaluation latency such that $\Lambda EVAL \geq \delta$.

Algorithm Outputs

The outputs are three performance measures (rTiB, rEHO, rBHO) and other parameters required for their calculation (DTiB, TST, nEHO, ToX, nBHO).

- DTiB: The dwelling-time in the best.
- TST: The total simulation/analysis time.
- rTiB: The rate of time in the best (DTiB/TST).
- nEHO: The total number of executed handoffs.
- ToX: The total number of crossing points.
- rEHO: The rate of executed handoffs (nEHO/ToX).
- nBHO: The total number of beneficial handoffs.
- rBHO: The rate of beneficial handoffs (nBHO/nEHO).

4.2.2 Pseudocode

No standard for pseudocode syntax exists, but we are going to follow, as much as possible, the format that Dr. Knuth uses throughout his classic books on algorithms [69].

Algorithm R (*Relative Desirability Handoff*). This algorithm performs a handoff from the current network to the best candidate network in order to stay in the best available connection most of the time; i.e., increase DTiB. Simultaneously, this algorithm tries to perform the fewer number of handoffs because each handoff entails some overload to communications; i.e., decrease nEHO. However, these tasks are in conflict, they cannot be improved simultaneously. As a result, this algorithm makes a balance between increasing DTiB and decreasing nEHO. The way of doing this balance is by delaying the execution of a handoff until it becomes really necessary, i.e., until the candidate network becomes sufficiently and consistently better. This algorithm obtains three performance measures (rTiB, rEHO, rBHO) which are associated to the particular handoff scenario under analysis. Values for rTiB ≥ 50% or rEHO ≤ 50% are considered good or acceptable results.

```
R1.  [Initialize.] Set curr ← 0 (number of current network, 0 = disconnected). Set best ← 0 (number of best network, 0 = disconnected). Set t ← x1 (initial value for time variable defined in the scenario). Set DTiB ← nEHO ← nBHO ← 0. Set TST ← (x2 – x1). Get ToX (subroutine that pre-analyzes the given handoff scenario to determine the number of cross points in the handoff region).
R2.  [t > x2?] If t > x2, the algorithm terminates; the answers are:
     a. rTiB ← DTiB/TST (rTiB ← 0 if TST = 0);
     b. rEHO ← nEHO/ToX (rEHO ← 0 if ToX = 0);
```

c. $rBHO \leftarrow nBHO/nEHO$ ($rBHO \leftarrow 0$ if $nEHO = 0$).

R3. [Find the best and its region.] Set $best \leftarrow j$ such that $D[j, t] = \max(D[1, t], D[2, t], \ldots, D[N, t])$. (The best available network is the one with highest desirability.) Set $regionB \leftarrow$ “handoff” if $L \leq D[best, t] \leq U$. Set $regionB \leftarrow$ “red” if $D[best, t] < L$. Set $regionB \leftarrow$ “green” if $D[best, t] > U$.

R4. [Is current network disconnected or connected to the best?] If ($curr = 0$ OR $curr = best$) then if $regionB$ = “red”, $curr \leftarrow 0$ (disconnect if no available network). If $regionB \neq$ “red”, $curr \leftarrow best$, $DTiB \leftarrow DTiB + \delta$ (connect to the best or remain connected to the best and increment DTiB.) Next, set $t \leftarrow t + \delta$, and return to step R2.

R5. [Find the region of the current network.] Set $regionC \leftarrow$ (“handoff”|”red”|”green”) if ($L \leq D[curr, t] \leq U$ | $D[curr, t] < L$ | $D[curr, t] >$ U.)

R6. [Is the current network in the “green” region?] If $regionC$ = “green”, $DTiB \leftarrow DTiB + \delta$, set $t \leftarrow t + \delta$, and go back to step R2. (All networks in the “green” region are the best.)

R7. [Is the current network in the “red” region?] If $regionC$ = “red” then curr $\leftarrow 0$, $t \leftarrow t + \delta$, and go back to step R2. (All networks in the “red” region are disconnected.)

R8. [Get level, Δ, and SP.] (Current network is in the “handoff” region and it is not connected to the best, thus, prepare for handoff.) Set $level \leftarrow \lceil (D[curr, t] - L)/0.5 \rceil$, $\Delta \leftarrow level \times \mathrm{m}\Delta$, and $SP \leftarrow level \times \mathrm{mSP}$. Initialize index variables $t1 \leftarrow tk \leftarrow t$.

R9. [Get the Relative Desirability at tk.] Set $\Delta\mathrm{R}(tk) \leftarrow (D[best, tk] - D[curr, tk])$.

R10. [Is ΔR(tk) < 0?] If $\Delta\mathrm{R}(tk) < 0$ then set $DTiB \leftarrow DTiB + \delta$, $t \leftarrow tk$, $t \leftarrow t + \delta$, and go back to R2.

R11. [Do we still have time to compare the networks?] If $(D[curr, tk] - L) < 0.1$ then go to step R14. (Current network is quite close to a disconnection, thus, initiate a handoff urgently.)

R12. [Is $\Delta\mathrm{R}(\mathrm{tk}) < \Delta$?] If $\Delta\mathrm{R}(tk) < \Delta$, set $tk \leftarrow tk + \delta$ and return to R9. (The candidate network is not sufficiently better.)

R13. [Is $(\mathrm{tk} - \mathrm{t1}) < \mathrm{SP}$?] If $(tk - t1) < SP$, set $tk \leftarrow tk + \delta$ and return to R9. (The candidate network is not consistently better.)

R14. [Initiate handoff execution.] (Candidate network is sufficiently and consistently better.) Set $nEHO \leftarrow nEHO + 1$. (Increment the number of executed handoffs.) Set $t1 \leftarrow tk$.

R15. [Make handoff from current to best.] Call *make-ho* (*curr*, *best*). (Execute handoff from curr to best, and wait until it terminates.)

R16. [Is handoff executed?] If $(tk - t1) < \Lambda\mathrm{EXEC}$, set $tk \leftarrow tk + \delta$ and return to R15.

R17. [Initiate handoff evaluation.] Set $new \leftarrow best$, $old \leftarrow curr$, $t1 \leftarrow tk$.

R18. [Perform handoff evaluation.] If $D[new, tk] > D[old, tk]$ then $BHO \leftarrow$ **true**; else, $BHO \leftarrow$ **false**. (BHO is true for beneficial handoffs.)

R19. [Is handoff evaluated?] If $(\mathrm{tk} - \mathrm{t1}) < \Lambda\mathrm{EVAL}$, set $tk \leftarrow tk + \delta$ and return to R18.

R20. [Is handoff successful?] If *BHO*, $nBHO \leftarrow nBHO + 1$, set $t \leftarrow tk$, $DTiB \leftarrow DTiB + \delta$, set $t \leftarrow t + \delta$, and go back to step R2. Otherwise set $t \leftarrow tk$, $t \leftarrow t + \delta$, and go back to R8. ■

4.2.3 Flowchart

Figure 4-7 depicts the accompanying flow chart of the Relative Desirability Handoff Algorithm. The twenty steps described in the pseudocode are expanded graphically in the flow chart so that the reader can picture the algorithm more readily.

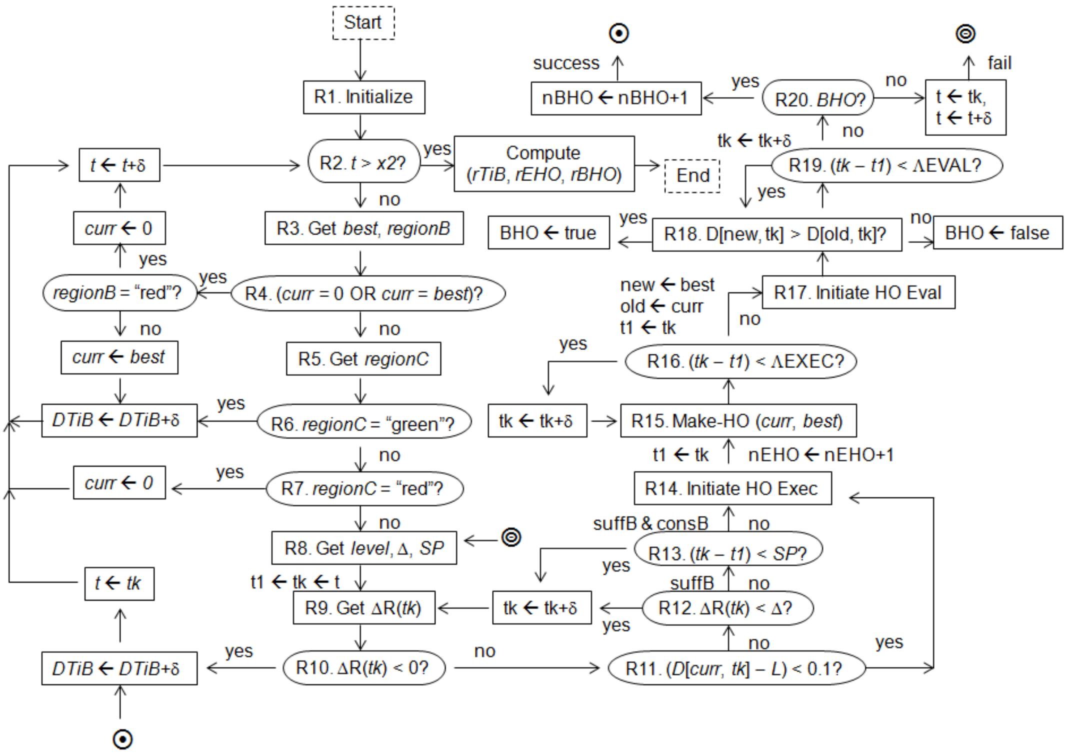


Figure 4-7. Flow chart for Algorithm R shows the 20 steps described in the pseudocode.

The algorithm R follows the deterministic state machine that we presented in Publication 1. We associate a *disconnection* state when *curr* = 0, an *initiation* state when *curr* = *best*, a *preparation* state when *curr* ≠ *best*, an *execution* state when *best* is SuffB & ConsB, and an *evaluation* state when *new* and *old* are compared. Notice that Δ and SP change according to a level of adaptability, they modify the conditions for sufficiency and consistency that are needed to execute a handoff. Step R11 shows the chance to perform an *urgent* handoff without checking the triggering conditions.

4.3 Development of a Handoff Simulation Instrument

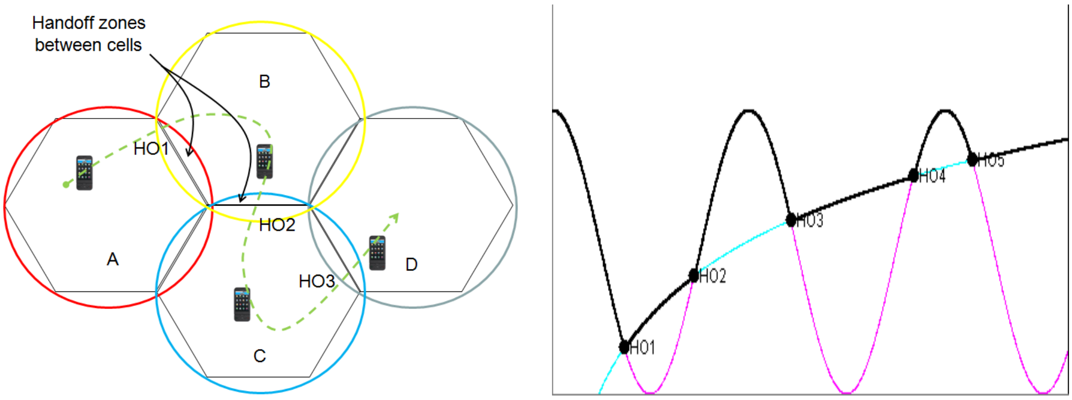
So far we have described a challenging handoff optimization problem and we have created a series of models to study the problem. Moreover, in the previous section we proposed a computational model that offers a heuristic solution to the problem. Therefore, we are now interested in developing a *simulation instrument* that can help us to validate the behavior of any handoff algorithm and measure its particular performance quantities.

According to Carson [70], *simulation* is a powerful tool used for the evaluation and analysis of new systems or modifications to existing systems. A simulation model allows study of the dynamics of a system, how it changes over time and how subsystems and components interact. On the other hand, Sumathi [71] defines an *instrument* as a device designed to collect data from a unit under test and to display information to a user based on the collected data. Merging these concepts, we claim that a *simulation instrument* is a simulation model with abilities to collect data from a unit under test and to display information, together with graphs and statistics, based on the collected data. A simulation instrument is also a *virtual instrument* if it is intangible or made purely from software [71].

Considering that our handoff algorithm and one handoff scenario is a unit under test, we can describe a *handoff simulation instrument* as a software device that allows the user to change the handoff scenario at will in order to run different tests of the handoff algorithm. Each test in the virtual instrument graphically displays the behavior of the handoff algorithm and yields handoff performance data which are collected in a structured archive after a session of tests. The handoff collected data include handoff performance measures and the handoff scenario under test that produced such results. These handoff results are stored into a delimited text file per session, which can be easily used by an external spreadsheet to visualize plots and statistics relative to handoff performance.

A handoff simulation instrument is an attractive idea because there are no specialized tools, at this time, to test the performance of handoff algorithms. Certainly, there are many network simulators, like NS3 [72], OPNET [73], and GloMoSim [74], but they mainly focus on analyzing the effect of various parameters on the network performance and not on the handoff performance itself. Some of these network simulators only can test handoffs in rather simple handoff scenarios, others have not user-friendly interfaces and demand the user to learn a specific programming language to carry out the simulation, and others simply are expensive.

A handoff simulator instrument is therefore focused on testing a handoff algorithm over a variety of handoff scenarios based on time, space, or both. Figure 4-8 shows the difference between them. In a space-based handoff scenario a terminal moves across a geographic service area and handoffs are performed within specific geographic zones. In a time-based scenario the desirability of networks changes with time, even if the terminal is not moving, and the crossing points between desirabilities determine a time for handoffs.



a) Space-based handoff scenario.

b) Time-based handoff scenario.

Figure 4-8. Two types of handoff scenarios: space-based and time-based.

The next sections describe the process of developing the handoff simulation instrument. As it is common in software engineering, we will describe this process through four stages of development: specification, design, implementation, and testing.

4.3.1 Specification

Specification for the handoff simulation instrument is presented as a list of requirements to be satisfied by the virtual instrument. Good requirements should have some characteristics that are acknowledged by many authors in software requirements: unitary, complete, consistent, atomic, feasible, unambiguous, and verifiable. Alan M. Davis in [75] explains in detail all attributes of requirements. Therefore, we are going to describe each requirement as a statement expressing concisely, clearly, and objectively what the instrument must satisfy. All of our requirements should be verifiable or they should be rewritten to be verifiable. The level of detail when expressing requirements is a trade-off; they should be easy to understand both for normal users and for developers.

Figure 4-9 presents a graphical overview of the instrument's functionality in terms of actors (drawn as stick figures), their goals (drawn as horizontal ellipses), and their associations (drawn by solid lines with arrowheads). This figure also shows the system boundary box (drawn as dimmed rectangles around the use cases) indicating the scope of our system. A first release, which is the current state of the system development, shows the need of an external information system so that the handoff simulation data can be processed and converted into statistical information that can be visualized and delivered to the user. A second release is a future work that will include the generation of statistics and visualization within the functionality of the system.

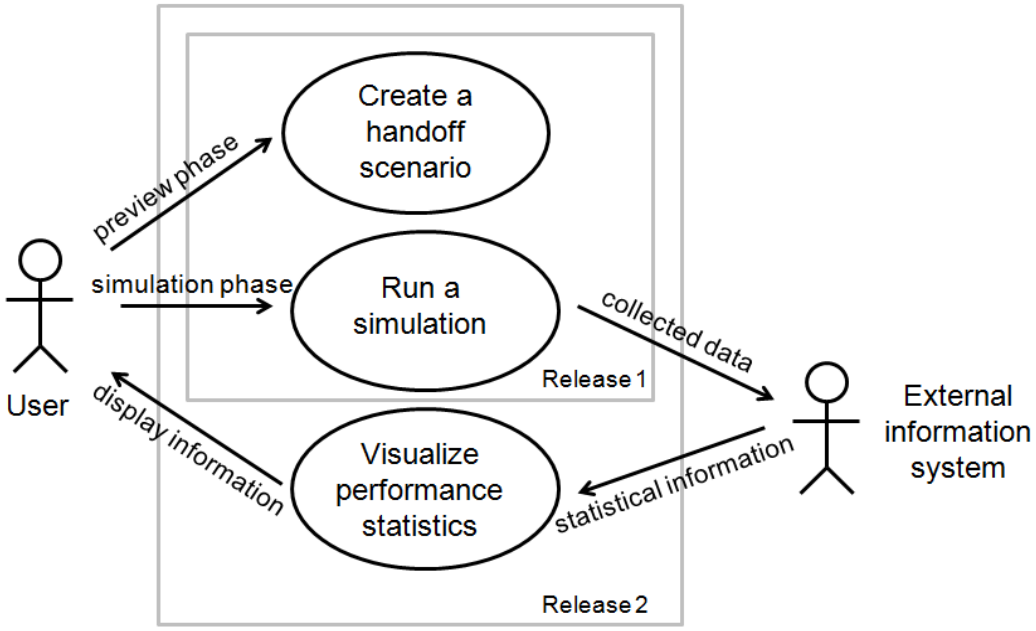


Figure 4-9. Use case diagram for the handoff simulation instrument, release 1 & 2.

<u>List of Requirements</u>

1. The virtual instrument works only with time-based handoff scenarios.
2. The simulation instrument is a discrete-time simulator. The system state changes only at discrete points in time, not continuously. This parameter is described as δ in the handoff scenario definition.
3. The instrument must operate in two phases: a preview phase and a simulation phase.
    a. A preview phase occurs when the user creates and visualizes a handoff scenario.
    b. A simulation phase occurs when the handoff algorithm runs with the current handoff scenario and saves handoff performance data in a local text file.
    c. The preview phase always precedes the simulation phase. A simulation cannot be run without previously define a handoff scenario.

4. The instrument must determine the number of crossing points (ToX) during the preview phase, at the moment when the handoff scenario is being displayed.

5. The instrument use the following set of symbols to define the functions of desirability.
   a. Numbers: real, integers, rational
   b. + Addition
   c. - Subtraction
   d. * Multiplication
   e. / Division
   f. ^ Power
   g. S(x) Sine of x
   h. C(x) Cosine of x
   i. L(x) Natural logarithm of x ($\log_e x$, ln x)
   j. e Exponential constant (2.71828…)
   k. ( ) Specify evaluation order

6. The function of desirability is a function of one variable (time) represented by the letter x. The symbols defined in the previous requirement allow the user to express desirability functions as a polynomial, a root of a polynomial, a quotient of polynomials, or transcendental functions. Examples of well-formed expressions are:
   a. C(x)+S(x*3^0.5) corresponds to the math expression: cos x + sin (x sqrt(3))
   b. 4*S(x/3-1.6) corresponds to the math expression: 4 sin (x/3 – 1.6)
   c. e^x+L(x) corresponds to the math expression: $e^x + \log_e x$
   d. 4*x^3+2*x^2+x-1 corresponds to the math expression: $4x^3 + 2x^2 + x - 1$

7. The instrument must allow users to capture parameters from the handoff scenario definition (7.a – 7.i) and from the handoff algorithm configuration settings (7.j – 7.m):
   a. Desirability function for network 1 (N1) (string)
   b. Desirability function for network 2 (N2) (string); plot only two functions.
   c. The minimum value of x (x1) (integer)
   d. The maximum value of x (x2) (integer); [x1, x2] specify an explicit range for variable x.
   e. The minimum value of y (y1) (integer)
   f. The maximum value of y (y2) (integer); [y1, y2] specify an explicit range of desirability.

g. The lower desirability threshold (L or LT) (integer)
h. The upper desirability threshold (U or UT) (integer)
i. The dot time or step time of x (δ or StX) (real)
j. The minimum value of relative desirability ($m\Delta$ or mDR) (real)
k. The minimum value of dwelling time (mSP) (real)
l. The average latency of handoff execution ($\Lambda EXEC$ or ExL) (real)
m. The average latency of handoff evaluation ($\Lambda EVAL$ or EvL) (real)

8. The instrument must plot the functions defined in 7.a and 7.b within the explicit ranges that were specified in 7.c, 7.d, 7.e, and 7.f.

9. All functions must be plotted using the same dot time specified in 7.i.

10. Requirements on colors of functions when they are plotted in the preview phase:
    a. Functions are displayed in different colors over a white background display area.
    b. Foreground is displayed in cyan for N1 when it is over the handoff region.
    c. Foreground is displayed in magenta for N2 when it is over the handoff region.
    d. Functions are plotted in red when they are over the red region.
    e. Functions are plotted in green when they are over the green region.

11. Requirements on colors of the current network when it is plotted in the simulation phase:
    a. Current network is displayed in bold red if it is in disconnection state.
    b. Current network is displayed in bold black if it is in initiation state.
    c. Current network is displayed in bold blue if it is in preparation state.
    d. Current network is displayed in bold red if it is in execution state.
    e. Current network is displayed in bold pink if it is in evaluation state.

12. The instrument must allow the user to save a text file per session containing the performance measures of handoffs per each handoff scenario that was tested. Scenario and results are expressed as strings of text where each parameter is delimited by the colon sign ":". Each string of results must be associated to one string of scenario.
    a. Scenario = N1:N2:x1:y1:x2:y2:L:U:StX:mDR:mSP:ExL:EvL
    b. Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO

We avoided “poisoning” the requirements by saying *how* the system should implement the requirements, leaving such decisions to the next development stage.

4.3.2 Design

This stage defines models for describing the structure and behavior of the handoff simulation instrument, in agreement with the requirements specified on the previous section. The structure model describes the system architecture, components, modules, inputs, outputs, interfaces, and data flows. The behavior model describes the states and state transitions. And both comprise what is called the instrument architecture.

The top level structural model describing the handoff simulation instrument is shown in figure 4-10.

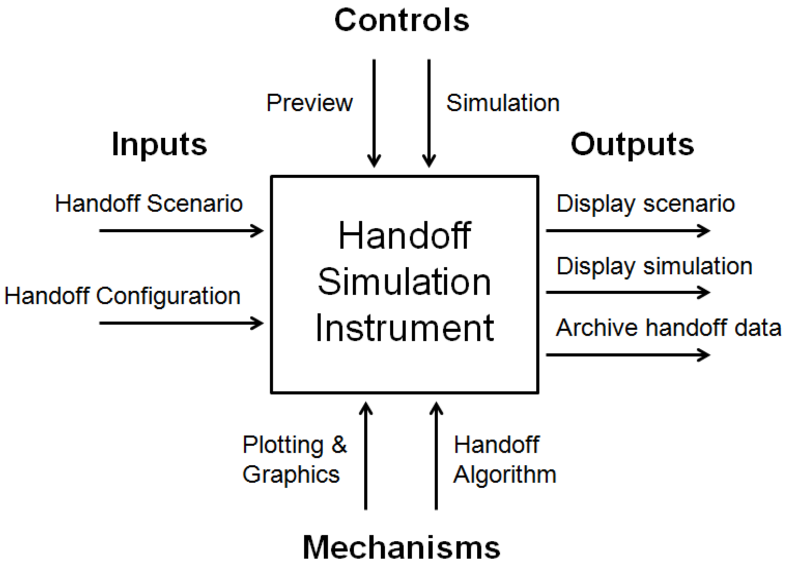


Figure 4-10. Top level model of the handoff simulation instrument.

This model describes different types of inputs, outputs, controls, and mechanisms that characterize the system. The requirement #7 specifies two types of inputs to the instrument: handoff scenario parameters and handoff configuration parameters. The requirement #3 specifies two controls that determine the task the instrument must perform: preview or simulation. Similarly, requirements #10, #11, and #12 specify three types of outputs the instrument may produce: graphics for the time-based handoff scenario (preview phase); graphics for the current network in different handoff states (simulation phase); and, text files containing handoff data (scenario + results) as specified in requirement #12. Finally, the model shows the mechanisms that support the instrument: the handoff algorithm (Algorithm R), specified in section 4.2, and a toolbox for plotting multiple functions of one variable and displaying graphics, as it was specified in requirements #5, #6, #8 and #9.

The next level structural model is the design of the user interface depicted in figure 4-11.

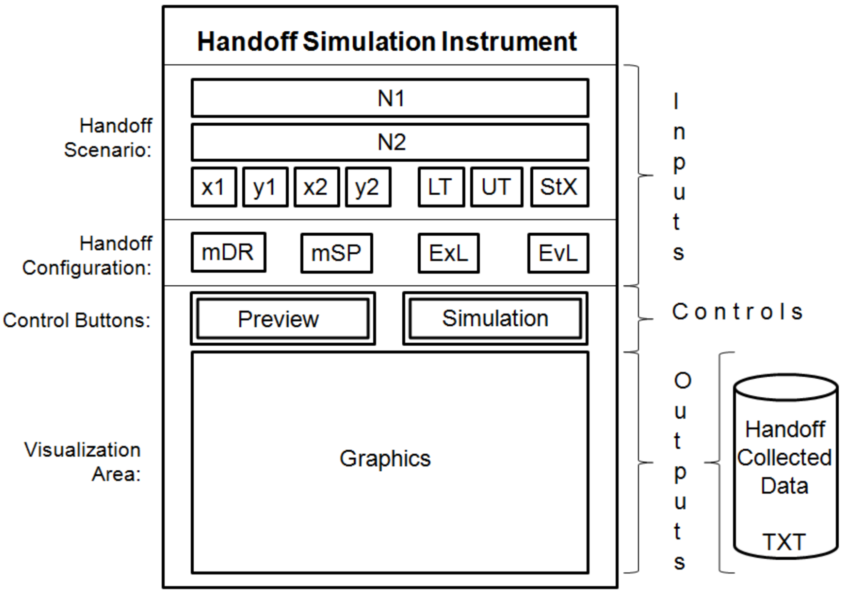


Figure 4-11. User interface design for the handoff simulation instrument.

This model describes the layout of inputs, outputs, and controls that a user sees through the interface. The inputs defining the handoff scenario are shown as text boxes with labels: N1, N2, x1, y1, x2, y2, LT, UT, and StX; the inputs for handoff configuration settings correspond to the boxes: mDR, mSP, ExL, and EvL. There are two large control buttons at the middle of the interface that can be activated only after having captured the inputs to the instrument. These buttons are labeled *preview* and *simulation* so that the user can easily select the type of action the instrument will do. The last but also the largest part of the interface is the visualization area. This area is addressed to picture the visual outputs of the preview phase and the simulation phase. Besides the display of graphics in the visualization area, every time a scenario is previewed or simulated, the instrument automatically saves a string of *results* and a string of *scenario* into a text file as specified by the requirements #12a and #12b. Although the management of the handoff data archive is not currently part of the user interface, a user can easily handle a few text files, which are processed by an external information system in order to convert handoff data into handoff statistics and handoff performance information.

Models of visual outputs that may be pictured in the visualization area are shown in figures 4-12 and 4-13. Figure 4-12 depicts a time-based handoff scenario in the preview phase. This type of graphic satisfies the requirements #1, #2, #3a, and #4. The number of crossing points (ToX) is determined at this stage. This parameter is required to estimate the rate of executed handoff (rEHO); hence a preview should be performed before a simulation test. Also notice that both functions are plotted with the same dot time (StX) as pointed out the requirement #9.

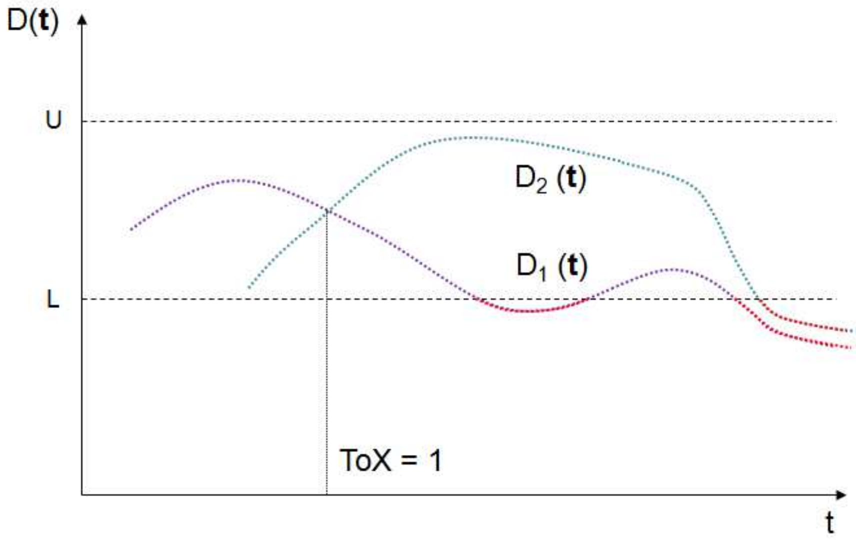


Figure 4-12. Model of visual output displaying a handoff scenario in preview.

Figure 4-13 depicts the current network passing through different handoff states (HO-DISCO: disconnection, HO-INIT: initiation, HO-PREP: preparation, HO-EXEC: execution, and HO-EVAL: evaluation.) This visual output is produced after running a simulation test.

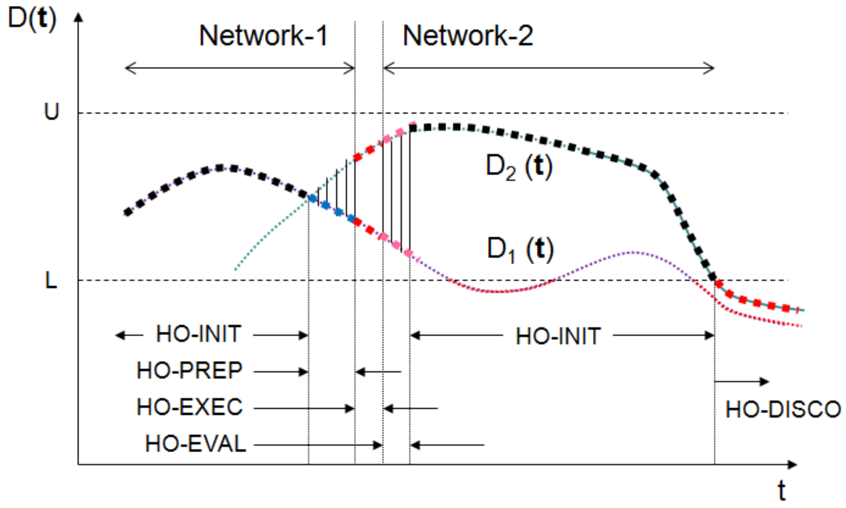


Figure 4-13. Model of visual output displaying a current network in simulation.

Notice that current network is modeled as a function changing or “jumping” from one network to another, as long as there are available networks. The current network is depicted with a thick dotted line where different colors are used to indicate the state of the handoff process. In this way, requirement #11 is satisfied.

Once we have presented general aspects of our handoff simulation instrument, we are able to go inside the instrument’s top level model, depicted in figure 4-10, and describe its inner components, modules, data flows, states, and transitions which together provide structural and behavioral views of the instrument. The figures 4-14 and 4-15 support the structural and behavioral views respectively.

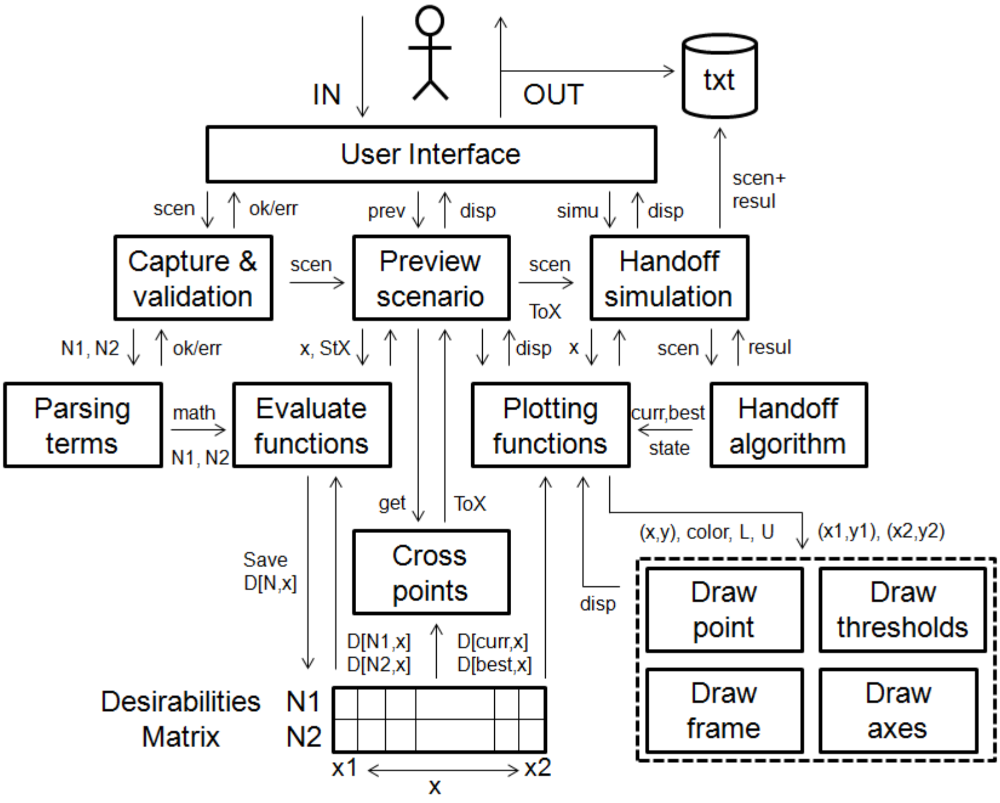


Figure 4-14. Structural view of the simulation instrument illustrating components, modules, and data flows.

Figure 4-14 illustrates the various components or subsystems that comprise the instrument architecture. Some of these components represent data, data structures, or data files, while others represent modules which describe segments of code like procedures, functions, routines, or methods. Modules communicate through data and share data structures, thus, data flows through modules transforming data into results.

The *user interface* module has three modules directly connected to it so that the system responds to user events like capturing inputs (*capture & validation*), pressing the preview button (*preview scenario*) or pressing the simulation button (*handoff simulation*). The capture and validation of inputs is the first logical step the system achieves. The inputs are arranged into a data structure named scenario (*scen*) as indicated in requirement #12a. If inputs are correctly validated then the capture and validation module signals this condition to the interface with *ok*, otherwise, it signals an *error*. Perhaps the most difficult part of validation is to detect a syntactically correct expression for desirability functions N1 and N2. Therefore, the module *parsing terms* is dedicated to the syntactic analysis of text strings N1 and N2, and converting them into valid mathematical expressions. This task is achieved as specified on requirements #5 and #6.

Next, when preview button is pressed (*prev*) and valid inputs are already captured, the instrument prepares for displaying (*disp*) the current handoff scenario into the user interface visualization area. This activity is performed in two steps, *evaluate functions* and *plotting functions*. Each function of desirability is evaluated for each x at steps StX and $x1 \leq x \leq x2$. The values of desirability are temporarily stored in a data structure called *desirability matrix*. This matrix is cleared and created every time a new scenario is going to be previewed. This matrix is also shared with other two modules: *cross points* and plotting functions. The cross points module use the matrix for calculating the number of crossing points in the active scenario. The plotting functions module use the matrix to get the values of desirability D[N1,x] and D[N2,x] and plot them. The plotting module achieves its job using a toolbox or set of modules for making graphics. The most important modules in the graphics toolbox are: *draw frame*, *draw axes*, *draw point*, and *draw thresholds*. In this way, the handoff scenario is displayed during the preview phase (see figure 4-12).

Once the scenario is displayed, the number ToX is calculated, and desirability matrix is loaded with the active scenario, then the next event that is expected to occur is the command (*simu*) to initiate a handoff simulation. The handoff simulation module is addressed to display at each step time the value for the current network over the graphics already displayed in the preview. The format for displaying the current network during the handoff simulation is specified in the requirement #11 and a model for the expected output is illustrated in figure 4-13. The way of performing this task is again in two parts. At every single step-time, the *handoff algorithm*, which is the last module composing the structural architecture in figure 4-14, determines the value for the current network (*curr*), the best network (*best*), and the handoff state (*state*). These variables are used by the plotting functions module to fetch their corresponding desirability values from the matrix, i.e., D[curr, x] and D[best, x]; and, the handoff state is used to determine the dot color to display. Following this cycle until the last step time is the way in which the handoff simulation will be performed. After the display cycle ends, the handoff algorithm sends its performance measures to the handoff simulation module so that it archives the handoff results and its corresponding scenario into a delimited text file as specified by the requirement #12.

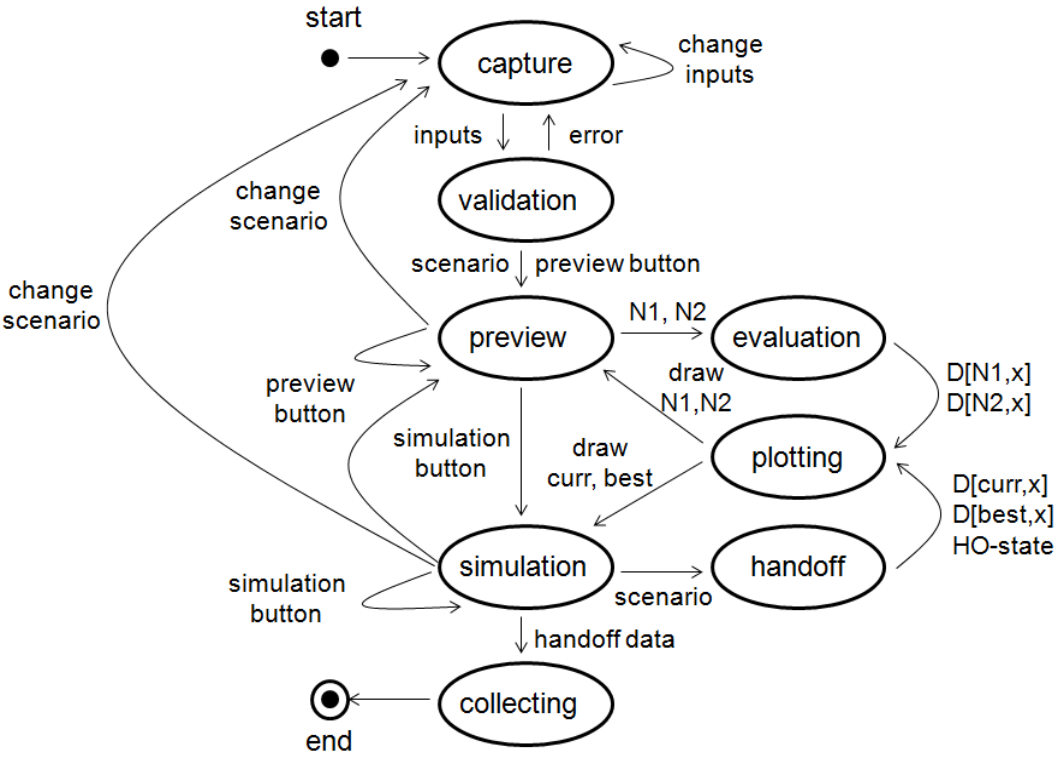


Figure 4-15. Behavioral view of the simulation instrument illustrating states and state transitions.

The discussion on the behavioral view of the architecture, depicted in figure 4-15, is almost done with the above discourse on the structural view. This is because both views are mutually interlaced; however, it is convenient that we make some remarks on this issue before closing this section.

First, we organized and divided the whole operation of the handoff simulation instrument into eight states which have very specific activities to achieve: capture, validation, preview, evaluation, plotting, simulation, handoff, and collecting. We already described these activities in the previous discussion, except for the collecting state. After a handoff simulation and before leaving the instrument, the user performs the collection of handoff data by saving the collected data into a text file on the hard disk. This task will be performed by the user manually; however, by doing this, we gain simplicity in the user interface.

A final remark is on the achievement of requirement #3c. A handoff simulation is always preceded by a preview, and in case that it is not, the instrument goes from the simulation state to the capture state in order to change or define a new scenario. The preview phase has at least two significant reasons to exist. It allows the user to know in advance the scenario where the handoff simulation test will be run, and, it prepares the simulation phase to run efficiently. This is done by filling the desirability matrix with specific values to display and by calculating the number of cross points which is a reference measure used by the handoff algorithm for estimating rEHO.

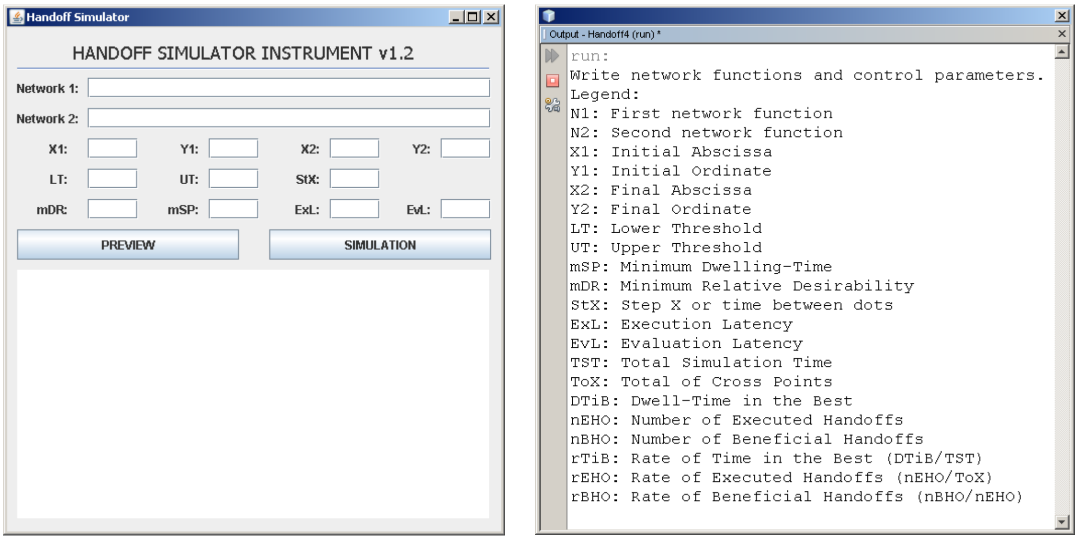
4.3.3 Implementation

The next step in the development process after specification and design is implementation, which is the process of *translating* an algorithm or technical specification into the source code of a computer program following the rules and syntax of particular programming languages. Although the process of writing the source code of our simulation instrument was interesting and challenging, we are not going to give a detailed description of the code in this section. Instead, we will present a few screens taken from the actual handoff simulation instrument showing behavior examples of our handoff algorithm and we will discuss only some aspects on its implementation.

The simulation instrument was programmed using the Java Platform, Standard Edition 6 Development Kit or JDK 6 and the integrated development environment NetBeans IDE 6.7.1. Java has many attractive features that made it the best choice especially for the type of application we are building.

First, in Java, a wealth of mathematical functions including trigonometric, logarithmic, exponential, and random functions are all encapsulated into the Math Class (see [76] for complete description of the available set of functions). This allows deploying a large variety of desirability functions, whether they are deterministic or stochastic. A second attractive feature of Java is the enhanced graphics and imaging classes defined by the Java 2D API, which provides a powerful framework for using device- and resolution-Independent graphics in Java programs. These graphic libraries made easier the plotting of mathematical functions and graphics handling. Finally, probably the most attractive feature in Java is its portability which has made it the most used programming language in the world. This helps the task of distributing and sharing this system within the research community for greater improvements in this area.

Let's start presenting the initial screen of the handoff simulator instrument illustrated in figure 4-16. Figure 4-16a shows the actual screen of the user interface in its initial state. Figure 4-16b shows the initial output in the IDE's console showing the legend of used terms so that the user can adequately interpret the handoff results. These screens correspond to the user interface design that we described in figure 4-11.



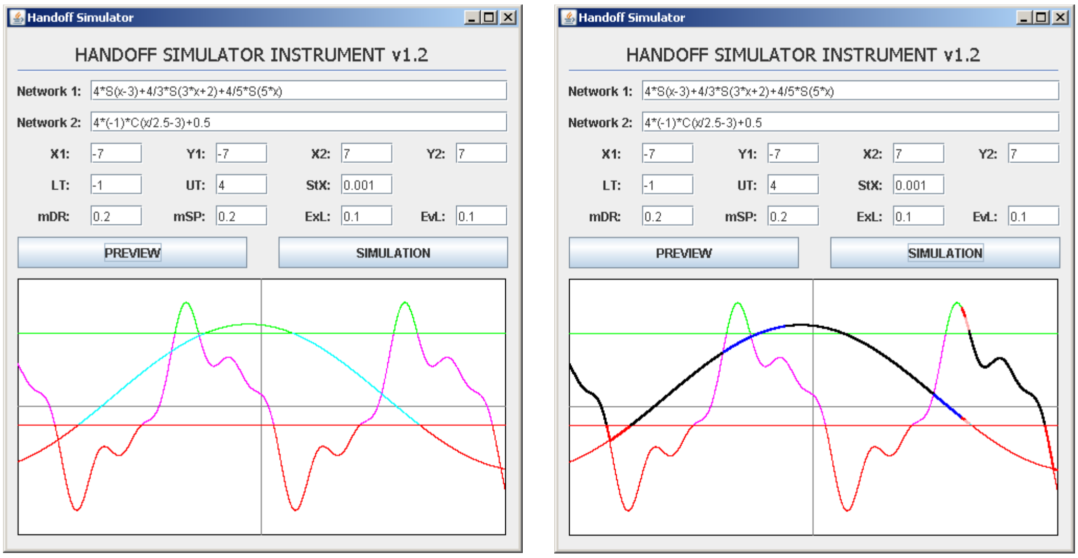
```
run:
Write network functions and control parameters.
Legend:
N1: First network function
N2: Second network function
X1: Initial Abscissa
Y1: Initial Ordinate
X2: Final Abscissa
Y2: Final Ordinate
LT: Lower Threshold
UT: Upper Threshold
mSP: Minimum Dwelling-Time
mDR: Minimum Relative Desirability
StX: Step X or time between dots
ExL: Execution Latency
EvL: Evaluation Latency
TST: Total Simulation Time
ToX: Total of Cross Points
DTiB: Dwell-Time in the Best
nEHO: Number of Executed Handoffs
nBHO: Number of Beneficial Handoffs
rTiB: Rate of Time in the Best (DTiB/TST)
rEHO: Rate of Executed Handoffs (nEHO/ToX)
rBHO: Rate of Beneficial Handoffs (nBHO/nEHO)
```

(a) User interface (b) Legend of terms

Figure 4-16. Initial screens in the user interface and console at the handoff simulator instrument.

The first two steps in the operation of the handoff instrument are capture and validation of a handoff scenario as illustrated in the structural and behavioral views of figures 4-14 and 4-15. After all the inputs in the interface are properly captured and validated, then the user presses the preview button in order to get the handoff scenario displayed in the graphic area.

Figure 4-17a shows an example of valid inputs that have been captured and graphically displayed as a preview scenario. The handoff scenario consists of two networks, one that changes abruptly and rapidly and another that changes smoothly and slowly. The visualization area has an aspect ratio of 1:1, 14 units on *x* by 14 units on *y*, given by the coordinates (-7, -7) and (7, 7). A lower and upper threshold is defined within the visual area, L = -1 and U = 4, separating the graphics into three regions (red, handoff, and green) as defined in Table 4-1. During this preview state, the number of crossing points in the handoff region is counted to 3 (not signaled in the graphic.)

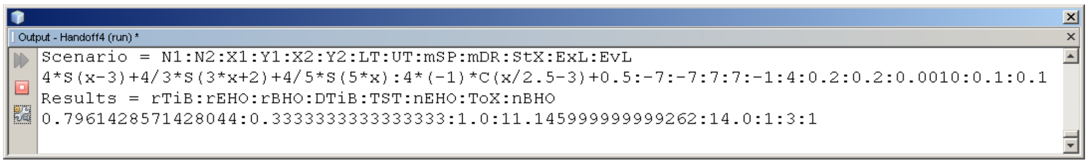


Network 1: 4*S(x-3)+4/3*S(3*x+2)+4/5*S(5*x)
Network 2: 4*(-1)*C(x/2.5-3)+0.5
X1: -7
Y1: -7
X2: 7
Y2: 7
LT: -1
UT: 4
StX: 0.001
mDR: 0.2
mSP: 0.2
ExL: 0.1
EvL: 0.1

Network 1: 4*S(x-3)+4/3*S(3*x+2)+4/5*S(5*x)
Network 2: 4*(-1)*C(x/2.5-3)+0.5
X1: -7
Y1: -7
X2: 7
Y2: 7
LT: -1
UT: 4
StX: 0.001
mDR: 0.2
mSP: 0.2
ExL: 0.1
EvL: 0.1

(a) Preview scenario

(b) Handoff simulation



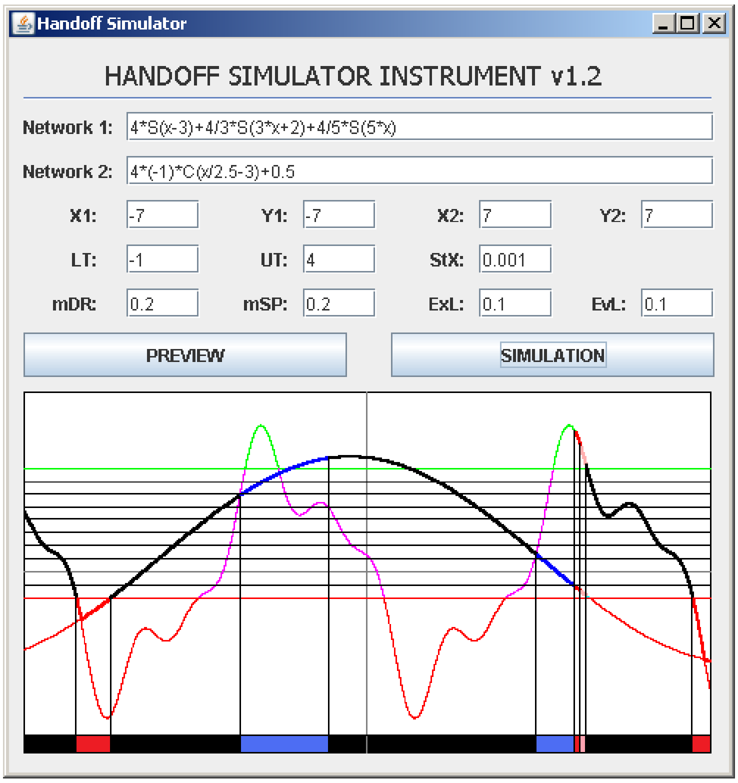
```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
4*S(x-3)+4/3*S(3*x+2)+4/5*S(5*x):4*(-1)*C(x/2.5-3)+0.5:-7:-7:7:7:-1:4:0.2:0.2:0.0010:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.7961428571428044:0.3333333333333333:1.0:11.145999999999262:14.0:1:3:1
```

(c) Handoff collected data

Figure 4-17. The three outputs for the handoff simulation instrument: (a) preview scenario, displays the actual handoff scenario; (b) handoff simulation, depicts the current network passing through different handoff states; (c) handoff collected data, depicts two delimited text strings defining the handoff scenario and its corresponding handoff results.

The network #1 is colored in magenta and network #2 in cyan while they are within the handoff region, or they are colored in green or red depending on the region where they are. The time between dots defined in this scenario is StX = 0.001; this is also the time at which the instrument checks for state changes as a time-discrete simulator. Values for mSP, ΛEXEC and ΛEVAL are chosen such that they are positive multiples of StX or δ, not necessarily the same multiple but any positive multiple ($k\delta$) for $k \in \mathrm{Z}^+$. In this case, mSP = 0.2 and ΛEXEC = ΛEVAL = 0.1 satisfy this condition. Finally, mDR is set at 0.2; this is the minimum difference between values of desirability used for checking the sufficiency condition. For a one-to-one visual aspect ratio, mDR may be set at the same value of mSP if we want to give the same chance for testing sufficiency and consistency conditions.

At this point, the user has the chance to press the simulation button and start a handoff simulation or go back to the capture state to change the current handoff scenario. Figure 4-17b depicts the visual output of the instrument after the user presses the simulation button. This output is a good example to illustrate the behavior of the handoff algorithm because it depicts the current network passing through all handoff states in a single scenario. In order to help the explanation of this visual output, we will use figure 4-18, which is a replica of figure 4-17b but includes additional visual aids that will ease the interpretation of these results.



Network 1: 4*S(x-3)+4/3*S(3*x+2)+4/5*S(5*x)

Network 2: 4*(-1)*C(x/2.5-3)+0.5

X1: -7
Y1: -7
X2: 7
Y2: 7
LT: -1
UT: 4
StX: 0.001
mDR: 0.2
mSP: 0.2
ExL: 0.1
EvL: 0.1

Figure 4-18. Visual output of handoff simulator with additional visual aids.

At the beginning, the terminal connects to the best network (N1) and stays there until disconnection occurs because the lack of available networks in scene. The terminal stays disconnected until network 2 appears for the first time in the handoff region and the terminal immediately connects to it. So far, the handoff algorithm changed its state from initiation in N1 (black bar at the bottom of visual area), to disconnection (red bar), to initiation in N2 (black bar).

After some time, N1 reappears at the bottom of the handoff region and very soon it becomes better than N2, which defines the first crossing point in the scenario. After this cross point, N1 becomes the best candidate network but N2 is still the current network, only that it changed its color from black to blue, indicating that it entered in preparation for making a handoff from N2 to N1; however, such handoff will not be achieved. The cross point occurs at the 8th level from 10 available levels of adaptability; this implies that $SP = \Delta = 8*0.2$, and therefore, $\Lambda PREP$ would last 1.6 units of time at least. This is much time, but as this handoff represents an opportunity and not a necessity, the testing time for sufficiency and consistency takes longer (blue bar). When testing time or handoff preparation time is over, the handoff algorithm decides not to perform the intended handoff and keep connected to N2, because, by that time, the current network (N2) is again the best available network, while candidate network N1 degrades rapidly until it vanishes below the lower threshold. Therefore, current network changed from preparation in N2 to initiation in N2, or from blue to black.

The terminal keeps connected to N2 which is also the best network; however, N2 starts to degrade slowly and constantly. Near the 4th level of adaptability another crossing point occurs. N1 reappears again and improves rapidly. The handoff algorithm instructs the terminal to prepare for a handoff, indicated again by plotting the current network in blue. However, this time the handoff becomes imperative as N2 approaches to the red region. The new values for SP and Δ are obtained by making SP = Δ = 4*0.2, and therefore, ΛPREP would last 0.8 units of time. In this second handoff trial, the candidate network N1 becomes the best as it appears in the green region, while current network keeps approaching to the red region. At the end of preparation time, the algorithm decides to make a handoff from N2 to N1. This is illustrated by painting both, the current and the best network, in red because we consider this can be a *break-before-make* handoff. This type of handoff is also known as "*hard*" handoff because it cannot be simultaneously connected to both networks, therefore, there must be a momentarily disconnection before the reconnection. Once handoff is executed, reconnection occurs but now in the new network (N1). Before releasing N1 for its normal utilization, the handoff algorithm evaluates its own performance by comparing the desirability of new and old networks. This is represented by plotting both networks, in pink color. If new network is consistently better than the old network, then the handoff is counted as beneficial, otherwise, it is considered harmful.

The last part of the handoff simulation is now straight. The handoff algorithm maintains the connectivity to N1 as long as possible. The algorithm makes its best-effort to keep connected to the best available network, but irremediably N1 degrades rapidly until it disappears from the scene. This is the end of the simulation.

Now, handoff results are sent to the console output as two text strings, one representing the handoff scenario, and the other, the handoff performance measures (see figure 4-17c). The first performance parameter is rTiB = 0.7961428571428044. This performance parameter indicates the terminal was connected to the best available network 79.61% of the total simulation time. This parameter was calculated using the rate DTiB/TST, where TST =

14.0 and DTiB = 11.145999999999262. The instrument measures DTiB by initializing DTiB in 0 and then incrementing its value at every step time (StX) where current network is the best available network. In this way, even some portions of preparation state may contribute to DTiB, e.g., after the second crossing point in figure 4-18, the terminal is in preparation but current network is the best. Neither execution states, nor evaluation states, nor disconnection states, nor some portions of preparation states contribute to DTiB. The second performance parameter is rEHO = 0.3333333333333333. This parameter indicates the terminal performed only 33.33% of the total number of handoffs that would be required to stay always in the best network. We have seen that this total number of possible handoffs is ToX. In this case, ToX is 3 and nEHO is 1, therefore, the rate nEHO/ToX is 1/3. The third and last key result the instrument provides is rBHO = 1.0. This parameter indicates the algorithm performed a 100% of beneficial handoffs. This handoff simulation produced one beneficial handoff from a total of one executed handoff, given by the rate nBHO/nEHO is 1.

We will close this section on implementation recalling the main characteristics that we proposed for the handoff algorithm in Section 4.2.1 and remarking how they can be observed in the handoff simulation results.

- *Determinism* can be noticed in figure 4-18 because the handoff algorithm just can be in one possible state at any time (disconnection, initiation, preparation, execution, or evaluation) we do not see the terminal staying in more than one state simultaneously.
- *Reactivity* is similarly observed by noticing that a handoff preparation only occurs after a crossing point, as a reaction to an event. The crossing point is the event that triggers a handoff preparation; it is a cause-effect relation.
- *Heuristics* is observed by noticing how handoff strategies sometimes may fail and sometimes may succeed. In this case, the performed

handoff was beneficial but, there will be other scenarios where the handoff strategy fails, making rBHO < 100%.

- *Autonomy* is observed because user only intervenes off-line, when he sets the handoff configuration parameters. User interventions are never required during a running handoff simulation or online operation.
- *Adaptability* is observed by noticing how the preparation latency may change depending on the crossing point location within the handoff region. This characteristic allows a gradual increment in preparation latencies as the crossing point approaches to the green region.

So far, these are the characteristics that we can observe through the handoff simulation instrument. Successfulness will be discussed in section 4.4.2.

4.3.4 Testing

The last step in the development of the handoff simulation instrument is testing; i.e., the process of verifying the instrument works as expected. In order to perform a functional testing, we expose the virtual instrument to different input scenarios and observe its behavior and outcomes. This testing approach has two purposes: finding software bugs (errors or other defects) and verifying the instrument outcomes meet the requirements that guided its design and development.

We do not describe the software bugs that we found in the code, we can just say that every detected bug was fixed and the instrument is now operationally stable. What we do describe is the outputs produced when the instrument is exposed to different input scenarios. We are interested in presenting testing cases that will make the handoff algorithm yield “good” and “bad” results as it was previously described. In this way, we can test the instrument outputs with different types of input scenarios. For detailed tests see Appendix A.

4.4 Discussion of Simulation Results

In this final section we assess the *performance goals* of the handoff simulation instrument. To achieve this assessment, we design a *nondeterministic experiment* for collecting *representative samples* of input handoff scenarios which are used to test the instrument performance. For each input scenario, the instrument records and measures two main handoff performance parameters: rTiB and rEHO. The space of handoff results is composed of data points (rTiB, rEHO) obtained from each test. We perform a *statistical analysis* of sampled data in order to create *probabilistic models* that describe and predict the distribution of results within specific *subspaces* of the sample space. Next, we perform a bivariate analysis to study the relationship and correlation between rTiB and rEHO. Finally, we discuss and summarize the simulation results obtained from the experiment.

4.4.1 Experiment Design

In order to verify the instrument correctness, we designed a *nondeterministic experiment* that can help us to predict the chance that a random handoff scenario will produce results falling within particular areas of the sampling space. This implies to build a probabilistic model that defines a probability function for the handoff results. This way, we could estimate probabilities for a handoff scenario to fall within specific result subspaces.

Before starting the instrument assessment, we must think in how to obtain a representative sample of handoff scenarios that will enable to collect the set of handoff data to study, in such a manner that, their statistics analysis will permit to draw valid conclusions about the population of handoff scenarios.

Recall that S is the universal set (or population) of handoff scenarios and we showed it is infinite but denumerable. Instead of testing the handoff instrument with every scenario, $s \in S$, which is impossible to do, we examine only a small part of this population with a random subset of S, named $S_n = \{s_1, s_2, \ldots, s_n\}$, a.k.a. *random sample*. Each handoff scenario, s_k, is entered into the instrument one after another, and after a specific amount of time, the instrument delivers three handoff performance measures for each input scenario: $rTiB_k$, $rEHO_k$, and $rBHO_k$. Therefore, we have three *random functions* defined on S, which assign a number to each scenario of the sample. Thus, we need a probabilistic model to predict the values for $rTiB_k$, $rEHO_k$, or $rBHO_k$ given a handoff scenario s_k. For this purpose, we use the functions X: S → rTiB, Y: S → rEHO, and Z: S → rBHO, to denote three random variables; where X(s), Y(s), and Z(s), represent numerical values of rTiB, rEHO, and rBHO, respectively.

We will concentrate mainly in two variables, X (rTiB) and Y (rEHO), because as you recall, the main purpose of the handoff algorithm, embedded in the handoff instrument, is increasing rTiB and reducing rEHO as much as possible. Moreover, as they appear simultaneously during each test, and as they are mutually compromised, we are going to study both variables X and Y, individually and together, so that we can understand how they interact with each other. We identify that (X, Y) is a *bivariate* random variable, where X = X(s) and Y = Y(s) are real numbers in the interval [0, 1] obtained, simultaneously, for the same handoff scenario. In particular, the variable (X, Y) is a *continuous* bidimensional random variable because it can take on, practically, any point on the Euclidean plane represented by $R_{X \times Y} = \{(x, y) | 0 \leq x \leq 1, 0 \leq y \leq 1\}$, where (x, y) represents any point within the square of side one, such that x = X(s) represents a value of rTiB and y = Y(s) represents a value of rEHO. We use capital letters to denote random variables and lower case letters to represent their values.

Sometimes we must use the language of probability in any statement of conclusions because inference from sample to population cannot be certain. Therefore, it is common writing, for instance, $P[X \geq 0.5, Y \leq 0.5]$ instead of $P[X(s) \geq 0.5, Y(s) \leq 0.5]$ to denote the probability that a given handoff scenario falls in the “green” region. In summary, the random sample of scenarios S_n will generate a sample of points in the plane bounded by the unit square, one point per scenario, as follows: (X, Y): $s_k \rightarrow (X_k, Y_k)$, or $(X_1, Y_1), \ldots, (X_n, Y_n)$. This sample of points represents the set of handoff data to analyze statistically. The bivariate random variable (X, Y) can take on different values depending on the input scenario defined by the following string of parameters: N1: N2: X1: Y1: X2: Y2: LT: UT: mSP: mDR: StX: ExL: EvL. A *joint probability distribution* will be used to describe the probabilities of different values (x, y) occurring.

Once we overviewed the experiment to deploy, we discuss details of how we chose a representative sample and its adequate size. In order to obtain a representative sample, we invited to three different users to try a session test with the handoff instrument. Each user was introduced with the meaning of each input parameter and the purpose of this trial. A special attention was set on the way they should create every handoff scenario. We asked they created *random* scenarios by experimenting with different network functions, thresholds, windows, latencies, and other configuration parameters. They were also asked to keep the same experimental conditions between measurements; e.g., by not allowing one handoff result will influence the way the next handoff scenario would be created. Independence between observations will make that every sample point has the same probability distribution. Besides, each user was asked to create and test at least 30 handoff scenarios, or the more they want the better, and save its handoff results into a delimited text file. In this way, we could arise more than 90 sample points, collected from three different and independent sources. We asked at least 30 measurements per user, because we empirically observed that after plotting a *scatter diagram* with more than 30 points, the distribution probability function begins to show an identifiable *statistical regularity* that we will discuss in the section 4.4.2.

The above described experiment (ε) can be summarized as follows:

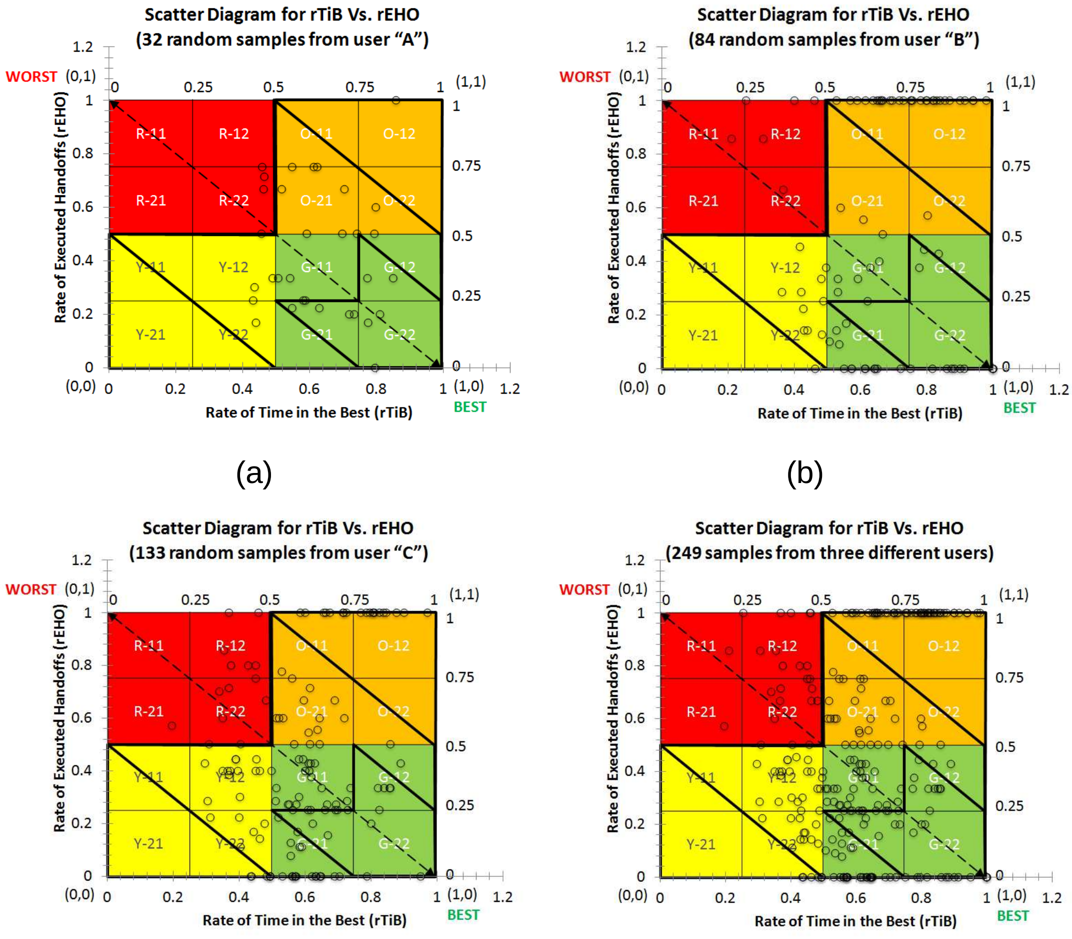
1. Choose and prepare a user that will perform the sampling experiment.
2. Ask the user to create a random handoff scenario via the handoff simulation instrument.
3. For each input handoff scenario,
    a. Make a preview plotting for validating the handoff scenario,
    b. Run a simulation test by executing the handoff algorithm on such scenario,
    c. The instrument records the scenario information and its performance measures,
    d. If sample size (n) is under 30, go back to step 2.
    e. If user wants to continue testing more scenarios, go back to step 2.
4. From the instrument records, get pairs (rTiB, rEHO) and save data in matrix [nx2] format.
5. If you want to repeat the experiment with another user then go to step 1, otherwise, the experiment ends.

This experiment initially works on the population of handoff scenarios S, a.k.a *sample space of non numerical results* or sample space of scenarios, to produce a random sequence of scenarios S_n. However, the space $R_{X\times Y}$, the set of all possible values of (X, Y), is considered another sample space, a.k.a *sample space of numerical results* or sample space of bivariate data (X, Y). The numbers X(s) and Y(s) in the tuple (X, Y) are considered the final results of the experiment, thus $R_{X\times Y}$ becomes the final sample space of the experiment. It is important to say that this experiment performs *sampling with replacement*; i.e., a particular handoff scenario may appear more than once in the sample. This would imply that a point (x, y) could come up several times in the space of results; however, that is not the main cause for a single point (x, y) to appear more than once in $R_{X \times Y}$. Effectively, for every $s \in S$, exactly one point (X(s), Y(s)) corresponds to s because X and Y are functions, but different input scenarios may give, approximately, the same values of x and y, i.e., if [$s_1 \neq s_2$ and $X(s_1) \approx X(s_2)$ and $Y(s_1) \approx Y(s_2)$] then s_1 and s_2 give the same point (x, y) in the plane, this may occur because X and Y are not one-to-one functions.

In the next section, we will provide more evidence on the instrument correctness; we will make a statistical analysis that shows the behavior and results of the handoff instrument when it is exposed to a massive amount of input scenarios.

4.4.2 Handoff Performance Goals Assessment

In this section, we assess the handoff instrument performance goals by implementing the ε-experiment and obtaining representative samples of handoff data (rTiB, rEHO) coming from the three different users. By observing the distribution of sample data within the space of results, we may compute the degree of achievement of each performance goal, which gives a measure of the instrument behavior. So, let us start by describing what each user delivered to us. User “A” made 32 observations, user “B” 84, and user “C” 133, which gives a total sample size of 249 tested scenarios. The original data files provided by these users can be overviewed in Appendix B of this manuscript. To illustrate the distribution of samples, a scatter plot for each random experiment is pictured in figures 4-19(a-d).



(a)

(b)

(c)

(d)

Figure 4-19. Scatter diagram for rTiB vs. rEHO in (a) 32 observations made by user "A", (b) 84 observations made by user "B", (c) 133 observations made by user "C", and (d) 249 cumulative observations of users A, B, C.

Figure 4-19a shows a scatter diagram for the 32 samples made by user "A". There are 11 samples in the region "very good results and very good balance." They represent a 34.48% from the total of 32 samples. There are 28 (17+11) measurements in the space for "good results and good balance," which give a hit rate of 87.5%. There are 29 (1+17+11) samples that lie in the space for "good results," giving a rate of good results of 90.63%. Finally, there are only 3 sample points in the space for "unacceptable results," which represent 9.37% of the sample size. This random experiment of 32 samples meets all the performance goals that were specified for the virtual handoff instrument.

Figure 4-19b depicts a scatter diagram containing 84 measurements made by user “B”. There are 12 sample points in the space for “very good results and very good balance,” which represent 14.29% of the sample size. There are 46 points (12+34) in the space for “good results and good balance,” which represent 54.76% of the sample size. There are 78 (12+34+32) measurements in the space for “good results” that represent 92.86% of the total amount of sample points. Finally, in the red squares there are 6 points that represent 7.14% of “bad” results. The random experiment of 84 samples meets all the percentage goals for “good results” (92.86%), for “good results and good balance” (54.76%), and for “very good results and very good balance” (14.29%).

Figure 4-19c shows a scatter diagram of 133 random sample points obtained by user “C”. The graphic presents 17 samples in the space for “very good results and very good balance,” which represent a percentage of 12.78%. It includes 95 (17+78) samples in the space for “good results and good balance,” which represent the 71.43% of the sample size; and, 121 (17+78+26) samples in the space for “good results,” which represent a hit rate of 90.98%. The diagram also illustrates 12 sample points located in the space for “bad results,” representing a 9.02% of bad results. The random experiment of 133 samples meets all the percentage goals: for “good results” (90.98% > 90%), for “good results and good balance” (71.43% > 50%), and for “very good results and very good balance” (12.78% > 10%).

Figure 4-19d presents the scatter diagram of collected results from users A, B, and C, giving a total of 249 *random* and *independent* samples. The graphic shows a total of 40 (11+12+17) samples in the space for “very good results and very good balance,” representing a 16.06% of the total cumulative sample size. It also depicts 169 (28+46+95) measurements that represents 67.87% of the total sample size in the space for “good results and good balance.” Finally, it contains 228 (29+78+121) samples in the space for “good results,” which represents 91.57% of the total sample size. In the red squares there are 21 (12+6+3) “bad” samples which represent 8.43% of the total number of points in the sampling space.

Table 4-5 presents a summarization of results taken from the testing experiment of the handoff instrument. This table compares the percentages of sample points falling in each region of handoff results with different random samples obtained from the experiments.

Table 4-5. Summary of results found by the experiments designed for testing the handoff instrument.

Experiments / Results	32 random samples from user A	84 random samples from user B	133 random samples from user C	249 samples from users A, B, and C	Performance Goals
Very good results & very good balance	34.48%	14.29%	12.78%	16.06%	>10%
Good results & good balance	87.5%	54.76%	71.43%	67.87%	>50%
Good results	90.63%	92.86%	90.98%	91.57%	>90%
Bad results	9.37%	7.14%	9.02%	8.43%	<10%

It can be seen that hit rates, in all testing cases, meet the performance goals defined for the handoff instrument. Therefore, these results provide empirical evidence that support the correctness of our instrument. The handoff simulation instrument produced, in average, a rate of “good” results above

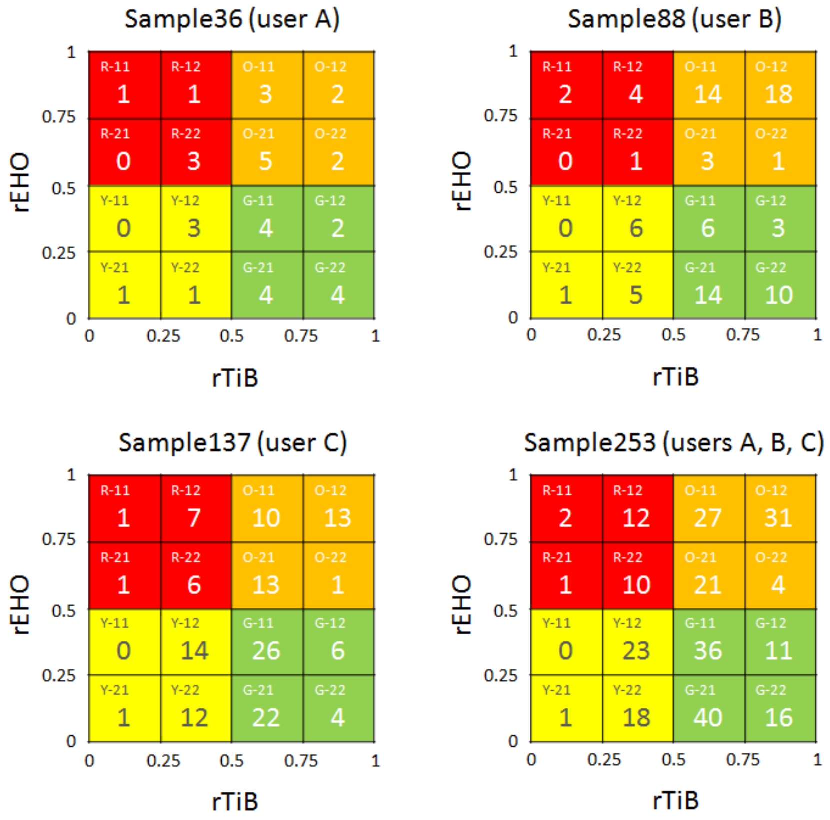
90% or a rate of “bad” results below 10%, a rate of “good” results and “good” balance above 50%, and a rate of “very good” results and “very good” balance above 10%.

4.4.3 Probabilistic Models of Handoff Results

So far, we have empirically verified the instrument handoff correctness by observing its behavior when it is exposed to specific samples of random handoff scenarios. Now, we are interested in developing probabilistic models based on the statistical analysis of those samples, which will allow drawing valid conclusions about the instrument performance trends when it is exposed to a large number of handoff scenarios. This section presents three probabilistic models that we built to predict the behavior of the handoff simulation instrument.

We organized the handoff data by *partitioning* the sample space of numerical results into 16 parts labeled as: R11, R12, R21, R22, Y11, Y12, Y21, Y22, O11, O12, O21, O22, G11, G12, G21, and G22. The boundaries of these parts were defined in Table 4-3. We may also refer to these parts as *subspaces*, *classes*, *cells*, or *events*. All these terms share the property of being *subsets* of the space of outcomes of our experiment. Moreover, as a partition of the sample space, these subsets are *mutually exclusive* because *one and only one* of them may *occur* every time the experiment is performed. The event E *occurs* if the outcome of the experiment is an element of the E class. If we repeat *n* times the ε-experiment and E is an event associated with ε then n_E is the number of times the event E occurred within the *n* repetitions. This number is called the *frequency* of the event E. Thus, we determine the *class frequency* by counting the number of sample points (rTiB, rEHO) belonging to each class. The resulting arrangement is called a *frequency* *distribution* or *frequency table*. Figure 4-20 depicts the frequency tables of our four experiments.

Frequencies in figure 4-20 correspond to the handoff data delivered by users “A”, “B”, and “C”, who took on 32, 84, and 133 samples respectively; however, we added 4 handoff scenarios to each sampling experiment, which are associated to each vertex of the unit square, as depicted in Figure 4-2. Such missing points are included so that we can plot data using the same range of space results; thus, we will consider 36 samples for user “A” (Sample36) instead of 32, 88 samples for user “B” (Sample88) instead of 84, 137 samples for user “C” (Sample137) instead of 133, and 253 cumulative sample points from users “A”, “B”, and “C” (Sample253) instead of 249.



Sample36 (user A)

R-11 1	R-12 1	O-11 3	O-12 2
R-21 0	R-22 3	O-21 5	O-22 2
Y-11 0	Y-12 3	G-11 4	G-12 2
Y-21 1	Y-22 1	G-21 4	G-22 4

Sample88 (user B)

R-11 2	R-12 4	O-11 14	O-12 18
R-21 0	R-22 1	O-21 3	O-22 1
Y-11 0	Y-12 6	G-11 6	G-12 3
Y-21 1	Y-22 5	G-21 14	G-22 10

Sample137 (user C)

R-11 1	R-12 7	O-11 10	O-12 13
R-21 1	R-22 6	O-21 13	O-22 1
Y-11 0	Y-12 14	G-11 26	G-12 6
Y-21 1	Y-22 12	G-21 22	G-22 4

Sample253 (users A, B, C)

R-11 2	R-12 12	O-11 27	O-12 31
R-21 1	R-22 10	O-21 21	O-22 4
Y-11 0	Y-12 23	G-11 36	G-12 11
Y-21 1	Y-22 18	G-21 40	G-22 16

Figure 4-20. Bivariate frequency tables obtained from different sampling experiments.

We can use the 4x4 partition to determine the frequencies of larger classes, like all the green zone labeled as G, by doing $n_G = n_{G11} + n_{G12} + n_{G21} + n_{G22}$. This way, using Sample253 we compute the frequencies $n_G = 103$, $n_Y = 42$, $n_O = 83$, $n_R = 25$, for the green, yellow, orange, and red zones, respectively. Figure 4-21 depicts such 2x2 frequency distribution.

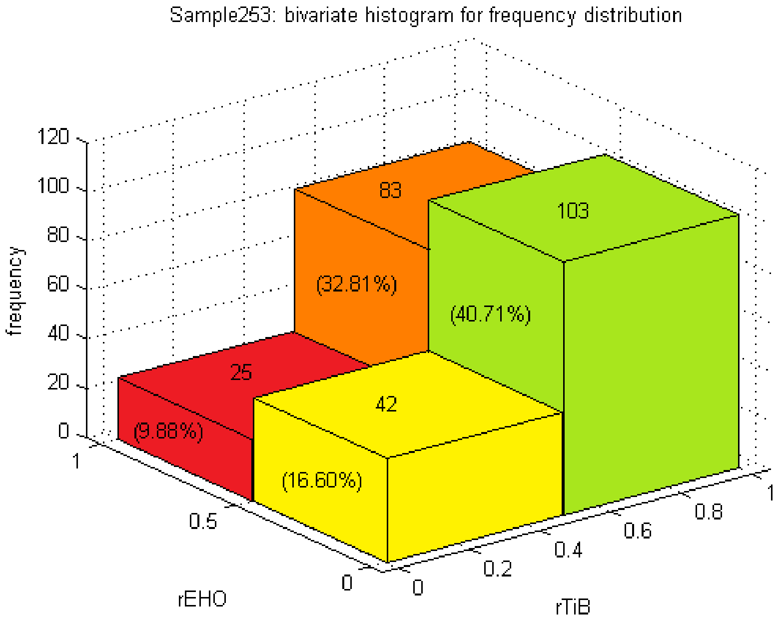
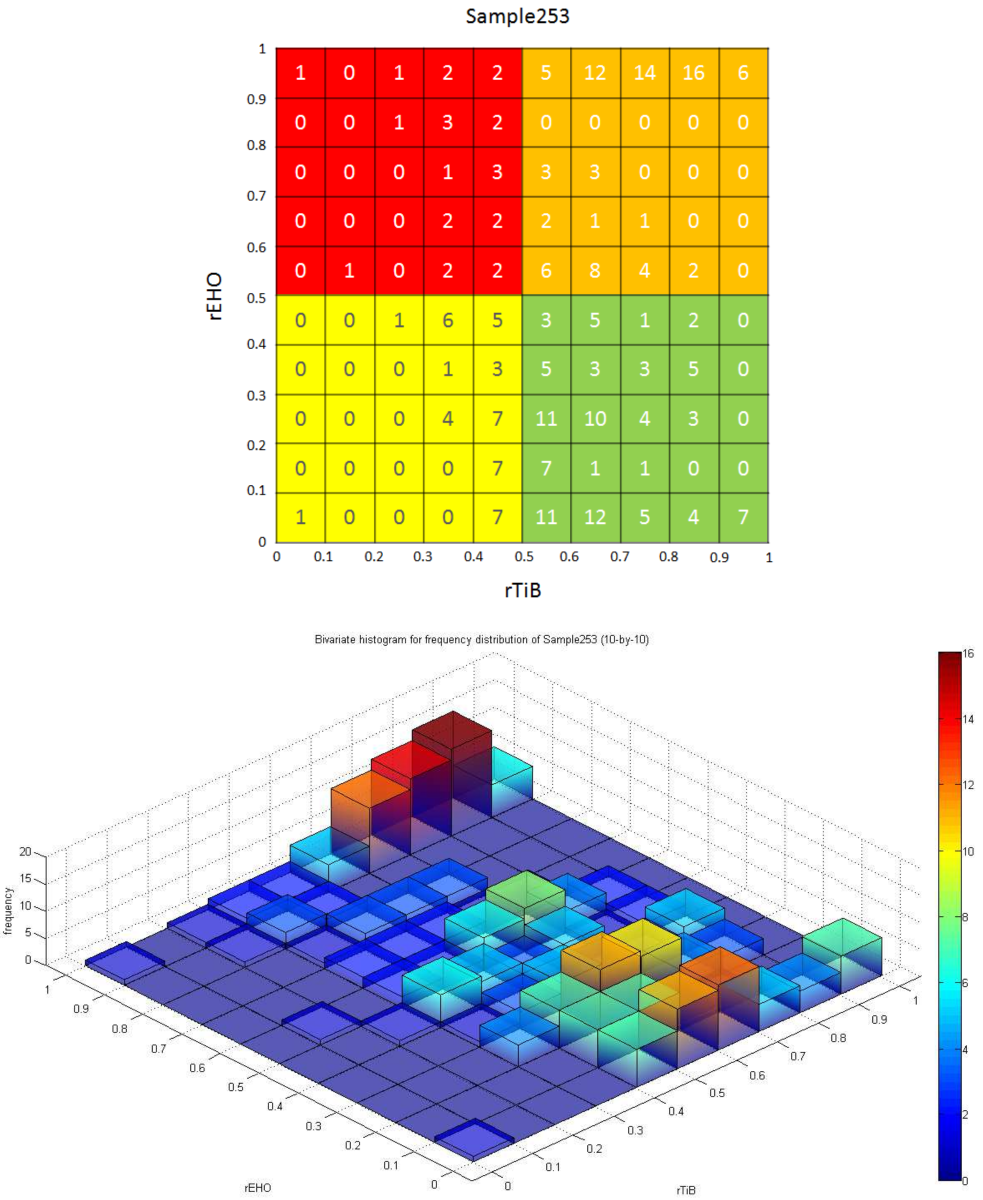


Figure 4-21. 2-by-2 bivariate histogram for frequency distribution of 253 tested scenarios.

If we wanted to know the number of times the event {(x, y) | $0.6 \leq x < 0.7$, $0.2 \leq y < 0.3$} has occurred, then it would be convenient to change the 4x4 partition into one with smaller subsets; i.e., to have a finer view of the frequencies distribution. The arrangement of the sample space into an $m \times m$ grid of equally spaced containers (bins), makes it possible to refer to such space as a matrix $[m,m]$ where its elements are those infinitesimal squares of side $1/m$, and $m > 0$. We use figures 4-22a and 4-22b to depict a 10x10 frequency table for Sample253 and its frequency distribution using a 3D histogram with bars colored according to height.



1	0	1	2	2	5	12	14	16	6
0	0	1	3	2	0	0	0	0	0
0	0	0	1	3	3	3	0	0	0
0	0	0	2	2	2	1	1	0	0
0	1	0	2	2	6	8	4	2	0
0	0	1	6	5	3	5	1	2	0
0	0	0	1	3	5	3	3	5	0
0	0	0	4	7	11	10	4	3	0
0	0	0	0	7	7	1	1	0	0
1	0	0	0	7	11	12	5	4	7

Figure 4-22. (a) 10-by-10 frequency table. (b) A 10-by-10 bivariate histogram.

In figure 4-22a and 4-22b, we can see how the results are distributed inside the red, green, yellow, and orange regions. This visualization enables to make some preliminary remarks about the observed performance measures:

- First, roughly 98% of scenarios in the sample have an rTiB ≥ 0.3. Thus, there is a noticeable gap in the containers of the grid located in the range 0 ≤ rTiB < 0.3, which indicates that is not likely to find many scenarios whose performance measures lay on this region of the grid.
- Second, more than 90% of scenarios from the red and yellow zones occur in the interval 0.3 ≤ rTiB < 0.5; i.e., results in red and yellow are skewed toward the central axis at rTiB = 0.5. Moreover, a noticeable rising in frequencies also occurs as rEHO < 0.5, which increases the amount of scenarios falling in the yellow region compared to those lying in the red region. Scenarios in the red and yellow zones trend to increase their number as rTiB approaches to 0.5 and as rEHO approximates to 0.
- Third, almost 75% of scenarios in the sample lie in the green and orange zones. In these zones, a kind of “belts” or sequences of points appear at specific values of rEHO; mainly at 0, 1, and 0.5. The higher density belts trend to cluster near the extreme values of rEHO; an upper belt spans at rEHO = 1 in the orange zone and a lower belt extends at rEHO = 0 in the green zone. A lower density middle belt trends to cluster at rEHO = 0.5. In figure 4-23, the histogram for rEHO depicts this trend. A low density of disperse scenarios lies in the orange zone between the upper and middle belts, and those scenarios become rarer as rTiB approaches to 1. On the contrary, a high density of disperse scenarios lies in the green zone between the lower and middle belts, and they tend to be more frequent as rTiB moves between 0.5 and 0.7. The histogram for rTiB in figure 4-23 shows this behavior.
- Fourth, the belts described above, are visible only horizontally, and not vertically, or diagonally. These belts are demarked by rectangular boxes in figure 4-23. This behavior occurs because rEHO is computed as the rate of two integers (nEHO/ToX), thus, it takes only rational numbers. In contrast, the variable rTiB is a rate of two real numbers (DTiB/TST), thus, rTiB has a wider range of variability than rEHO, which prevents the forming of vertical belts.

Now, let us state the relationship between frequency and probability of an event. In general terms, the more frequent an event is, the more probable that event is to occur. The frequency tables in Figure 4-20 show that events G21, G11, and O12 regularly occur with more frequency than other events in the partition. This trend is clearer as the number of samples increases. Thus, we expect a greater *probability* for these events to occur in any repetition of the random experiment.

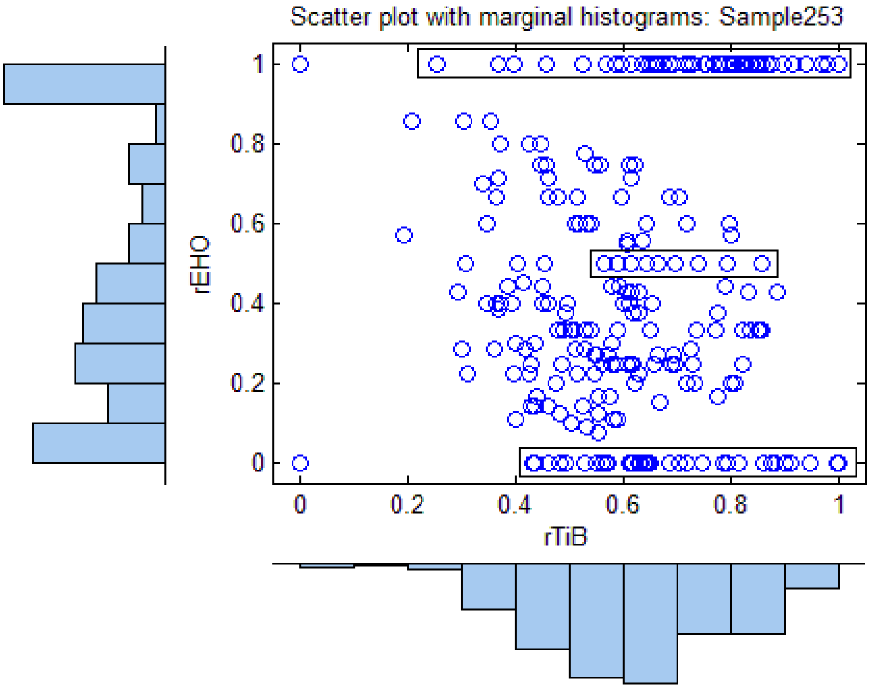


Figure 4-23. Scatter plot for Sample253 with univariate histograms for rTiB & rEHO.

In any random experiment there is always uncertainty as to whether a particular event will or will not occur. Probability is a measure of the *chance* with which we can expect an event E to occur; designated by P(E). It is convenient to assign a number between 0 and 1 to P(E). If we are sure or certain that the event will occur, we say that its probability P(E) is 100% or 1, but if we are sure that the event will not occur, we say that its probability is zero. If, for example, $P(E) = 1/4$, we would say that there is a 25% chance E will occur and a 75% chance that E will not occur. If after n repetitions of an experiment, E is observed to occur in n_E of these, then the *empirical probability* or *relative frequency* of event E is $f_E = n_E/n$, this is the *frequency approach* to probability. So, if in our frequency tables we recorded the relative frequency rather than the frequency of the events, the result would be a *relative frequency distribution* or *empirical probability distribution*. For example, in figure 4-21 the relative frequency corresponding to the G event is $f_G = n_G/n = 103/253 = 40.71\%$, and so on for $f_R = 9.88\%$, $f_O = 32.81\%$, and $f_Y = 16.60\%$. The corresponding histogram would be similar to that in Figure 4-21 except that the vertical axis is relative frequency instead of frequency.

We can change the arrangement of the sample space from an $m \times m$ grid of containers (GRID [i, j]) into a column vector CLASS[k] formed from the columns of the grid. In fact, it is possible to refer to the elements of a matrix with a single subscript, k. A single subscript is the usual way of referencing row and column vectors; however, it can also apply to a fully two-dimensional matrix, in which case the array is regarded as one long column vector. So, as Table 4-6 shows, CLASS[8] is another way of referencing the event GRID[4,2] or Y22 in our 16-squares layout; in general, a relationship between indexes in GRID[i, j] and CLASS[k] is given by $k = (i \times j) + [(m - i) \times (j - 1)]$, for $k = 1, 2, \ldots, N = m \times m$; $i = 1, 2, \ldots, m$; and $j = 1, 2, \ldots, m$.

In table 4-6, we changed the sample space of results from a 4x4 grid of bins into a 16 column vector of events. For each event k we assigned a relative frequency f_k, thus a set of data points (k, f_k) is obtained for each sampling experiment.

Table 4-6. Relative frequency vectors on each sampling experiment.

Index (k)	Classes or events	f_k Sample36 User A	f_k Sample88 User B	f_k Sample137 User C	f_k Sample253 Users A, B, C
1	R11	1/36 = .0278	2/88 = .0227	1/137 = .0073	2/253 = .0079
2	R21	0	0	1/137 = .0073	1/253 = .0040
3	Y11	0	0	0	0
4	Y21	1/36 = .0278	1/88 = .0114	1/137 = .0073	1/253 = .0040
5	R12	1/36 = .0278	4/88 = .0455	7/137 = .0511	12/253 = .0474
6	R22	3/36 = .0833	1/88 = .0114	6/137 = .0438	10/253 = .0395
7	Y12	3/36 = .0833	6/88 = .0682	14/137 = .1022	23/253 = .0909
8	Y22	1/36 = .0278	5/88 = .0568	12/137 = .0876	18/253 = .0712
9	O11	3/36 = .0833	14/88 = .1591	10/137 = .0730	27/253 = .1067
10	O21	5/36 = .1389	3/88 = .0341	13/137 = .0949	21/253 = .0830
11	G11	4/36 = .1111	6/88 = .0682	26/137 = .1898	36/253 = .1423
12	G21	4/36 = .1111	14/88 = .1591	22/137 = .1606	40/253 = .1581
13	O12	2/36 = .0556	18/88 = .2046	13/137 = .0949	31/253 = .1225
14	O22	2/36 = .0556	1/88 = .0114	1/137 = .0073	4/253 = .0158
15	G12	2/36 = .0556	3/88 = .0341	6/137 = .0438	11/253 = .0435
16	G22	4/36 = .1111	10/88 = .1136	4/137 = .0292	16/253 = .0632

Figure 4-24, presents the empirical probability distributions for each performed experiment using relative frequency histograms and trending curves. We use cubic polynomials to visualize a smooth curve approximating the data. Such a curve is called an approximating or trending curve. It can be observed that a similar nonlinear pattern repeats across all experiments; i.e., the shape of trending curves seems to be more alike one another, as the number of samples increases. Their shape indicates that there is no symmetry about any particular class; conversely, they are *skewed to the left* as the left tail is longer than the right tail.

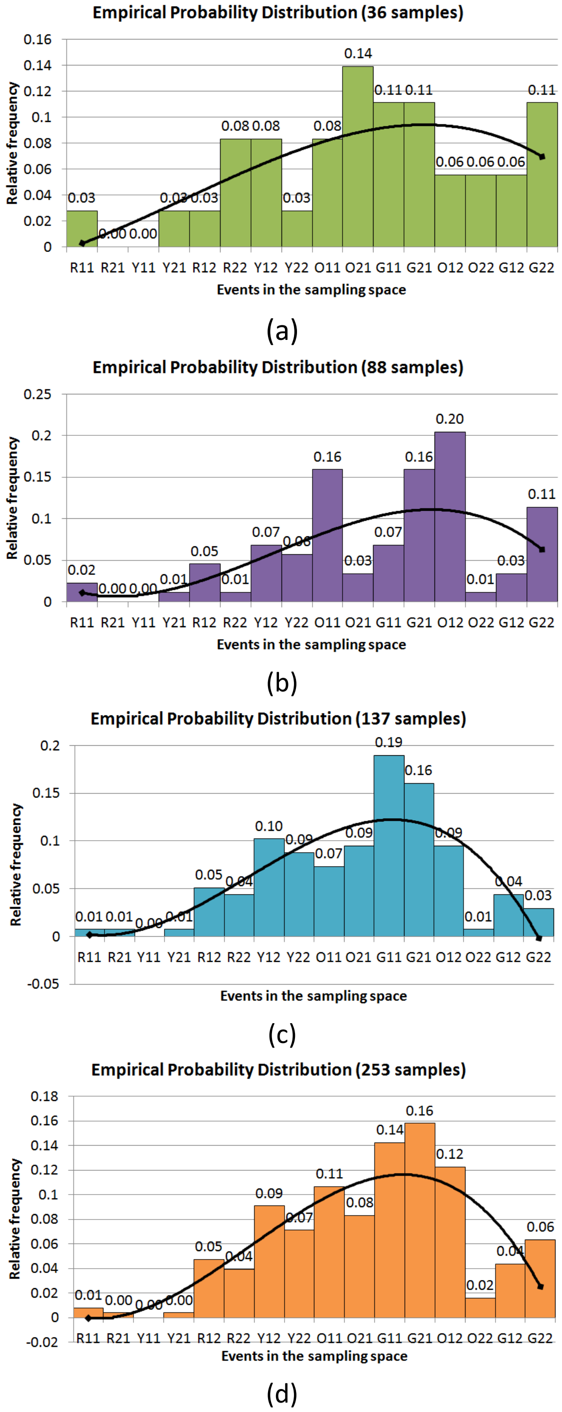


Figure 4-24. Empirical probability distributions: (a) 36 samples from user “A”, (b) 88 samples from user “B”, (c) 137 samples from user “C”, (d) 253 samples collected from users A, B, C.

The relative frequencies f_k have the following interesting properties that can be easily verified:

a) $0 \leq f_k \leq 1$, for any k. This results from the fact that $0 \leq n_k \leq n$. In Figures 4-24a-d, you can observe that all relative frequencies in the histograms satisfy this property. The trending curves represent the empirical probability distribution, which is an approximation to the probability distribution function.

b) $f_k = 1$ if k occurs every time in the *n* repetitions of ε (i.e., $n_k = n$). If $k = R_{X \times Y}$ then $f_k = 1$. It can be verified that the sum of all the rectangular areas in the histograms yields 100% or the sum $f_1 + f_2 + \ldots + f_{16} = 1$.

c) $f_k = 0$ if k never occurs in the *n* repetitions of ε (i.e., $n_k = 0$). The event Y11 or k = 3 never occurred along 253 repetitions; i.e., $n_3 = 0$, but this does not mean that it will never occur in a random experiment, it only indicates that their probability of occurrence is very small.

d) If A and B are two mutually exclusive events and if $f_{A \cup B}$ is the relative frequency associated to the event $A \cup B$, then $f_{A \cup B} = f_A + f_B$; this property will allow us, for instance, to estimate the empirical probability that a point occurs in any part of the "green" region by making $f_G = f_{G11} + f_{G12} + f_{G21} + f_{G22}$, which yields an empirical probability of 40.71%.

e) f_k *converges* to $P(E=k) = p_k$ when *n* trends to ∞; this is a consequence of the *law of large numbers*, which states that lim $n \rightarrow \infty$ of $P(|f_k - p_k| < \in) = 1$, for any $\in > 0$. If *n* is very large, a relative frequency distribution can be considered as a probability distribution in which probabilities are replaced by relative frequencies. With a growing number of observations, the relative frequency f_k tends to be stabilized nearby a definite value p_k. This property of *stability* can be visualized in Figure 4-25, where trending curves tend to vary less and less as the number of repetitions (n) increases. This characteristic of relative frequency is known as *statistical regularity*. Therefore, f_k approaches to p_k as *n* increases, but how large should be *n* before we reach such stability? In practice, you can steeply increase the number of samples between experiments and plot a trending curve per experiment. When you observe the trending curve of the largest sample resembles the previous trending curve, then, you can stop the experiments and consider that you have reached stability; otherwise, you can keep on this process until the current and previous trending curves have almost the same graph shape. This condition will necessarily occur if the random events in the experiment exhibit statistical regularity.

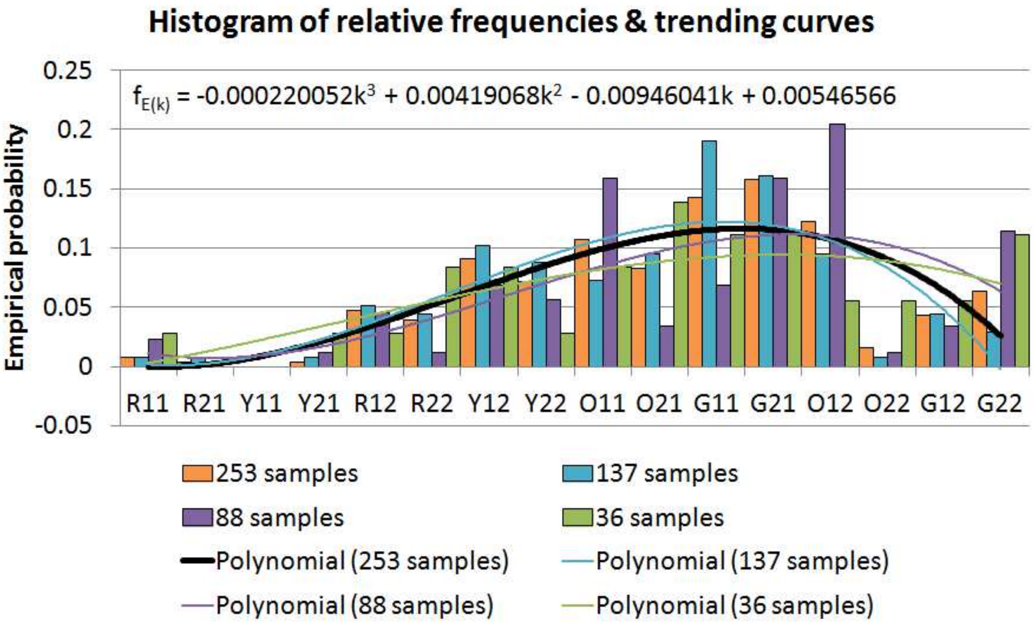


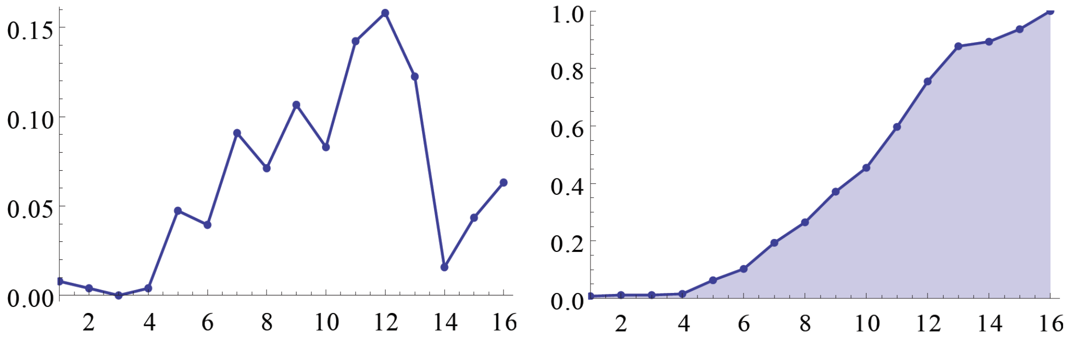
Figure 4-25. Comparison of different empirical probability distribution curves.

The problem of finding equations of curves that fit the given sets of data (k, f_k) is called *curve fitting*. One of the main purposes of curve fitting is to estimate one of the variables (the *dependent variable*) from the other (the *independent variable*). The estimated value (e_k) represents the expected (average) value of the dependent variable (f_k) given the independent variable (k). The process of estimation is often referred to as *regression*. If the estimation is performed by means of some equation, we call the equation a *regression equation* and the corresponding curve a *regression curve*, described by the set of points (k, e_k). A regression curve that fits the data using the method of least squares is called *least-squares regression curve*. The least-squares curve represents the *best-fitting trending curve* in a given family of curves approximating a set of N data points. The best-fitting curve is a curve having the property of minimizing the sum of the squared *residuals*, where a residual d_k is the difference between the value f_k and its corresponding estimation e_k.

Using WolframAlpha (www.wolframalpha.com), we obtain other useful visualizations (figure 4-26) which provide further insights into the regression curve of relative frequencies for Sample253.

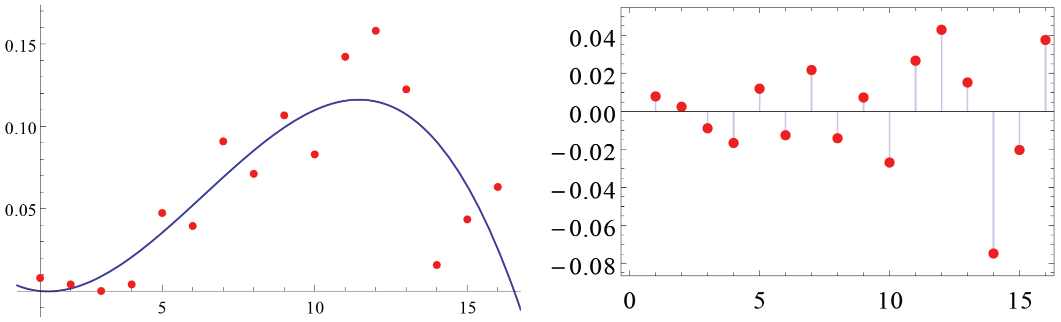
Fit data (k, f_k): {
(1, 0.0079), (2, 0.004), (3, 0), (4, 0.004), (5, 0.0474), (6, 0.0395), (7, 0.0909), (8, 0.0712), (9, 0.1067), (10, 0.083), (11, 0.1423), (12, 0.1581), (13, 0.1225), (14, 0.0158), (15, 0.0435), (16, 0.0632) }
Fit model: Polynomial of degree 3
Least-squares best fit:

$$e3_k = 0.0054 - 0.0095k + 0.0042k^2 - 0.00022002k^3 \tag{2}$$



(a) Plot of relative frequencies

(b) Plot of cumulative sums



(c) Plot of the least-squares best fit

(d) Plot of the residuals

Figure 4-26. Relative frequency distribution plots for Sample253 in a 4x4 column vector.

Figure 4-26a depicts a relative frequency polygon. The shape of the graph indicates the same trend to produce more results occurring in classes 11, 12, and 13, than other classes in the partition. Figure 4-26b approximates a cumulative distribution function through cumulative sums of relative frequencies. It shows that the sum of all the rectangular areas in the histogram yields 100%. Figure 4-26c depicts the best-fitting curve of relative frequency using a cubic polynomial and the least-squares regression approach. This curve is skewed to the left with a local maximum in class 11 or G11. Dots on the least-squares curve represent estimated values or *trend values* of the empirical probability distribution (k, e_k). Figure 4-26d, presents a plot of the residuals; they can be used to compute the *standard error of estimate*. There are usually several curves of a given type that will appear to fit a set of N data points. Out of all possible regression curves the least-squares curve has the smallest standard error of estimate of f on k, which is supplied by the quantity:

$$S_{f.k} = \sqrt{\frac{\sum(f_k - e_k)^2}{N}} \quad . \tag{3}$$

Since $\sum(f_k - e_k)^2 = \sum d_k^2$ is minimal in the least-squares curve, then we can expect that e_k can be a good approximation to the probability distribution function of subspaces (p_k). This claim is based on the following rationale, where notation (a → b) means "a" approximates to "b":

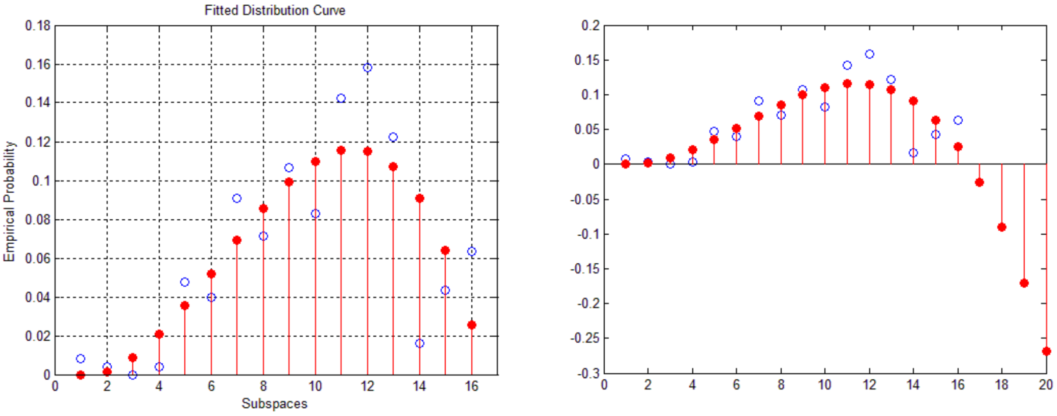
($e_k \rightarrow f_k$) as $\sum d_k^2$ is minimal;	property of the least-squares method.
($f_k \rightarrow p_k$) as $n \rightarrow \infty$;	property of the law of large numbers.

$\therefore$ ($e_k \rightarrow p_k$);	by transitivity.

This means that probability of the events $\{|n_k/n - p_k| < \in\}$ or $\{|e_k - p_k| < \in\}$ for any $\in > 0$, approximates to 1 as n is a large number. However, prior to considering the regression function as a probability function, the following two conditions must be satisfied:

$$e_k \geq 0,\ for\ all\ k, \tag{3a}$$
$$\textstyle\sum_{k=1}^{\infty} e_k = 1. \tag{3b}$$

In general, a regression function of empirical probabilities e_k does not satisfy such conditions despite f_k data, which are used to estimate e_k, do meet these conditions. For instance, in figure 4-27, we plot in blue circles the set of relative frequencies f_k taken from Table 4-6 and in red stems with filled red circles the regression function e_k defined by equation (2). The regression curve e_k yields some negative numbers, one for $k = 1$ and others for $k > 16$, as shown in figure 4-27b. This situation clearly violates condition (3a).



(a) (b)

Figure 4-27. (a) Cubic polynomial approximating to a probability function of subspaces. (b) The fitted curve does not satisfy the axioms of probability.

Therefore, some transformations should be made to e_k so that we can create a set of numbers p_k that satisfy conditions (3a and 3b) and thus it can be used to describe the probability distribution of subspaces. This transformation of ek into pk should be made without distorting the shape of the trending curve or minimizing such distortion. We describe this transformation process as follows:

1. [Make e_k = 0 for all k > N and k < 1.] The index of subspaces (k) only takes a finite number of values. For instance, k = 1, 2, …, N, where N = (m*m) and m = 1, 2, 3,… represents the grid size used to partition the unit square. As a consequence, e_k must be 0 for all k > N and k < 1; therefore, the infinite sum in equation (3b) becomes a finite sum.
2. [Make $e_k \geq 0$ for $1 \leq k \leq N$.] If h is the sum of all negatives values of e_k and δ is the amount of such negative values, then for k = 1 to N change $e_k \leftarrow e_k + |h|$. This makes the minimum $e_k \geq 0$, thus, condition (3a) is met.
3. [Make $e_1 + e_2 \ldots + e_N = 1$.] Now, let us make $\Delta \leftarrow 1 - \sum_{k=1}^{N} e_k$. If $\Delta = 0$ then we are done; e_k satisfies also condition (3b) and now e_k can be considered as p_k. Otherwise, distribute Δ equally among all subspaces whose e_k value was originally positive. Thus, make $e_k \leftarrow e_k + \Delta/(N-\delta)$. After this step, the new e_k meets conditions 3a and 3b; therefore, e_k has been transformed into p_k with minimal shape distortion. The transformation process makes $p_k = e_k + |h| + \Delta/(N-\delta)$.

As an example of this procedure, we present three families of regression curves e_k that we use for estimating a probability distribution p_k from the same data set of relative frequencies per subspace f_k. Each regression curve will be transformed into one *probability function of subspaces* describing the behavior of the observed handoff data. The collection of points (k, p_k) is called the *probability distribution of subspaces*. These probability models are based on polynomial trending curves of third, fifth, and seventh degree. Figure 4-28 plots the best-fitting curves for polynomials of degree 3, 5, and 7. Table 4-7 describes the regression equation of each polynomial by means of its coefficients. The polynomial's degree controls the smoothness of the probability distribution curve. The third degree polynomial seems to be so smooth that the behavior of data at the last four subspaces is obscured. On the contrary, the seventh degree polynomial seems to show too many details of data behavior. Therefore, the fifth degree polynomial seems to be doing a good job on this task; reasonably smooth, but not as smooth as to obscure features of the data.

Table 4-7. Regression polynomials coefficients (degrees: 3, 5, and 7).

K^7	K^6	K^5	K^4	K^3	K^2	K^1	K^0
				-2.2002e-4	0.0042	-0.0095	0.0054
		9.3092e-6	-3.6381e-4	0.0048	-0.0245	0.0535	-0.0319
4.2875e-7	-2.2437e-5	4.6123e-4	-0.0047	0.0250	-0.0618	0.0581	-0.0075

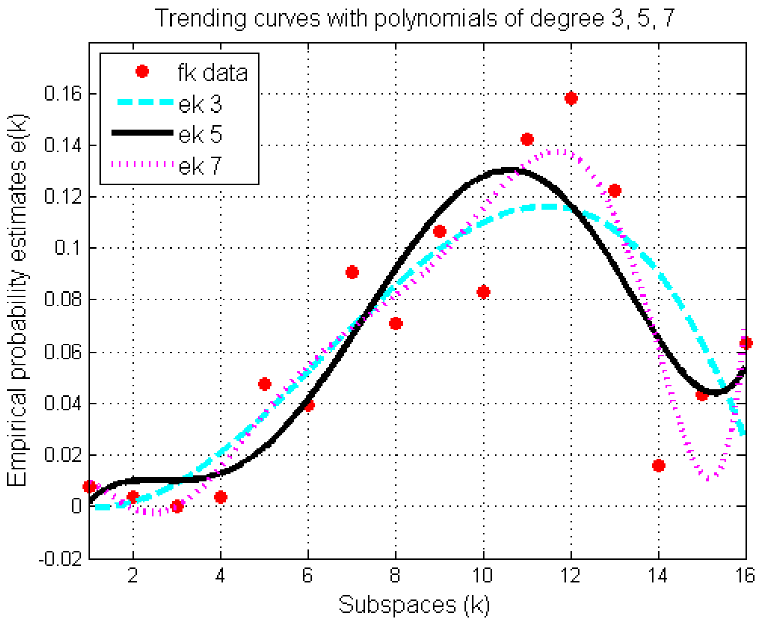


Figure 4-28. Different types of empirical probability distribution curves.

In Tables 4-8, 4-9, and 4-10 we present the transformation from sets of points (e_k) into sets of points (p_k) for polynomials of degree 3, 5, and 7, respectively. We use the symbols e3(k) and p3(k) in table 4-8 to represent discrete values of the regression curve and the probability function of subspaces for the cubic polynomial; equivalent terminology is used in tables 4-9 and 4-10 for the other families of curves.

In table 4-8, the cubic polynomial is evaluated for each subspace k in column e3(k). Parameter h is taken as the sum of all negatives values of e3(k). Then, |h| is added to each e3(k) value so that we can have all points positive (see column e3(k)+|h|). The exceeded amount represented by Δ is equally distributed among 15 subspaces in order to avoid e3(1) becomes again negative. Figure 4-29 depicts the plot of discrete probability distributed per subspaces. This probability model is obtained from the cubic polynomial regression curve.

In table 4-9, the fifth degree least-squares regression equation meets conditions 3a and 3b directly, therefore, it may be considered a discrete probability function without any transformation (i.e., e5(k) = p5(k). Its discrete shape is plotted in figure 4-30.

In table 4-10, the seventh degree least-squares regression is evaluated at column e7(k). Parameters h and Δ are obtained as indicated and used to obtain p7(k). The equation e7(k) is described in Table 4-7. The probability function p7(k) is plotted in figure 4-31.

Table 4-8. Transforming a 3rd degree polynomial into a discrete probability distribution.

k	f(k)	e3(k)	e3(k) + |h|	p3(k)	%p3(k)
1	0.00791	-4.283E-05	0	0	0.00%
2	0.00395	0.00153371	0.001576541	0.001530855	0.15%
3	0	0.00884972	0.008892553	0.008846867	0.88%
4	0.00395	0.02058509	0.020627923	0.020582238	2.06%
5	0.04743	0.03541971	0.035462541	0.035416856	3.54%
6	0.03953	0.05203346	0.052076295	0.05203061	5.20%
7	0.09091	0.06910624	0.069149073	0.069103387	6.91%
8	0.07115	0.08531793	0.085360763	0.085315078	8.53%
9	0.10672	0.09934842	0.099391254	0.099345569	9.93%
10	0.083	0.1098776	0.109920434	0.109874749	10.99%
11	0.14229	0.11558536	0.115628192	0.115582506	11.56%
12	0.1581	0.11515158	0.115194415	0.115148729	11.51%
13	0.12253	0.10725616	0.107298992	0.107253307	10.73%
14	0.01581	0.09057898	0.090621812	0.090576126	9.06%
15	0.04348	0.06379993	0.063842763	0.063797077	6.38%
16	0.06324	0.0255989	0.025641732	0.025596047	2.56%
	Sum f(k):	Sum e(k):	Sum e(k)+|h|:	Sum p(k):	Sum %p(k):
	1	1	1.000685282	1	100.00%
		Parameter h:	Parameter Δ:	Param. Δ/(N-1):	
		-4.283E-05	-0.000685282	-4.56855E-05	

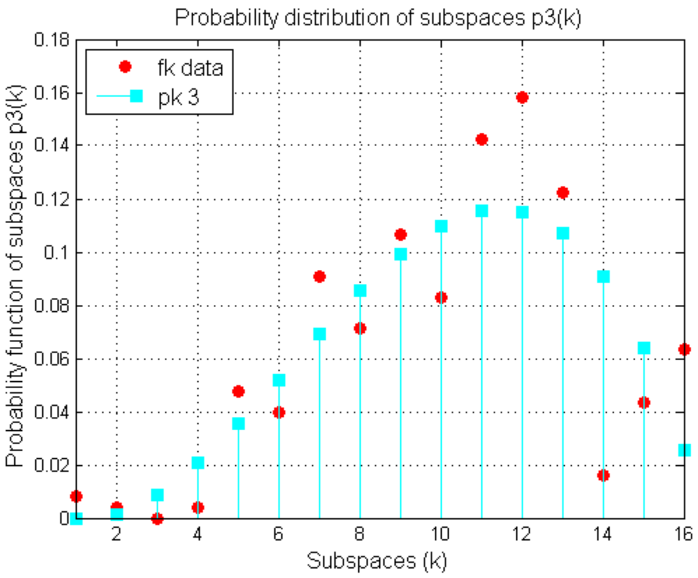


Figure 4-29. Probability distribution based on a 3rd degree regression curve.

Table 4-9. Transforming a 5th degree polynomial into a discrete probability distribution.

k	f(k)	e5(k)	p5(k)	%p5(k)
1	0.00791	0.001543	0.001543	0.15%
2	0.00395	0.00988	0.00988	0.99%
3	0	0.010102	0.010102	1.01%
4	0.00395	0.012688	0.012688	1.27%
5	0.04743	0.02274	0.02274	2.27%
6	0.03953	0.041094	0.041094	4.11%
7	0.09091	0.06544	0.06544	6.54%
8	0.07115	0.091443	0.091443	9.14%
9	0.10672	0.113851	0.113851	11.39%
10	0.083	0.127623	0.127623	12.76%
11	0.14229	0.129036	0.129036	12.90%
12	0.1581	0.116808	0.116808	11.68%
13	0.12253	0.093215	0.093215	9.32%
14	0.01581	0.065207	0.065207	6.52%
15	0.04348	0.045522	0.045522	4.55%
16	0.06324	0.053809	0.053809	5.38%
	Sum f(k):	Sum e(k):	Sum p(k):	Sum %p(k):
	1	1	1	100.00%
		h = 0	$\Delta = 0$	

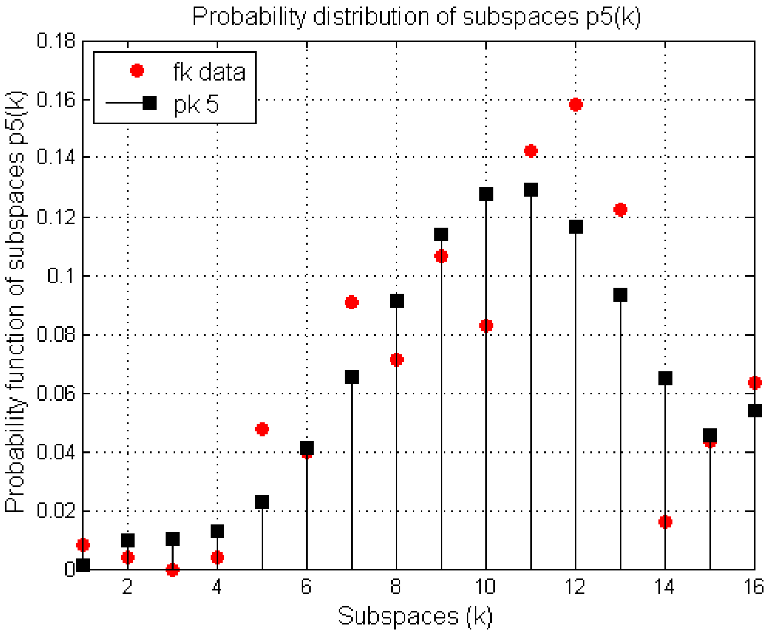


Figure 4-30. Probability distribution based on a 5th degree regression curve.

Table 4-10. Transforming a 7th degree polynomial into a discrete probability distribution.

k	f(k)	e7(k)	e7(k) + |h|	p7(k)	%p7(k)
1	0.00791	0.00947866	0.01016362	0.00938081	0.94%
2	0.00395	-0.0006229	6.20366E-05	6.2037E-05	0.01%
3	0	-6.204E-05	0.00062292	0.00062292	0.06%
4	0.00395	0.01478025	0.015465204	0.0146824	1.47%
5	0.04743	0.03552261	0.036207571	0.03542476	3.54%
6	0.03953	0.0542754	0.054960352	0.05417755	5.42%
7	0.09091	0.06862148	0.069306439	0.06852363	6.85%
8	0.07115	0.08124714	0.081932093	0.08114929	8.11%
9	0.10672	0.09638362	0.097068575	0.09628577	9.63%
10	0.083	0.11522052	0.115905477	0.11512267	11.51%
11	0.14229	0.13245173	0.133136684	0.13235388	13.24%
12	0.1581	0.1361149	0.136799857	0.13601705	13.60%
13	0.12253	0.11288538	0.113570339	0.11278753	11.28%
14	0.01581	0.06098544	0.061670401	0.06088759	6.09%
15	0.04348	0.01286977	0.013554722	0.01277191	1.28%
16	0.06324	0.06984805	0.070533009	0.0697502	6.98%
	Sum f(k):	Sum e(k):	Sum e(k)+|h|:	Sum p(k):	Sum %p(k):
	1	1	1.0109593	1	100.00%
		Parameter h:	Parameter Δ:	Param. Δ/(N-2):	
		-6.850E-04	-0.0109593	-0.00078281	

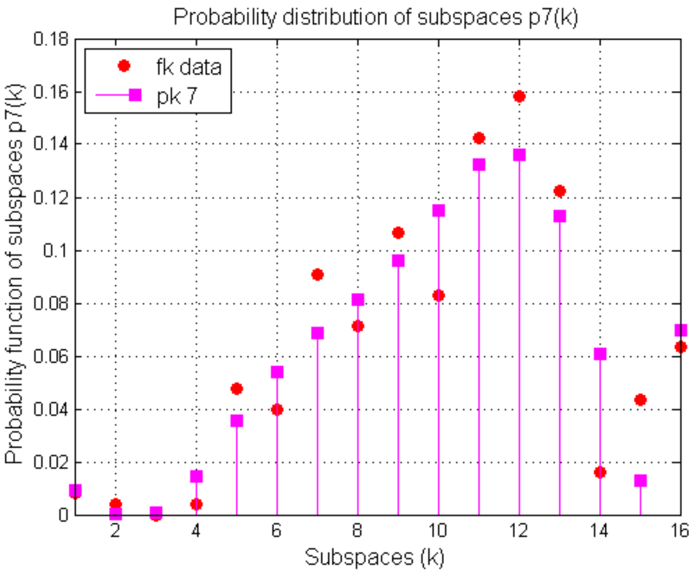


Figure 4-31. Probability distribution based on a 7th degree regression curve.

4.4.4 Bivariate Analysis between rTiB and rEHO

This section involves the analysis of two variables rTiB (X) and rEHO (Y) for the purpose of determining the empirical relationship between them. The analysis compares summary statistics (Table 4-11) and uses regression analysis to estimate probability density functions (pdf) and cumulative distribution functions (cdf) of single variables. We compute the sampling correlation coefficient so that we can determine the type of correlation and degree of linear relationship between X and Y.

The following summary statistics table is based on the set of 253 handoff data pairs (rTiB, rEHO) which includes 32 sample points from user "A", 84 from user "B", 133 from user "C", and 4 extra sample points, one for each vertex of the unit square.

Table 4-11. Summary Statistics for Sample253.

Sample Statistics	rTiB (X)	rEHO (Y)
Mean	0.6166	0.4708
Median	0.6133	0.4000
Mode	0	1
Min	0	0
Max	1	1
Range	1	1
1st Quartile	0.49365	0.19167
3rd Quartile	0.74395	0.8
Interquartile range	0.2503	0.6083
Standard deviation	0.1786	0.3613
Variance	0.0319	0.1306
Skewness	-0.1534	0.2888

The graph in Figure 4-32, created with the boxplot command in Matlab®, compares the rate of time in the best (rTiB) and the rate of executed handoffs (rEHO) from 253 handoff scenarios.

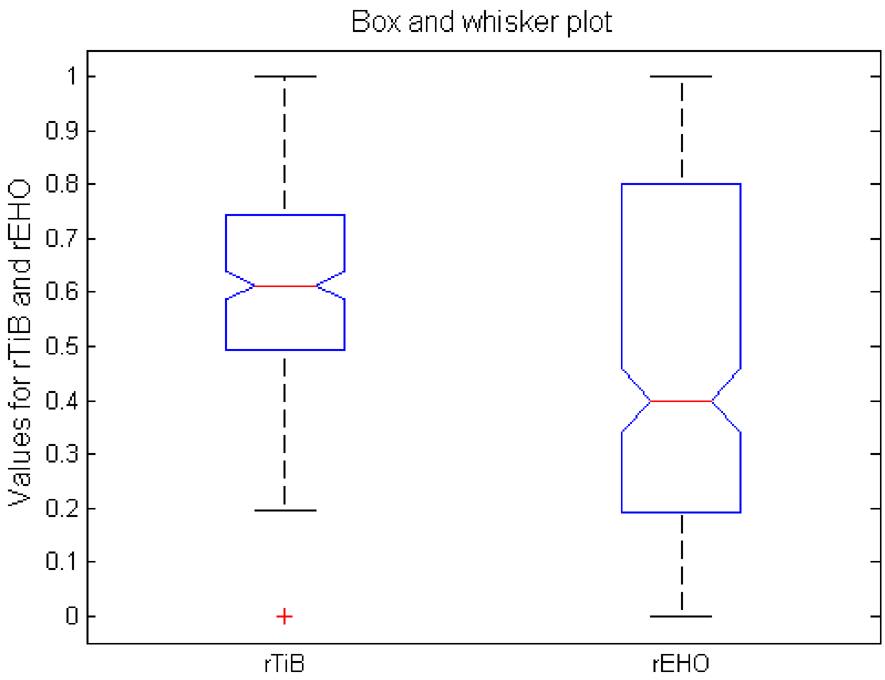


Figure 4-32. Box and whisker plot for 253 samples collected from users A, B, and C.

This plot has the following features:

- The tops and bottoms of each "box" are the 25th and 75th percentiles of the samples, respectively. The distances between the tops and bottoms are the interquartile ranges (IQR). This statistic is a robust estimate of the spread of the data, since changes in the upper and lower 25% of the data do not affect it. If there are outliers in the data, then the IQR is more representative than the standard deviation as an estimate of the spread of the body of data.

- The line in the middle of each box is the sample median (the 50th percentile). If the median is not centered in the box, it shows sample skewness. For instance, the variable rEHO shows to be skewed towards its first quartile.

- The whiskers are lines extending above and below each box. Whiskers are drawn from the ends of the interquartile ranges to the furthest observations within the whisker length. The length of the whiskers is specified, by default, as 1.5 times the interquartile range.

- Observations beyond the whisker length are marked as outliers. Outliers are displayed with a red '+' sign. An outlier is a value that is more than 1.5 times the interquartile range away from the top or bottom of the box. The two points where rTiB = 0 are outliers.

- Notches display the variability of the median between samples. The width of a notch is computed so that box plots whose notches do not overlap have different medians at the 5% significance level. Since the notches in the box plot do not overlap (as below), we can conclude, with 95% confidence that the true medians do differ.

The graph in Figure 4-33, created with the plotmatrix command in Matlab®, shows the distribution of rTiB and rEHO values across a data range.

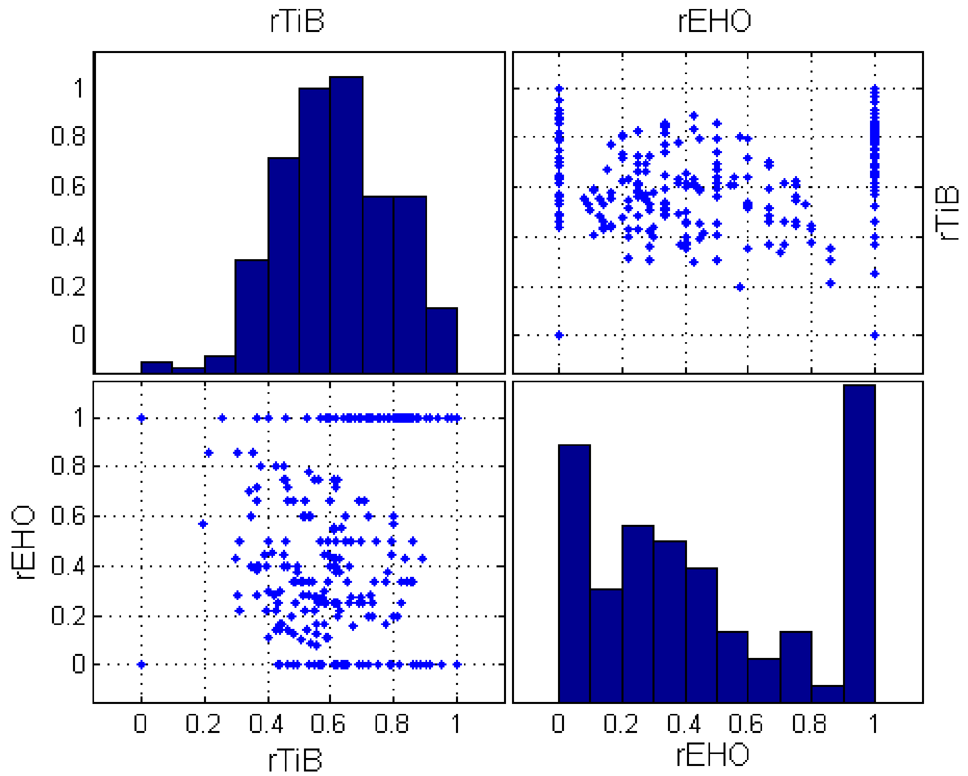


Figure 4-33. Histograms and scatter plots show the distribution of rTiB and rEHO.

- The histograms for rTiB and rEHO show the distribution of 253 values of rTiB and rEHO among 10 intervals or "bins" that divide the data range in equally spaced containers. Each rectangle represents the number of values in a particular container.
- The histograms for rTiB and rEHO do not exhibit symmetry of the data around their respective sample means. Skewness is a measure of the asymmetry of the data around the sample mean. The skewness of any perfectly symmetric distribution is zero. If skewness is negative, the data are spread out more to the left of the mean than to the right. If skewness is positive, the data are spread out more to the right. According to this, rTiB, which has a negative skewness, is skewed to the left; i.e., a high density of rTiB values occurs to the right of its mean (0.6166). In fact, nearly 50% of the rTiB values occur in the interval (0.5, 0.7). On the contrary, rEHO, which has a positive skewness, is skewed to the right; i.e., a high density of rEHO values occurs to the left of its mean (0.4708). In fact, more than 50% of the rEHO values lie in the interval (0, 0.4). Therefore, skewness is a good performance indicator of the handoff algorithm showing a trend to have the bulk of rEHO values below 0.4708 and the bulk of rTiB values above 0.6166.
- The scatter plots at the lower left (rTiB, rEHO) and upper right (rEHO, rTiB) may help us to visualize two types of causal relationships between the variables. Do the values of rTiB determine the values of rEHO or vice versa? The handoff algorithm makes decisions to execute or not a handoff. Each decision directly changes the number of executed handoffs or rEHO values and indirectly modifies the dwelling-time in the best or rTiB values. This relation suggests that rEHO may be the independent variable and rTiB the dependent variable. However, the control variables of the handoff algorithm: mΔR, mSP, ΛEXEC, ΛEVAL, may change the influence of the independent variable on the dependent. Thus, we should consider that both types of causal relations may occur.

The graphs in Figure 4-34 depict 253 (rEHO, rTiB) points on the left and 253 (rTiB, rEHO) points on the right. Three polynomials of degree 3, 5, and 7 fit the points using the least-squares method.

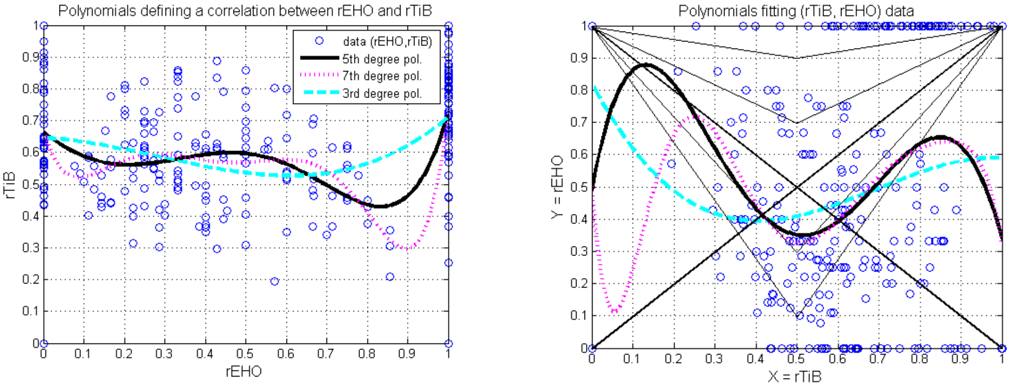


Figure 4-34. Polynomials fitting (rTiB, rEHO) and (rEHO, rTiB) data points.

This plot has the following features:

- The scatter diagrams graphically show a *nonlinear* relationship between X and Y. The Pearson's correlation coefficient, denoted by *r*, measures the degree of linear relationship between X and Y. This correlation parameter cannot be used to determine a causal relationship between the variables; it only can be used to measure linear dependences between two variables. The *r* parameter takes on values between –1 and +1. If *r* is ±1, then Y is a linear function of X with probability 1. If $r = 0$ we say that X and Y are *uncorrelated*, but this does not imply that they are independent variables. The closer the correlation is to ±1, the more linear is the relation between X and Y. The closer the correlation is to 0, the less linear relation exists between the variables. The *sample correlation coefficient* can be computed using the corr2 function in Matlab®. This function yields $r = 0.1247$ for the sample vectors rTiB and rEHO, which is nearby to 0, thus the lack of a linear relation between X and Y.

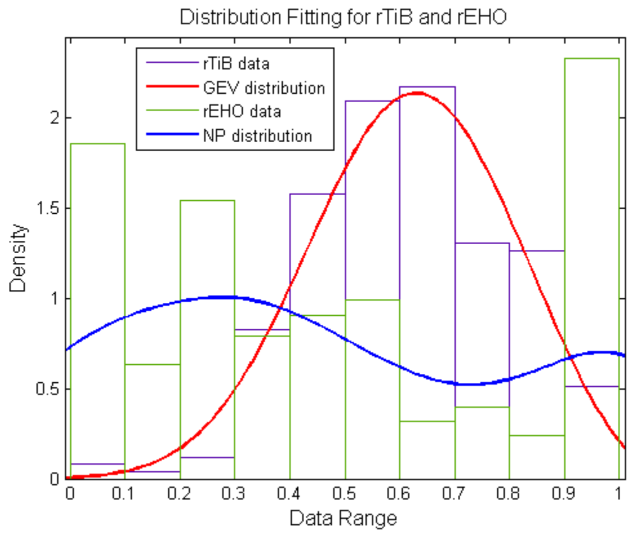
- The fitting polynomials in (rEHO, rTiB) scatter diagram show a slightly trend to increase rTiB as rEHO decreases. This is a good indicator for the handoff algorithm, whose main goal is to reduce rEHO and to increase rTiB simultaneously. Particularly, the 5th degree polynomial is again the one that shows this trend more clearly.

- The fitting polynomials in (rTiB, rEHO) scatter diagram show the same trend as before, of slightly decreasing rEHO values as rTiB increases. However, the fitting polynomials in these diagrams, specially the fifth and seventh degree polynomials, show a change of behavior roughly at the same rTiB or rEHO value of 0.5.

- If we consider instantaneous handoffs, i.e., if we make all the handoff control variables mΔR = mSP = ΛEXEC = ΛEVAL = 0, then the relation between rTiB and rEHO tends to be linear and positive, as depicts the diagonal from (0,0) to (1,1). That is, the more instantaneous handoffs are performed, the more dwelling time is spent in the best network. However, as we increase the handoff control variables, the relation between X and Y becomes nonlinear. The algorithm behavior starts to change from a trending line X = Y towards a trending line X + Y = 1. The points at rTiB or rEHO equal to 0.5 demark this behavior change. The trending polynomials in both diagrams depict this change of behavior around this central point. A change in the direction of the trending curve occurs at rTiB = 0.5 or rEHO = 0.5; this change in direction is "weak" on the polynomials of (rEHO, rTiB), but "strong" on the polynomials of (rTiB, rEHO).

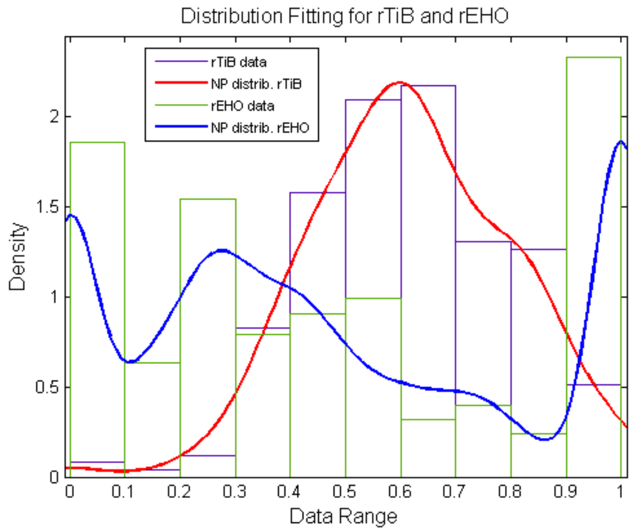
The graph in figure 4-35, created with the dfittool command in Matlab®, fits probability density functions (PDFs) to each variable. To visually assess how good the fit is, we plot the fitted density against a probability histogram of the raw data. This histogram is scaled so that the bar heights times their width sum to 1, to make it comparable to the PDF. This plot fits a Generalized Extreme Value (GEV) distribution to rTiB and a Nonparametric (NP) distribution to rEHO.

Using this interactive Matlab® tool, we fitted many parametric distributions to the raw data. By visual checking, we observed that GEV is the parametric distribution that best fits the rTiB data. Nevertheless, an NP distribution for rTiB seems to have the best fit over all distribution families. Moreover, the NP fitted distribution for rEHO, with bandwidth 0.150013, is so smooth that it obscures much of the rEHO data behavior. Therefore, by reducing the bandwidth, we can also fit a better nonparametric distribution to rEHO. Figure 4-36 shows these new fitting distributions.



```
Results:
-------------------
rTiB data
Distribution: GEV
Mean: 0.61705
Variance: 0.0318699
Distribution Parameters
K(shape): -0.339026
Sigma(scale): 0.183809
Mu(location): 0.558671
-------------------
rEHO data
Distribution: NP
Kernel: normal
Bandwidth: 0.150013
-------------------
Confidence level: 95%
```

Figure 4-35. Fitting a GEV distribution to rTiB and a nonparametric distribution to rEHO.



```
Results:
-----------------
rTiB data
Distribution: NP
Kernel: normal
Bandwidth: 0.0640243
-----------------
rEHO data
Distribution: NP
Kernel: normal
Bandwidth: 0.05
-----------------
Confidence level: 95%
```

Figure 4-36. Fitting nonparametric density estimates of rTiB and rEHO data.

Nonparametric distributions in Matlab® fit a probability density function to data distributions using the function ksdensity. The ksdensity function does this using a kernel smoothing method to a single variable. Figures 4-37 and 4-38 plot the estimated densities for each variable using the default kernel and default bandwidth, except for the rEHO plot in figure 4-37, which uses the modified bandwidth of 0.05 or u/3 so that it describe better the behavior of rEHO data.

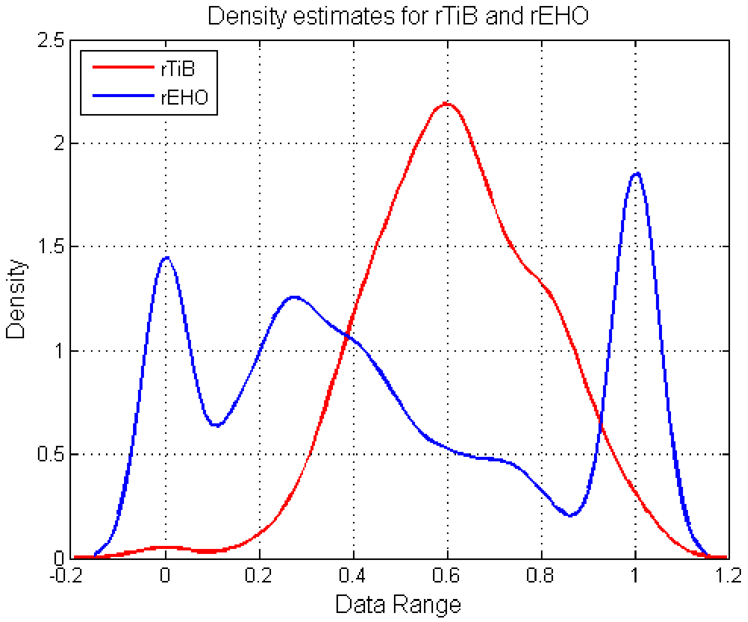


Figure 4-37. Comparing density estimates for rTiB and rEHO using modified bandwidth.

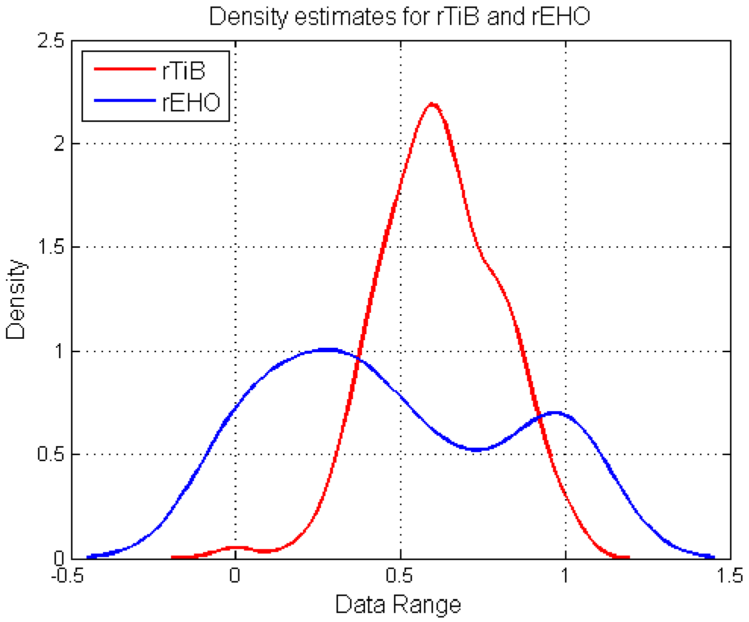
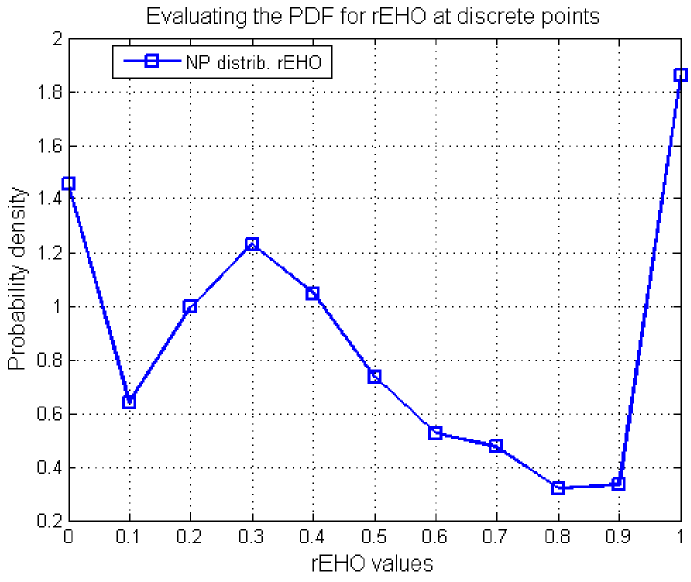


Figure 4-38. Comparing density estimates for rTiB and rEHO using default bandwidth.

The following code in Matlab® was used to create these plots.

```
>> figure
>> [f,x,u] = ksdensity(rEHO);
>> [f,x] = ksdensity(rEHO,'width',u/3);
>> [f1,x1] = ksdensity(rTiB);
>> plot(x1,f1,'r')
>> hold on
>> plot(x,f)
>> hold off
```

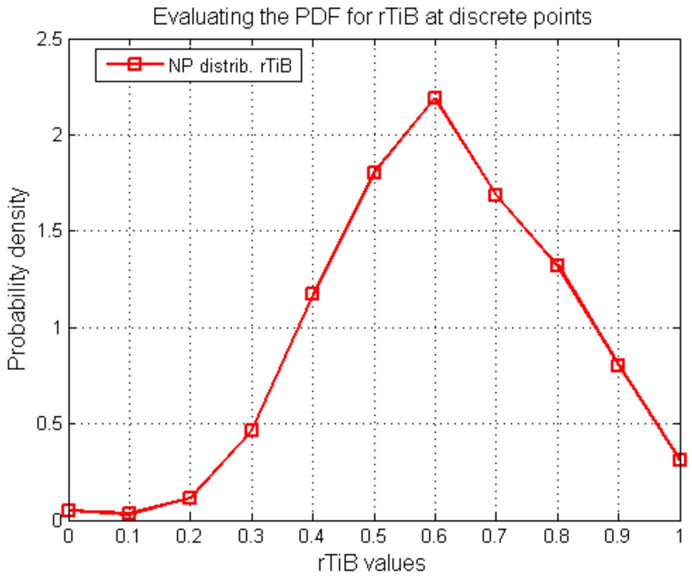
The choice of kernel bandwidth controls the smoothness of the probability density curve. The overlay of smooth density estimates in figures 4-37 and 4-38 eases the comparison of the two variables simultaneously. In both graphs, it can be observed that: rTiB has the higher density when it is in the interval (0.5, 0.7) and rEHO has the higher density when it is in the interval (0, 0.4). A tabular form of results in figure 4-37 is shown in figures 4-39 and 4-40.



x	f(x)	p(x)
0	1.45302	14.53%
0.1	0.64126	6.41%
0.2	0.99596	9.96%
0.3	1.2292	12.29%
0.4	1.04721	10.47%
0.5	0.73435	7.34%
0.6	0.52375	5.24%
0.7	0.47457	4.75%
0.8	0.32022	3.20%
0.9	0.33389	3.34%
1	1.86231	18.62%

Figure 4-39. Discrete evaluation of nonparametric density for rEHO.

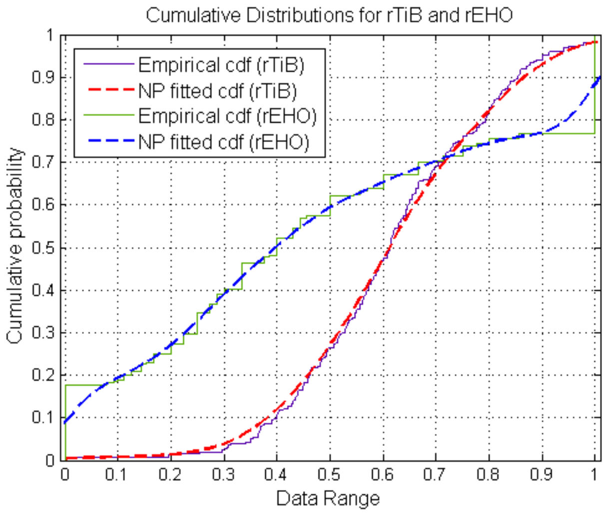
The ksdensity function produces an empirical version of a probability density function. That is, instead of selecting a density with a particular parametric form and estimating the parameters, it produces a nonparametric density estimate that adapts itself to the data.



x	f(x)	p(x)
0	0.04962	0.50%
0.1	0.03055	0.31%
0.2	0.11425	1.14%
0.3	0.46256	4.63%
0.4	1.17298	11.73%
0.5	1.80272	18.03%
0.6	2.18832	21.88%
0.7	1.68486	16.85%
0.8	1.32014	13.20%
0.9	0.80073	8.01%
1	0.30839	3.08%

Figure 4-40. Discrete evaluation of nonparametric density for rTiB.

Similarly, it is possible to produce an empirical version of the cumulative distribution function (CDF). The ecdf function in Matlab® computes this empirical cdf. It returns the values of a function *F* such that *F(x)* represents the proportion of observations in a sample less than or equal to *x*. Figure 4-41 depicts the empirical and theoretical CDFs for the single variables rTiB and rEHO.



x	F(rTiB)	F(rEHO)
0	0.00396	0.08966
0.1	0.00793	0.19431
0.2	0.01387	0.27094
0.3	0.03919	0.38934
0.4	0.11969	0.50231
0.5	0.26991	0.5932
0.6	0.47437	0.65353
0.7	0.67344	0.7027
0.8	0.82005	0.74476
0.9	0.92974	0.76945
1	0.98252	0.88337

Figure 4-41. Empirical cumulative distributions for rTiB and rEHO.

4.4.5 Summary of Case Study Results

Chapter 4 scopes the tasks of specifying, designing, developing, and assessing *correct* handoffs in the future wireless communication systems. A correct handoff is a multipurpose or cognitive handoff intended to optimize two conflicting objectives: minimizing the rate of executed handoffs and maximizing the rate of dwelling-time in the best network. The case study problem and background was described in section 4.1.1. In section 4.1.2, the problem modeling defined some basic concepts such as:

- Desirability functions
- Desirability thresholds
- Handoff regions
- Handoff scenarios
- Handoff performance variables, e.g., rTiB and rEHO

- Handoff control variables e.g. mΔR, mSP, ΛEXEC, ΛEVAL
- Data range for rTiB and rEHO
- Metrics for best, very good, good, bad, very bad, and worst results and balance
- Handoff performance goals

The handoff algorithm description, in section 4.2, provided the following results:

- The algorithm R, or Relative Desirability Handoff Algorithm with hysteresis margins, dwell-timers, and two desirability thresholds.
- The algorithm R is: deterministic, reactive, heuristic, autonomous, adaptive, and correct
- The algorithm R performs imperative and opportunist handoffs
- Handoff heuristics rely on the concepts of best candidate, sufficiently better, and consistently better
- The algorithm R inputs: handoff scenario and control parameters
- The algorithm R outputs: handoff performance parameters
- The algorithm R pseudocode: solution description using structured human language with similar constructions used by computer languages.
- The algorithm R flowchart: flow control diagram used to quickly understand and visualize the program logic.

Section 4.3 presents the development of a *handoff simulation instrument* as a software tool that enables the user to test the handoff algorithm R on a variety of handoff scenarios. The user may change the handoff scenarios at will in order to run different testing instances of the algorithm. Each test in the *virtual instrument* graphically displays the behavior of the handoff algorithm and yields handoff performance data which are collected in a structured archive after a session test. Four stages of development were described along this section:

- Specification: functional requirements and use case diagrams.
- Design: top level model, user interface design, structural and behavioral model.
- Implementation: translating pseudocode into a computer program.
- Testing: debugging errors and verifying the instrument works as expected.

Finally, in Section 4.4, we provided statistical evidences and probabilistic models that support the instrument correctness. For this purpose, we exposed the handoff instrument to a massive amount of handoff scenarios and evaluated the handoff performance goals. To achieve this assessment, we developed the following results:

- Design a nondeterministic experiment for collecting representative samples of input handoff scenarios which are used to test the instrument performance.
- A random sample of handoff data points (rTiB, rEHO) obtained from each test (See Appendix).
- A statistical analysis and probabilistic models that describe and predict the distribution of bivariate handoff data within specific subspaces of the sample space.
- Fitting of joint probability distributions within specific subspaces of the sample space (see figures 4-29, 4-30, and 4-31).

- Fitting of density probability functions and cumulative distribution functions on single handoff performance variables (see figures 4-39, 4-40, and 4-41).
- Correlation coefficient measuring the degree of linearity between rTiB and rEHO vectors.
- Causal relation study between variables.

This case study provides the description and modeling of a significant problem in the new area of cognitive mobility, its systematic solution, and the evaluation of results. One key feature of our proposed solution is that we have considered heuristics for finding either an exact or an approximation of the optimal solution. Heuristics solutions gain computational performance or conceptual simplicity, potentially at the cost of accuracy or precision. Therefore, as different degrees of accuracy on results can be obtained, we dedicated a substantial part of this work to the classification and evaluation of handoff results.

When we partitioned the space of results into 16 mutually exclusive subspaces, we made the space finite and discrete in classes. For each handoff scenario s, we assigned exactly one point (x, y) in the sample space $R_{X \times Y}$. Next, to each point (x, y) in the unit square plane we assigned exactly one subspace in the column vector with index k. Then, to each subspace k we assigned exactly one relative frequency number f_k. Then, we assigned to each empirical probability f_k an estimated value e_k, which is transformed into a probability distribution p_k. Therefore, we have a function that assigns a probability to any random handoff scenario from occurring in any particular subspace of the sample space. The use of PDFs and CDFs helps to know better the distribution of handoff results and predict future results.

Chapter 5

Conclusions

This chapter summarizes the main accomplishments of this dissertation and discusses potential directions for future research in the area.

5.1 Concluding Remarks

Handoff and Mobility in wireless networks are becoming multipurpose services, which are going beyond the traditional seamless handoff or seamless mobility service. A cognitive handoff is a key enabler for cognitive mobility, which is intended to achieve many desirable features simultaneously; e.g., seamless, autonomous, secure, correct, adaptive, etc. However, the development of cognitive handoffs is a challenging task that has not been properly addressed in the literature. Many of the existing handoff schemes do not exploit advantages of multi-objective handoff. They optimize a particular objective but ignore others completely. Therefore, we proposed a new model-driven methodology for developing cognitive handoffs. We applied the proposed methodology and obtained several significant results: a relationship between handoff purposes and handoff context information, a new taxonomy of handoff scenarios, a first-level functional decomposition model for cognitive handoffs, an original handoff control state-based model, a hierarchical context management model, a set of handoff performance measures for evaluating cognitive handoffs, and a case study about a specific kind of multi-objective handoff. This research creates a knowledge base for understanding, developing, and evaluating multipurpose handoffs, which supports our general objective. A summary of major accomplishments is described as follows:

First, we identified a gap in literature about the study of handoffs achieving multiple desirable features. We observed that there is a trend in recent literature to deploy handoffs achieving multiple desired features, but there is neither a common agreement on how to measure the success of each desired feature, nor a methodology for their systematic deployment. Moreover, we reviewed the major trends and challenges of the future Internet and we argued that seamless handoffs will not be able to support the mobility of the future handoff scenarios. Therefore, we proposed the development of a new class of multipurpose handoff that simultaneously is seamless, autonomous, secure, correct, and adaptive. We named such kind of handoffs, multipurpose, as each desirable feature to achieve is typically associated to one specific purpose. We showed the evolution from single-purpose handoffs in the first networks to multipurpose handoffs in the future networks.

Second, we used a holistic approach to develop the study of multipurpose handoffs. This approach allowed us to develop a new taxonomy of handoff scenarios based on different types of transitions that may occur among radio channels, base stations, IP networks, service providers, user terminals, and any feasible combination of such elements. Moreover, such holistic approach also led us to define a rich set of important desirable handoff features, handoff purposes, handoff objectives, handoff goals, and handoff context data, which support the vision of a cognitive handoff, that is, a handoff that can achieve multiple desirable features, using a great diversity of context information, and operating with good performance in any handoff scenario.

Third, we used the problem-solving theory, the functional decomposition approach, and the model-based design paradigm to develop a model-driven methodology for systematically building cognitive handoffs. The application of such methodology produced two main results: the cognitive handoff functional architecture and the strategy for evaluating the performance of multi-objective handoffs. Such results are founded, as much as possible, with clear and logical arguments because at this stage of the development process of a new system, models are intended to support understanding rather than predicting.

Fourth, according to the steps defined by the proposed methodology, we changed the development paradigm from holistic to reductionist, as we are now interested in validating and verifying the particular models conforming the cognitive handoff functional architecture. For this purpose and as a proof of concept, we developed a case study about a particular type of multi-objective handoff. This case study described the correct handoff problem, defined a correct handoff algorithm, developed a virtual instrument addressed to evaluate the performance of the correct handoff algorithm, and performed a statistic and probabilistic analysis on hard data produced by the simulation instrument. Several probabilistic models were developed in order to obtain the probability that a random handoff scenario yields a result occurring in a particular metric space. For these reasons, we believe this case study will facilitate the analysis and research of higher order multi-objective handoffs.

This work can be extended in several directions as described next.

5.2 Major Areas of Future Work

Some of the major future directions in cognitive handoff related research are listed and briefly discussed here.

- **Further levels of functional decomposition.** Using the functional decomposition approach [77], we divided the functional behavior of a cognitive handoff into six general modules: control algorithm, network discovery, handoff decisions, handoff execution, handoff evaluation, and context management. At a second level of decomposition, we provided models for the control handoff process, the context management task, and performance measures for multi-objective evaluation. However, a future work is to organize a comprehensive model-based framework hierarchy breadth and depth. Further work is needed to modeling network discovery, handoff execution protocols, and handoff decisions.

- **Further development of the correct handoff virtual instrument.** Building a virtual instrument for testing a correct handoff scheme is an open door for further development and research in this area. Many improvements can be done to this simulation tool; e.g., the ability to embed any user-defined handoff algorithm, the ability to create handoff scenarios with an arbitrary number of network desirability curves, the facility to visualize online performance graphics and statistic results, and the capacity to work with both, space-based and time-based handoff scenarios.
- **Experimental validation of the correct handoff algorithm.** After observing the successful results obtained by simulation, Algorithm R is a good candidate to validation tests using experimental test-beds or real production networks. The implementation of cognitive handoffs is conceived as a network of distributed agents (HCEs and CMAs), cooperating and competing to take any type of handoff to success. However, the rules of interaction HCE-HCE, HCE-CMA, CMA-CMA need to be specified. A middleware using the IEEE 802.21 MIH services can be used to implement the Algorithm R in particular mobile terminals.
- **Experimental validation of the hierarchical context management model.** Further development is necessary to provide real context information to handoff control entities. Full and partial context management agents are responsible for collecting context data and distributing context information to HCEs. Therefore, an implementation of Handoff Algorithm R in HCEs requires the support of context management agents. Implementing CMAs in IEEE 802.21 enabled devices is allowing a quick development of context managers using the MIH Services [78].

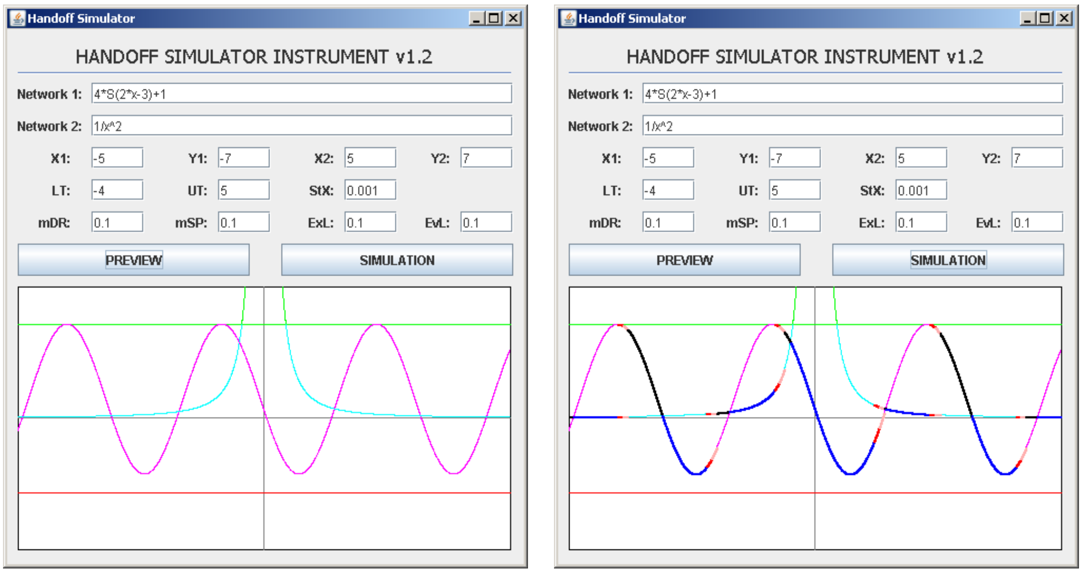
There is still much work to do before we can see cognitive handoffs practically implemented. The cognitive handoff project follows theoretical and practical avenues. A theoretical challenge is to further develop the cognitive handoff MOP to study the structure of the variables in the handoff context (e.g., continuous/discrete, deterministic/stochastic, etc.) and the types of constraints required to create a convex optimization problem. In the practical and Applicability Avenue, we have deployed simulation models to observe and predict the behavior of cognitive handoffs with two conflictive objective functions; however, further development is required to demonstrate the feasibility and applicability of cognitive handoffs in complex scenarios.

The Handoff Simulator Instrument v1.2 that was developed for this research work is a software product that will be available for free to researchers in mobility management as part of our wish to promote advances in this field. Today, many authors who contribute with handoff algorithms validate their algorithms by testing them under a very limited amount of scenarios, whether they are computer simulations or experimental test-beds. This is because they lack one instrument able to generate large amounts of handoff scenarios to test their algorithms. Most Network Simulators allow the designer to define a particular testing scenario, but changing such scenario is not graceful, they often require several steps for reconfiguring the testing scenario and run new simulations; thus, the adaptability test of the handoff algorithm is quite limited. For this reason, the development of such handoff virtual instrument is very important. In case you are interested in this product, please contact the author of this thesis at fglez6211@gmail.com.

Appendix A

Testing Cases

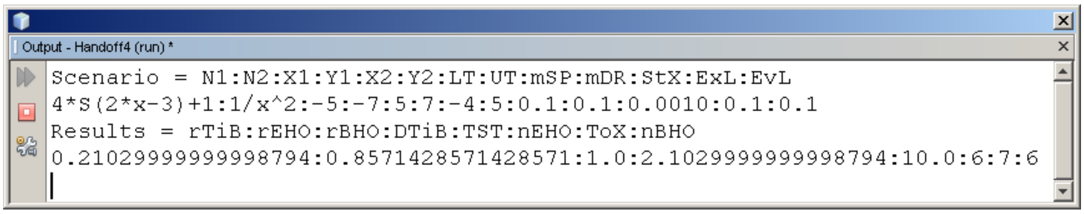
Let us start with the input scenario depicted in figure A-1a and its corresponding outputs shown in figures A-1b and A-1c.



Network 1: 4*S(2*x-3)+1
Network 2: 1/x^2
X1: -5 Y1: -7 X2: 5 Y2: 7
LT: -4 UT: 5 StX: 0.001
mDR: 0.1 mSP: 0.1 ExL: 0.1 EvL: 0.1

Network 1: 4*S(2*x-3)+1
Network 2: 1/x^2
X1: -5 Y1: -7 X2: 5 Y2: 7
LT: -4 UT: 5 StX: 0.001
mDR: 0.1 mSP: 0.1 ExL: 0.1 EvL: 0.1

(a) Preview scenario (b) Handoff simulation



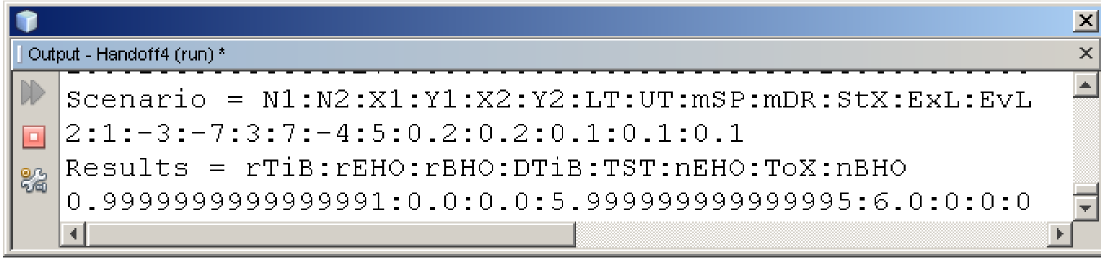
```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
4*S(2*x-3)+1:1/x^2:-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.21029999999998794:0.8571428571428571:1.0:2.1029999999998794:10.0:6:7:6
```

(c) Handoff data

Figure A-1. Handoff scenario producing a “bad” result located at subspace R11.

First, notice the plotted graphics meet all the requirements of the input scenario (visual frame, thresholds, network functions, and dot rates.) Next, observe that there are 7 cross points in the scenario, which meet the output value ToX = 7 in figure A-1c. The value for TST = 10.0 is correctly calculated as (x2 – x1) and nEHO = 6 corresponds with 6 executed handoffs that can be visually observed in figure A-1b. Calculation for rEHO = 6/7 or 85.71% is correctly displayed in figure A-1c. Visually, every performed handoff is beneficial because at the evaluation time the new network is better than the old network; thus, nBHO = 6 and rBHO = 1.0 or 100% as indicated in the handoff collected data. The dwelling-time in the best (DTiB) corresponds, in this case, with the time the current network is plotted in black, which yields 2.102999 and therefore rTiB = 0.2102999 or 21.02%. Despite this scenario yields a 100% of beneficial handoffs, the global results are classified as “bad” or unacceptable because DTiB is lower than 25% and rEHO is greater than 75%; i.e, there are too many handoffs and too short dwelling time in the best. However, this type of results and behavior were expected to occur at some input scenarios, thus, we say the handoff instrument works, for this input scenario, according to requirements of specification and design.

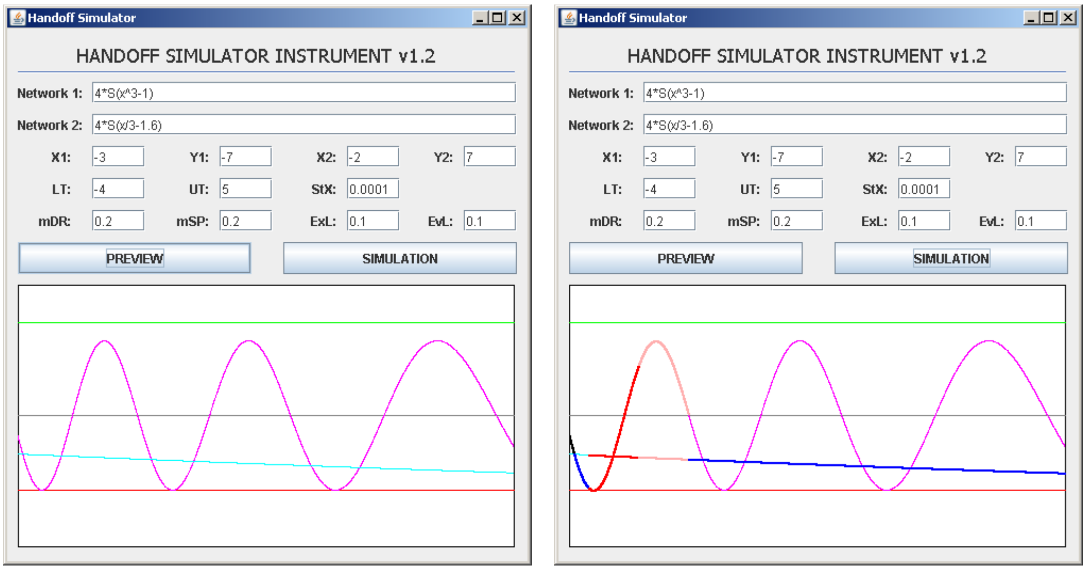
If we wanted to verify the instrument measures DTiB correctly, we may create simple scenarios where DTiB can be easily calculated and then compared with instrument results. For instance, consider two parallel lines as network functions. The algorithm will connect to the top line and will keep connected to this line without making any handoff until the end of simulation time. In this scenario, defined in figure A-2, DTiB should be equal to TST, and TST is easy to estimate. The simulation time (TST) is 6.0, thus DTiB should also be 6.0, but DTiB is measured as 5.9999…, which is correct and proofs the algorithm is counting correctly this key parameter.



```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
2:1:-3:-7:3:7:-4:5:0.2:0.2:0.1:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.9999999999999991:0.0:0.0:5.999999999999995:6.0:0:0:0
```

Figure A-2. Simple handoff scenario showing DTiB is correctly calculated.

Now, let's test the handoff instrument with another input scenario (see figure A-3). The graphics in figures A-3a and A-3b are plotted satisfying the requirements of the input scenario. The number of crossing points and simulation time are correctly estimated at 6 and 1.0, respectively. There is only one visible handoff in figure A-3b, which correspond to the estimated value of nEHO = 1. This gives a value for rEHO = 1/6 or 16.67% that is correctly calculated, see figure A-3c.

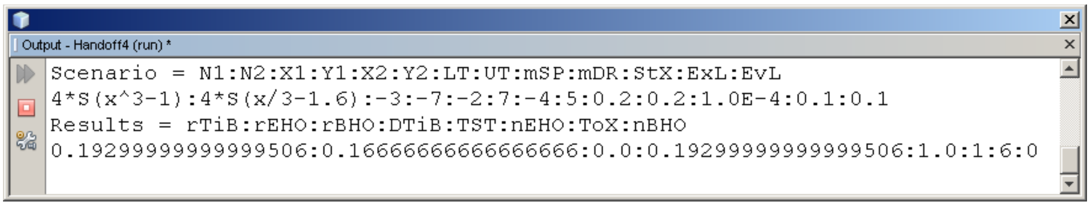


Network 1: 4*S(x^3-1)
Network 2: 4*S(x/3-1.6)
X1: -3 Y1: -7 X2: -2 Y2: 7
LT: -4 UT: 5 StX: 0.0001
mDR: 0.2 mSP: 0.2 ExL: 0.1 EvL: 0.1

Network 1: 4*S(x^3-1)
Network 2: 4*S(x/3-1.6)
X1: -3 Y1: -7 X2: -2 Y2: 7
LT: -4 UT: 5 StX: 0.0001
mDR: 0.2 mSP: 0.2 ExL: 0.1 EvL: 0.1

(a) Preview scenario

(b) Handoff simulation



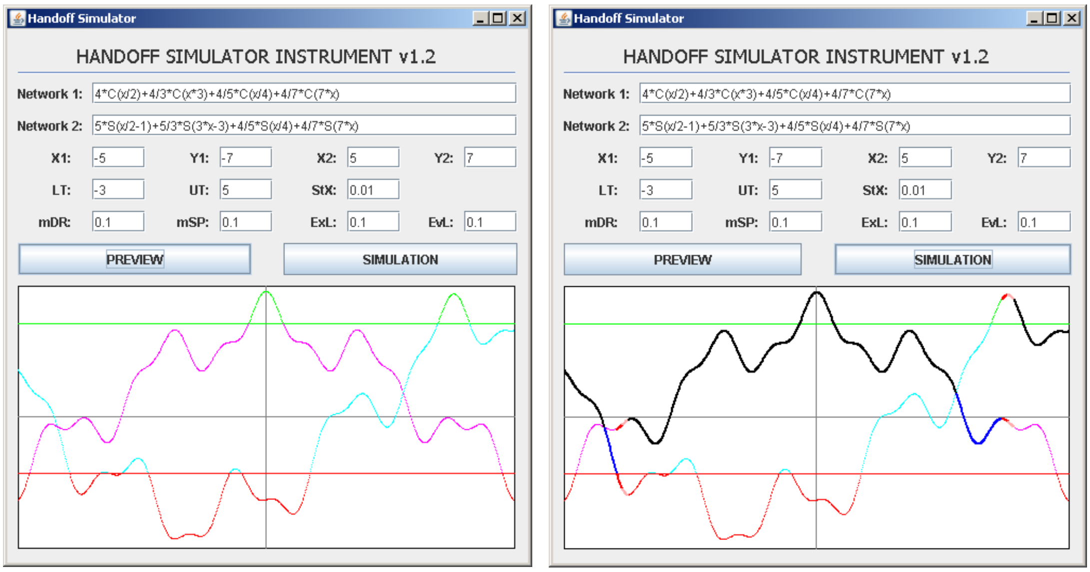
```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
4*S(x^3-1):4*S(x/3-1.6):-3:-7:-2:7:-4:5:0.2:0.2:1.0E-4:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.19299999999999506:0.16666666666666666:0.0:0.19299999999999506:1.0:1:6:0
```

(c) Handoff data

Figure A-3. Handoff scenario producing a “good” but unbalanced result at Y21.

The only one performed handoff is harmful because the new network is worse than the old network, this conclusion can be drawn by comparing the network functions in the evaluation state. Hence, the parameters nBHO = rBHO = 0.0 are correctly estimated by the instrument. The level of adaptability for the first crossing point is 4, which yields a preparation latency of 0.8; however, the simulation shows that preparation lasted much less than this quantity of time. The reason for this behavior is in the rule the handoff algorithm follows when current network is quite close to a disconnection and there is another better network to go. This rule was specified in the step R11 of our algorithm R. Therefore, the instrument behaves as expected. A small value for DTiB counts for the tiny time in black, at the beginning of simulation, and the intervals of preparation state in blue where current network is also the best network. The instrument measures DTiB = rTiB as expected because TST = 1.0, giving an rTiB of 19.29%. Despite of having the only one executed handoff as harmful and small rate of time in the best (19.29%), the global result is considered “good” because it has a very low rate of executed handoffs (16.67%). This type of results are considered good but unbalanced because they only optimize one performance parameter and ignore the other.

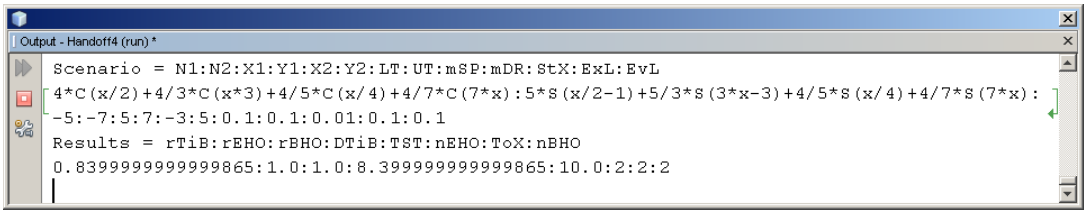
Next, we test the instrument with another input scenario (see figure A-4). The graphics shown in figures A-4a and A-4b are plotted correctly meeting the input scenario parameters. In this case, we validate this result using the plotting function in http://www.wolphramalpha.com (figure A-5).



Network 1: 4*C(x/2)+4/3*C(x*3)+4/5*C(x/4)+4/7*C(7*x)
Network 2: 5*S(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x)
X1: -5 Y1: -7 X2: 5 Y2: 7
LT: -3 UT: 5 StX: 0.01
mDR: 0.1 mSP: 0.1 ExL: 0.1 EvL: 0.1

Network 1: 4*C(x/2)+4/3*C(x*3)+4/5*C(x/4)+4/7*C(7*x)
Network 2: 5*S(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x)
X1: -5 Y1: -7 X2: 5 Y2: 7
LT: -3 UT: 5 StX: 0.01
mDR: 0.1 mSP: 0.1 ExL: 0.1 EvL: 0.1

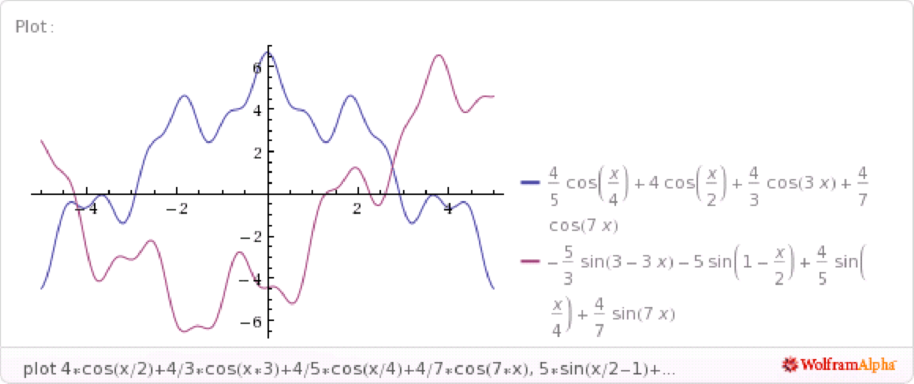
(a) Preview scenario (b) Handoff simulation



```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
4*C(x/2)+4/3*C(x*3)+4/5*C(x/4)+4/7*C(7*x):5*S(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x):
-5:-7:5:7:-3:5:0.1:0.1:0.01:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.8399999999999865:1.0:1.0:8.399999999999865:10.0:2:2:2
```

(c) Handoff data

Figure A-4. Handoff scenario producing a "good" but unbalanced result located at O12.

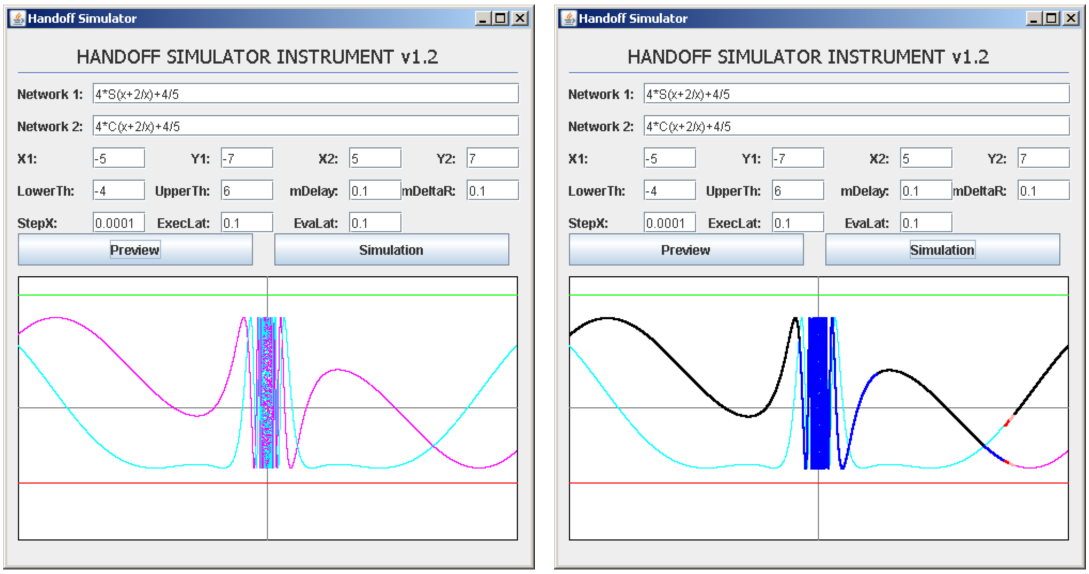


```
plot 4*cos(x/2)+4/3*cos(x*3)+4/5*cos(x/4)+4/7*cos(7*x), 5*sin(x/2−1)+...
```

Figure A-5. Use of the plotting function in WolframAlpha^{TM} for validating purposes.

This test case presents a scenario with two cross points and two executed handoffs, which correspond with the results shown in figure A-4c, ToX = 2, nEHO = 2, and rEHO = 1.0. Notice the first handoff was *urgent* because during the preparation state, the current network approached too much to the lower threshold and the algorithm R decided to initiate a handoff before a disconnection will occur. We assume execution and evaluation stages may be successfully completed, even though they are partially performed in the red region, as long as handoff execution had been initiated in the handoff region. Thus, as shown in the simulation graphic, the terminal connects successfully to the best network after execution and evaluation, in fact, the two performed handoffs are beneficial, thus, rBHO = 100%. The instrument measured a value for DTiB at 8.3999… which yields a rate of time in the best of 83.99%. This scenario performs a very good value for rTiB, which makes it an acceptable result; however, because the rate of executed handoffs is 100%, although they were only two, makes this result unbalanced. The instrument optimized rTiB but did not pay attention to rEHO. In this case, the ordered pair (rTiB, rEHO) places this scenario in the subspace O12.

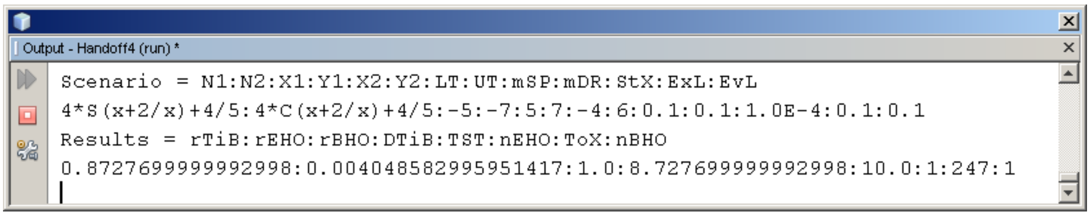
Now, let us expose the instrument to an interesting handoff scenario, depicted in figure A-6, where the number of crossing points can be excessively large. The network functions present an increasing oscillating condition as *x* approaches to 0 and decreasing oscillating condition as *x* retreats from 0. The mathematical analysis of these functions would be an interesting and tempting open door to discovery, but we are not going to get in at this moment. The instrument counts 247 crossing points but this quantity is different depending on the value of StX. This dependence is however correct, the more dots the curves have, the more number of crossing points can be detected. Despite the excessive amount of crossing points, the instrument performs just one handoff that occurs outside the “whirlpool” as depicted in figure A-6b. Therefore, the value of rEHO is 1/247 or 0.4% that is a very good result near the optimal value which is 0. Moreover, the instrument obtained a value of 87.28% for rTiB, which is also a very good result for this parameter. Therefore, these results are considered very good and balanced because both, rTiB and rEHO, are simultaneously improved.



Network 1: 4*S(x+2/x)+4/5
Network 2: 4*C(x+2/x)+4/5
X1: -5 Y1: -7 X2: 5 Y2: 7
LowerTh: -4 UpperTh: 6 mDelay: 0.1 mDeltaR: 0.1
StepX: 0.0001 ExecLat: 0.1 EvaLat: 0.1

Network 1: 4*S(x+2/x)+4/5
Network 2: 4*C(x+2/x)+4/5
X1: -5 Y1: -7 X2: 5 Y2: 7
LowerTh: -4 UpperTh: 6 mDelay: 0.1 mDeltaR: 0.1
StepX: 0.0001 ExecLat: 0.1 EvaLat: 0.1

(a) Preview scenario (b) Handoff simulation

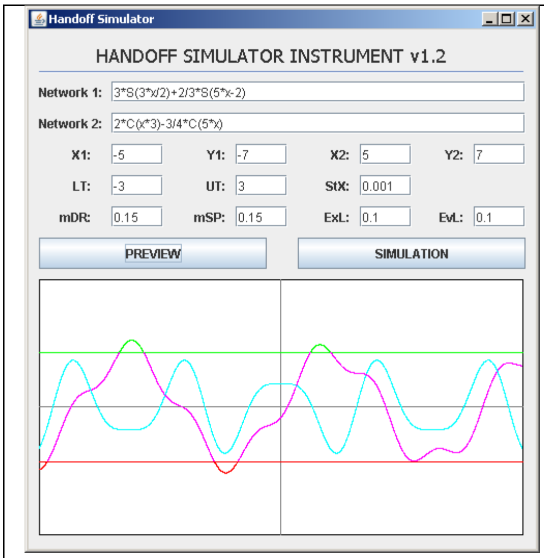


```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
4*S(x+2/x)+4/5:4*C(x+2/x)+4/5:-5:-7:5:7:-4:6:0.1:0.1:1.0E-4:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.8727699999992998:0.004048582995951417:1.0:8.727699999992998:10.0:1:247:1
```

(c) Handoff data

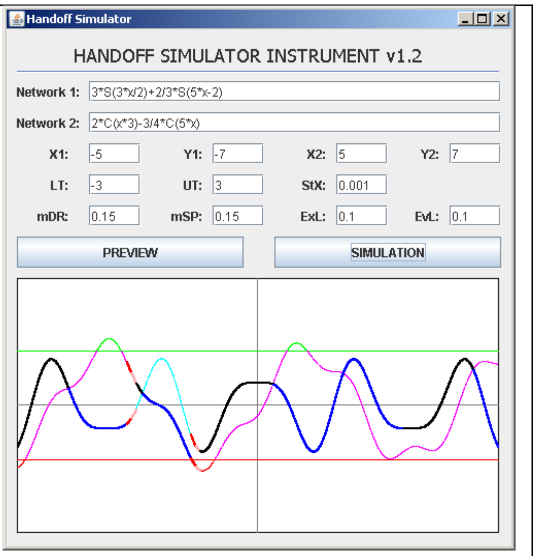
Figure A-6. Handoff scenario producing a good and balanced result at G22.

In this Appendix, we presented a series of test cases which support the statement that the handoff simulator instrument behaves as expected and gives results that meet its requirements. So far, every input scenario showed rather extreme and opposite results located in subspaces R11, Y21, O12, and G22. However, finding scenarios for subspaces R11, Y21, and O12, was rather more difficult to achieve than finding scenarios for the green subspace. Such difficulty is a “good sign” because it means that the handoff algorithm is doing its work, by increasing DTiB and reducing nEHO as much as possible. As we found more handoff scenarios lying in the green subspace than in any other subspace, we believe it is convenient to close this discussion by showing testing cases that lay in G11, G12, and G21. Figure A-7 presents the screen outputs of these cases. Perhaps the last significant aspect that we want to discuss is that of aperiodic functions. It is convenient to expose the handoff instrument to network desirability functions that exhibit periodicity and nonperiodicity. For our purposes, a periodic function f is a function that repeats its values in regular intervals or periods, satisfying f(x + T) = f(x) for x ∊ [x1, x2] and T some nonzero constant representing the period. In figures A-7a and A-7b we combine periodic and nonperiodic functions, while in A-7c, A-7d, A-7f, and A-7g we test the instrument with both aperiodic functions. In all these cases, the handoff results in A-7e and A-7h showed a good performance and achieved all the expected requirements.



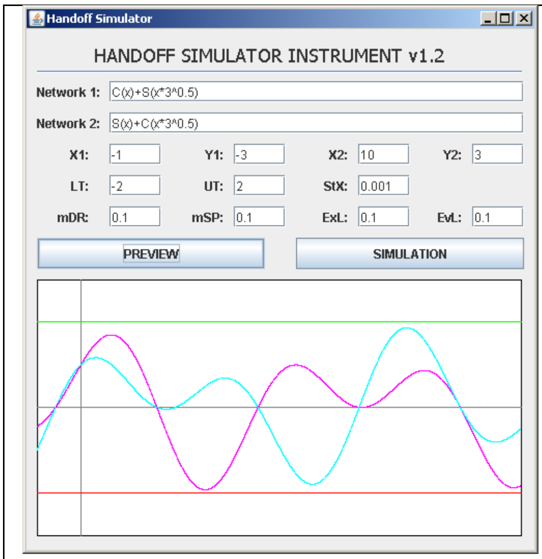
Network 1: 3*S(3*x/2)+2/3*S(5*x-2)
Network 2: 2*C(x*3)-3/4*C(5*x)
X1: -5 Y1: -7 X2: 5 Y2: 7
LT: -3 UT: 3 StX: 0.001
mDR: 0.15 mSP: 0.15 ExL: 0.1 EvL: 0.1

(a) Preview scenario G11



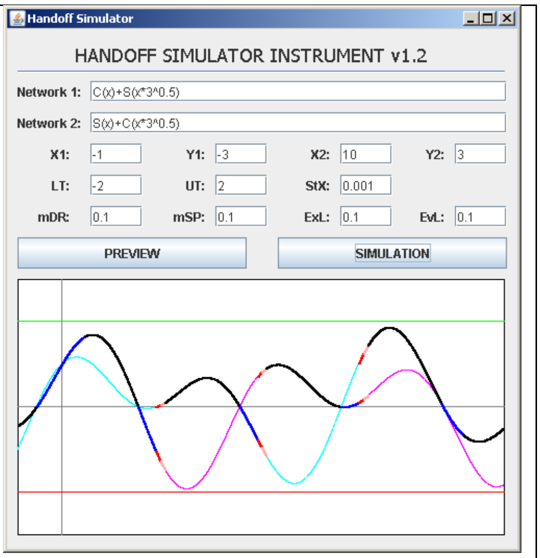
Network 1: 3*S(3*x/2)+2/3*S(5*x-2)
Network 2: 2*C(x*3)-3/4*C(5*x)
X1: -5 Y1: -7 X2: 5 Y2: 7
LT: -3 UT: 3 StX: 0.001
mDR: 0.15 mSP: 0.15 ExL: 0.1 EvL: 0.1

(b) Handoff simulation G11



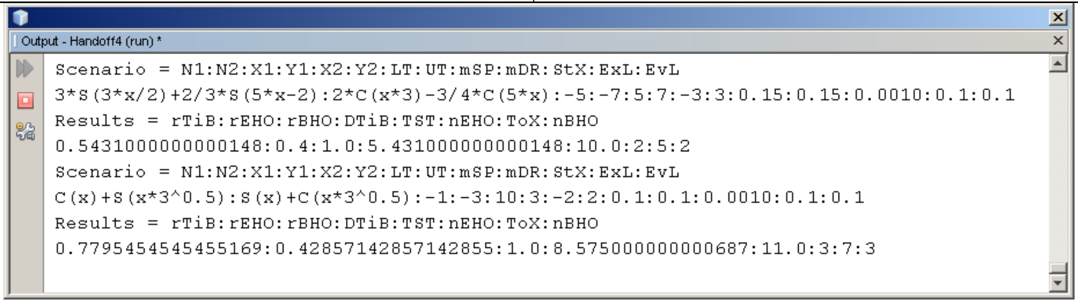
Network 1: C(x)+S(x*3^0.5)
Network 2: S(x)+C(x*3^0.5)
X1: -1
Y1: -3
X2: 10
Y2: 3
LT: -2
UT: 2
StX: 0.001
mDR: 0.1
mSP: 0.1
ExL: 0.1
EvL: 0.1

(c) Preview scenario G12



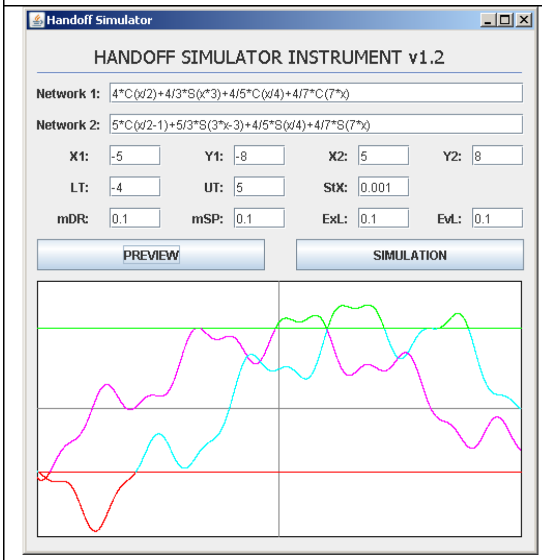
Network 1: C(x)+S(x*3^0.5)
Network 2: S(x)+C(x*3^0.5)
X1: -1
Y1: -3
X2: 10
Y2: 3
LT: -2
UT: 2
StX: 0.001
mDR: 0.1
mSP: 0.1
ExL: 0.1
EvL: 0.1

(d) Handoff simulation G12



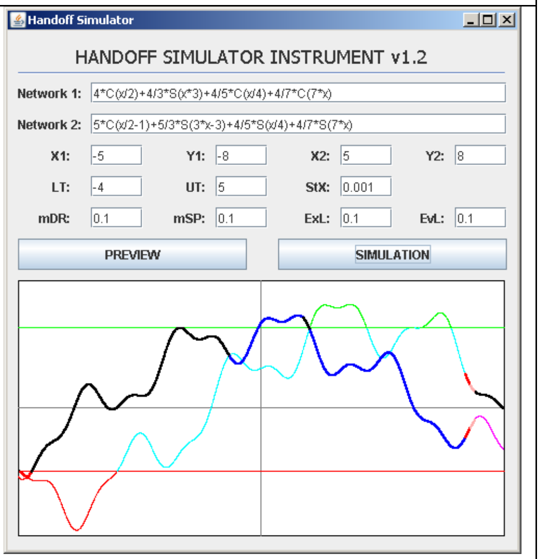
```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-3/4*C(5*x):-5:-7:5:7:-3:3:0.15:0.15:0.0010:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.5431000000000148:0.4:1.0:5.431000000000148:10.0:2:5:2
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
C(x)+S(x*3^0.5):S(x)+C(x*3^0.5):-1:-3:10:3:-2:2:0.1:0.1:0.0010:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.7795454545455169:0.42857142857142855:1.0:8.575000000000687:11.0:3:7:3
```

(e) Handoff data for G11 and G12



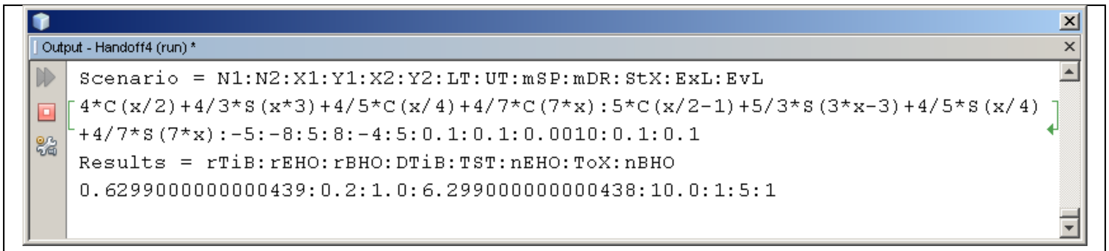
Network 1: 4*C(x/2)+4/3*S(x*3)+4/5*C(x/4)+4/7*C(7*x)
Network 2: 5*C(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x)
X1: -5
Y1: -8
X2: 5
Y2: 8
LT: -4
UT: 5
StX: 0.001
mDR: 0.1
mSP: 0.1
ExL: 0.1
EvL: 0.1

(f) Preview scenario G21



Network 1: 4*C(x/2)+4/3*S(x*3)+4/5*C(x/4)+4/7*C(7*x)
Network 2: 5*C(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x)
X1: -5
Y1: -8
X2: 5
Y2: 8
LT: -4
UT: 5
StX: 0.001
mDR: 0.1
mSP: 0.1
ExL: 0.1
EvL: 0.1

(g) Handoff simulation G21



```
Scenario = N1:N2:X1:Y1:X2:Y2:LT:UT:mSP:mDR:StX:ExL:EvL
4*C(x/2)+4/3*S(x*3)+4/5*C(x/4)+4/7*C(7*x):5*C(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)
+4/7*S(7*x):-5:-8:5:8:-4:5:0.1:0.1:0.0010:0.1:0.1
Results = rTiB:rEHO:rBHO:DTiB:TST:nEHO:ToX:nBHO
0.6299000000000439:0.2:1.0:6.299000000000438:10.0:1:5:1
```

(h) Handoff data for G21

Figure A-7. Input scenarios producing results falling in G11, G12, and G21.

Appendix B

Experimental Samples

This appendix presents the sample points (rTiB, rEHO) obtained by the random experiment specified in section 4.4.1 and the original data files that users "A", "B", and "C" delivered to us during the handoff simulation tests.

B.1. Summary of Sample Points per User

The 32 sample points created by user “A” are:

(0.858, 1)	(0.793, 0.5)	(0.581, 0.25)	(0.612, 0.75)
(0.718, 0.2)	(0.464, 0.7143)	(0.591, 0.5)	(0.49, 0.3333)
(0.733, 0.2)	(0.459, 0.75)	(0.457, 0.5)	(0.463, 0.6667)
(0.796, 0)	(0.851, 0.3333)	(0.588, 0.25)	(0.547, 0.2222)
(0.776, 0.1667)	(0.799, 0.6)	(0.44, 0.1667)	(0.516, 0.6667)
(0.774, 0.3333)	(0.697, 0.5)	(0.506, 0.3333)	(0.63, 0.22222)
(0.81, 0.2)	(0.742, 0.5)	(0.431, 0.25)	(0.705, 0.6667)
(0.542, 0.3333)	(0.622, 0.75)	(0.548, 0.75)	(0.436, 0.3)

The 84 sample points measured by user “B” are:

(0.9137, 0)	(0.4829, 0.125)	(0.5059, 0.1)	(0.6425, 0)
(0.6953, 1)	(0.6294, 0.375)	(0.9, 0)	(0.4818, 0.3333)
(0.6889, 1)	(0.7777, 0.375)	(0.7996, 1)	(0.5733, 0)
(0.6669, 1)	(0.8018, 0.5714)	(0.55, 0)	(0.5321, 0.3333)
(0.7299, 1)	(0.7922, 0.4444)	(0.9794, 1)	(0.6674, 0.5)
(0.638, 1)	(0.8346, 0.4285)	(0.9993, 0)	(0.62, 0.25)
(0.7986, 1)	(0.7175, 1)	(0.9992, 0)	(0.4171, 0.4545)
(0.8535, 1)	(0.5684, 1)	(0.8397, 1)	(0.535, 0.0909)
(0.6496, 1)	(0.6129, 0)	(0.752, 1)	(0.4203, 0.2857)
(0.6146, 1)	(0.6437, 0)	(0.8196, 1)	(0.3631, 0.2857)
(0.589, 1)	(0.5923, 0.3333)	(0.8295, 1)	(0.2536, 1)
(0.662, 1)	(0.4876, 0.25)	(0.8999, 1)	(0.439, 0.1428)
(0.5393, 0.6)	(0.5274, 0.1428)	(0.8696, 1)	(0.4627, 0)
(0.6089, 0.5555)	(0.8609, 0)	(0.7498, 0)	(0.5318, 0.2857)
(0.5265, 1)	(0.8845, 0)	(0.7202, 0)	(0.4593, 1)
(0.9406, 1)	(0.4265, 0.2222)	(0.875, 0)	(0.6153, 0)

(0.94, 1)	(0.3659, 0.6666)	(0.8166, 0)	(0.8218, 1)
(0.6616, 1)	(0.3065, 0.8571)	(0.9997, 0)	(0.9154, 1)
(0.7571, 1)	(0.7518, 1)	(0.65, 0)	(0.3993, 1)
(0.6559, 0.4)	(0.2103, 0.8571)	(0.5553, 0.1666)	(0.6557, 1)
(0.4956, 0.375)	(0.4294, 0.1429)	(0.5736, 0)	(0.7806, 1)

The 133 samples delivered by user “C” are:

(0.7695, 1)	(0.5967, 0.6666)	(0.6229, 0.2)	(0.6469, 0)
(0.8586, 0.5)	(0.5598, 0.75)	(0.6559, 1)	(0.3749, 0.8)
(0.8888, 0.4285)	(0.6104, 0.4285)	(0.6759, 1)	(0.4279, 0.8)
(0.6286, 0.4285)	(0.644, 0.6)	(0.8259, 1)	(0.6459, 0)
(0.6164, 0.4285)	(0.7189, 0.6)	(0.7859, 1)	(0.6199, 0)
(0.5903, 0.1111)	(0.4622, 0.4)	(0.3679, 1)	(0.3889, 0.4444)
(0.5727, 0)	(0.801, 0.2)	(0.6889, 0.6666)	(0.4369, 0)
(0.5936, 0.4444)	(0.7037, 0)	(0.8999, 1)	(0.3889, 0.4444)
(0.5819, 0.4444)	(0.8096, 1)	(0.9709, 1)	(0.4349, 0)
(0.5989, 1)	(0.6886, 0)	(0.8779, 1)	(0.4029, 0.1111)
(0.3959, 0.4)	(0.8595, 0.3333)	(0.4939, 0)	(0.3989, 0.2222)
(0.4769, 0.2)	(0.8069, 1)	(0.3539, 0.8571)	(0.5129, 0.3333)
(0.3682, 0.3846)	(0.7149, 1)	(0.4939, 0)	(0.6369, 0.5555)
(0.557, 0.0769)	(0.8469, 1)	(0.4929, 0)	(0.3129, 0.2222)
(0.5807, 0.3)	(0.8369, 1)	(0.5839, 0.1111)	(0.195, 0.5714)
(0.8242, 0.25)	(0.6509, 0.3333)	(0.6339, 0)	(0.2959, 0.4285)
(0.4969, 0.4)	(0.7249, 1)	(0.5699, 0)	(0.3029, 0.2857)
(0.6689, 0.1538)	(0.7379, 0.3333)	(0.5679, 0)	(0.4619, 0.1428)
(0.5109, 0.2857)	(0.7289, 0.25)	(0.3489, 0.6)	(0.6149, 0.7142)
(0.6188, 0.375)	(0.8569, 0.3333)	(0.9499, 0)	(0.5287, 0.7777)
(0.6624, 1)	(0.8389, 0.3333)	(0.7879, 0)	(0.4509, 0.4444)
(0.5862, 1)	(0.8219, 0.3333)	(0.6319, 0)	(0.5178, 0.2222)
(0.3683, 0.7142)	(0.5629, 0.25)	(0.3649, 0.4)	(0.5632, 0)
(0.6079, 0.25)	(0.5559, 0.125)	(0.3729, 0.4)	(0.5609, 0)
(0.6984, 0.25)	(0.5779, 0.1666)	(0.4589, 1)	(0.4491, 0.8)
(0.7272, 0.2857)	(0.6159, 0.25)	(0.5329, 0.6)	(0.45, 0.4)
(0.6133, 0.4)	(0.6149, 0.5)	(0.5199, 0.6)	(0.4425, 0.1666)
(0.6, 0.4)	(0.5659, 0.5)	(0.3489, 0.4)	(0.404, 0.5)
(0.6105, 0.5454)	(0.6439, 0.5)	(0.5129, 0.6)	(0.308, 0.5)
(0.6665, 0.2727)	(0.6599, 0.25)	(0.4489, 0.75)	(0.3398, 0.7)
(0.5737, 0.2727)	(0.6919, 0.25)	(0.4819, 0.6666)	(0.401, 0.3)
(0.5526, 0.2727)	(0.7159, 1)	(0.4839, 0)	
(0.548, 0.2727)	(0.8059, 1)	(0.5309, 0)	
(0.693, 0.2727)	(0.7969, 1)	(0.6459, 0)	

B.2. Original Data Files

LEGEND

N1:	First network function
N2:	Second network function
X1:	Initial Abscissa
Y1:	Initial Ordinate
X2:	Final Abscissa
Y2:	Final Ordinate
LT:	Lower Threshold
UT:	Upper Threshold
mDly:	Minimum Delay
mDR:	Minimum Relative Desirability
StX:	Step X
ExL:	Execution Latency
EvL:	Evaluation Latency
ToS:	Time of Simulation
ToC:	Total of Crosses
TiB:	Time in the Best
nEHO:	Number of Executed Handoffs
nBHO:	Number of Beneficial Handoffs
rTiB:	Rate of Time in the Best (TiB/ToS)
rEHO:	Rate of Executed Handoffs (nEHO/ToC)
rBHO:	Rate of Beneficial Handoffs (nBHO/nEHO)

HANDOFF DATA COLLECTED FROM USER "A" (32 samples)

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x/3-1.6):-5:-7:5:7:-3:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8579999999999861:1.0:1.0:8.579999999999862:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x/3+1.6):-5:-7:5:7:-3:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7179999999999891:0.2:1.0:7.179999999999891:10.0:1:5:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x/3+1.6):-5:-7:5:7:-2:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7329999999999888:0.2:1.0:7.329999999999888:10.0:1:5:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x/3+1.6):-5:-7:5:7:-2:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7959999999999875:0.0:0.0:7.959999999999875:10.0:0:5:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x)+0.5:4*S(x/3+1.6):-5:-7:5:7:-2:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7759999999999879:0.16666666666666666:1.0:7.759999999999879:10.0:1:6:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x)+0.5:4*S(x/3+1.6):-5:-7:5:7:-2:5:0.1:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7739999999999879:0.3333333333333333:1.0:7.739999999999879:10.0:2:6:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x)+0.5:4*S(x/2+1.6):-5:-7:5:7:-2:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8099999999999872:0.2:1.0:8.099999999999872:10.0:1:5:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x)+0.5:4*S(x+1.6):-5:-7:5:7:-2:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5419999999999929:0.3333333333333333:1.0:5.419999999999929:10.0:1:3:1

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x)+0.5:4*S(2*x+1.6):-5:-7:5:7:-2:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7929999999999875:0.5:1.0:7.929999999999875:10.0:2:4:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*C(x)+4/3*C(3*x)+4/5*C(5*x)+1:-5:-7:5:7:-2:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.46399999999999453:0.7142857142857143:0.6:4.639999999999455:10.0:5:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*C(x)+4/3*C(3*x)+4/5*C(5*x):-5:-7:5:7:-2:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.45899999999999463:0.75:1.0:4.589999999999947:10.0:6:8:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:-2:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8509999999999863:0.3333333333333333:1.0:8.509999999999863:10.0:1:3:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:-3:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7989999999999874:0.6:1.0:7.989999999999874:10.0:3:5:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:-3:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6969999999999896:0.5:1.0:6.969999999999896:10.0:1:2:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7419999999999887:0.5:1.0:7.419999999999886:10.0:1:2:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:-5:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6219999999999912:0.75:1.0:6.219999999999912:10.0:3:4:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:-5:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5809999999999921:0.25:1.0:5.809999999999921:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:0:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5909999999999919:0.5:1.0:5.909999999999918:10.0:1:2:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:1:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4569999999999947:0.5:1.0:4.569999999999947:10.0:1:2:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x-1)+4/5*S(5*x):-5:-7:5:7:1:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5879999999999919:0.25:1.0:5.879999999999919:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-3)+4/3*S(3*x-1)+4/5*S(5*x):-5:-7:5:7:-6:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.43999999999999506:0.16666666666666666:1.0:4.399999999999951:10.0:1:6:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-1)+4/3*S(3*x-1)+4/5*S(5*x):-5:-7:5:7:-6:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5059999999999937:0.3333333333333333:1.0:5.059999999999365:10.0:1:3:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-2)+4/3*S(3*x-1)+4/5*S(5*x):-5:-7:5:7:-6:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4309999999999953:0.25:1.0:4.3099999999999525:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-2)+4/3*S(3*x-1)+4/5*S(5*x):-5:-7:5:7:-6:5:0.1:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5479999999999927:0.75:1.0:5.479999999999928:10.0:3:4:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-2)+4/3*S(3*x-1)+4/5*S(5*x):-5:-7:5:7:-5:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6119999999999914:0.75:1.0:6.119999999999914:10.0:3:4:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(2*x-2)+4/3*S(3*x-1)+4/5*S(5*x):-5:-7:5:7:-5:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4899999999999994:0.3333333333333333:1.0:4.899999999999994:10.0:3:9:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(2*x-2)+4/3*S(3*x-1)+4/5*S(5*x)+0.5:-5:-7:5:7:-5:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4629999999999946:0.6666666666666666:0.5:4.629999999999946:10.0:4:6:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO

4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(2*x-2)+4/3*S(3*x-2)+4/5*S(5*x)+0.5:-5:-7:5:7:-5:5:0.1:0.1:0.01:0.1:0.1	0.5469999999999928:0.2222222222222222:1.0:5.469999999999928:10.0:2:9:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(2*x-2)+4/3*S(3*x-2)+4/5*S(5*x)+0.5:-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5159999999999935:0.6666666666666666:1.0:5.159999999999934:10.0:6:9:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(2*x-2)+4/3*S(3*x-2)+4/5*S(5*x)+0.5:-5:-7:5:7:-4:5:0.2:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.629999999999991:0.2222222222222222:1.0:6.29999999999991:10.0:2:9:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+2)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-1)+4/3*S(3*x-2)+4/5*S(5*x)+0.5:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7049999999999894:0.6666666666666666:1.0:7.049999999999894:10.0:2:3:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+0)+4/3*S(3*x-1)+4/5*S(5*x+2)+0.5:4*S(x-1)+4/3*S(3*x-2)+4/5*S(5*x)+0.5:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4359999999999517:0.3:1.0:4.359999999999515:10.0:3:10:3

HANDOFF DATA COLLECTED FROM USER "B" (84 samples)

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x)+4/3*S(3*x)+4/5*S(5*x):-5:-7:5:7:-3:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9137000000000375:0.0:0.0:9.137000000000375:10.0:0:0:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x-1)+4/3*S(3*x-1)+4/5*S(5*x-1):-5:-7:5:7:-3:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6953000000000656:1.0:1.0:6.953000000000657:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x-1)+4/3*S(3*x-1)+4/5*S(5*x-1):-5:-7:5:7:-3:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6889999999999897:1.0:1.0:6.8899999999998975:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x):4*S(x-1)+4/3*S(3*x-1)+4/5*S(5*x-1):-5:-7:5:7:-3:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6669999999999903:1.0:1.0:6.669999999999902:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x):4*S(x-1)+4/3*S(3*x-1)+4/5*S(5*x-1):-5:-7:5:7:-3:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7299000000000773:1.0:1.0:7.299000000000772:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x):4*S(x-1)+4/3*S(3*x-1)+4/5*S(5*x-1):-5:-7:5:7:-2:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6380000000000465:1.0:1.0:6.380000000000465:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x):4*S(x-2)+4/3*S(3*x-1)+4/5*S(5*x-1):-5:-7:5:7:-2:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7986000000001001:1.0:1.0:7.986000000001002:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x):4*S(x-2)+4/3*S(3*x-3)+4/5*S(5*x-1):-5:-7:5:7:-2:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8535000000000709:1.0:1.0:8.535000000000709:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x)+4/5*S(5*x):4*S(x-2)+4/3*S(3*x-3)+4/5*S(5*x-1):-5:-7:5:7:-2:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6496000000000504:1.0:1.0:6.496000000000504:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):4*S(x-2)+4/3*S(3*x-3)+4/5*S(5*x-1):-5:-7:5:7:-2:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6146000000000387:1.0:1.0:6.146000000000387:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):4*S(x-2):-5:-7:5:7:-2:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5890000000000302:1.0:1.0:5.890000000000302:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):4*S(x-2):-5:-7:5:7:-3:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6620000000000545:1.0:1.0:6.6200000000005454:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):4*S(2*x-2):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5393000000000135:0.6:1.0:5.393000000000136:10.0:6:10:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):4*S(3*x+2):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6089000000000369:0.5555555555555556:1.0:6.089000000000368:10.0:5:9:5
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):4*L(3*x+2):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5265000000000093:1.0:1.0:5.265000000000093:10.0:1:1:1

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):4*e^(3*x+2):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9406000000000226:1.0:1.0:9.406000000000226:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):e^(x):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9400000000000229:1.0:1.0:9.40000000000023:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):e^(x-2):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6616000000000544:1.0:1.0:6.616000000000544:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x-1)+4/3*S(3*x+3)+4/5*S(5*x):2*S(x^2):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7571000000000863:1.0:1.0:7.571000000000863:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+3)+4/3*S(3*x+3)+4/5*S(5*x):2*S(x^2):-5:-7:5:7:-4:5:0.2:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6559000000000526:0.4:1.0:6.559000000000525:10.0:2:5:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x+3):2*S(x^2):-5:-7:5:7:-4:5:0.2:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4955999999999999:0.375:1.0:4.955999999999999:10.0:3:8:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x+3):2*S(x^2):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.48299999999999477:0.125:1.0:4.829999999999948:10.0:1:8:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x+3):2*S(x^2):-5:-7:5:7:-3:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6294000000000437:0.375:1.0:6.294000000000437:10.0:3:8:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x+3):2*S(x^2):-5:-7:5:7:-2:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7777000000000932:0.375:0.6666666666666666:7.777000000000932:10.0:3:8:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x+3):2*S(x^2):-5:-7:5:7:-1:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8018000000000995:0.5714285714285714:0.75:8.018000000000995:10.0:4:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x+3):3*S(x^2):-5:-7:5:7:-1:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.792200000000098:0.4444444444444444:0.75:7.92200000000098:10.0:4:9:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x+3):3*S(x^2):-5:-7:5:7:0:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8346000000000814:0.42857142857142855:1.0:8.346000000000814:10.0:3:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(2*x+3):3*S(x^2):-5:-7:5:7:0:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7175000000000731:1.0:1.0:7.175000000000731:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(2*x+3):3*S(x^2):-5:-7:5:7:1:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5684000000000233:1.0:1.0:5.684000000000233:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(2*x+3):3*S(x^2-1):-5:-7:5:7:-5:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6129000000000382:0.0:0.0:6.1290000000003815:10.0:0:8:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(2*x+3):4*S(x^2-1):-5:-7:5:7:-5:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6437000000000485:0.0:0.0:6.437000000000484:10.0:0:18:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(2*x+3):4*S(x^2-1):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5923000000000312:0.3333333333333333:0.8333333333333334:5.923000000000313:10.0:6:18:5
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3):4*S(x^2-1):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.48759999999999963:0.25:0.75:4.875999999999963:10.0:4:16:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3)+1:4*S(x^2-1):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5274000000000096:0.14285714285714285:1.0:5.274000000000096:10.0:2:14:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3)+1:4*x^2-1:-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8609000000000668:0.0:0.0:8.609000000000668:10.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3)+1:4*x^2-x:-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8845000000000537:0.0:0.0:8.845000000000537:10.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3)+1:1/(x-1):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.42649999999999759:0.2222222222222222:1.0:4.264999999999759:10.0:2:9:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3)+1:1/(x-1):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.36589999999999708:0.6666666666666666:1.0:3.658999999999708:10.0:6:9:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3)+1:1/(x):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.30659999999997734:0.8571428571428571:1.0:3.0659999999997734:10.0:6:7:6

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+3)+1:1/(x):-5:-7:5:7:-4:5:0.01:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7518000000000845:1.0:1.0:7.518000000000845:10.0:7:7:7
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x-3)+1:1/(x^2):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.21029999999998794:0.8571428571428571:1.0:2.1029999999998794:10.0:6:7:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x-3)+1:1/(x^2):-5:-7:5:7:-4:5:0.2:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.42949999999999769:0.14285714285714285:1.0:4.2949999999999769:10.0:1:7:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x-3)+1:1/(x^2-1):-5:-7:5:7:-4:5:0.2:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5059000000000025:0.1:0.0:5.059000000000024:10.0:1:10:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:x-1:-5:-7:5:7:-4:5:0.2:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9000000000000451:0.0:0.0:9.000000000000451:10.0:0:0:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:1-x:-5:-7:5:7:-4:5:0.2:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7996000000001005:1.0:1.0:7.996000000001005:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:1-x:-5:-7:5:7:-4:5:0.0:0.0:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5500000000000171:0.0:0.0:5.500000000000171:10.0:0:1:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:1-x:-5:-7:5:7:-4:5:1.0E-5:1.0E-6:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9794000000000012:1.0:1.0:9.794000000000011:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:1-x:-5:-7:5:7:-4:5:1.0E-5:1.0E-6:0.0010:0.0:0.0	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9993999999999901:0.0:0.0:9.993999999999:10.0:0:1:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x*S(x):1-x:-5:-7:5:7:-4:5:1.0E-5:1.0E-6:0.0010:0.0:0.0	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9991999999999901:0.0:0.0:9.991999999999901:10.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x*S(x):1-x:-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8397000000000785:1.0:1.0:8.397000000000785:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x*S(x):0-x:-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7520000000000846:1.0:1.0:7.520000000000846:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:0-x:-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8196000000000897:1.0:1.0:8.196000000000897:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:0-x:-5:-7:5:7:-4:5:0.1:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8295000000000842:1.0:1.0:8.295000000000842:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:0-x:-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8999000000000452:1.0:1.0:8.999000000000452:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x^3:x^2:-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.869600000000062:1.0:1.0:8.69600000000062:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x^4:x^2:-4:-7:4:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7498750000000423:0.0:0.0:5.999000000000338:8.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x^4+x^3:x^2:-4:-7:4:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7202500000000324:0.0:0.0:5.762000000000259:8.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x^4+x^3+x^2:x^2:-4:-7:4:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.875000000000084:0.0:0.0:7.000000000000672:8.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x^4+x^3+x^2+x:x^2:-4:-7:4:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8166250000000645:0.0:0.0:6.533000000000516:8.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x^4+x^3+x^2+x+1:x^2:-4:-7:4:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9997500000001257:0.0:0.0:7.998000000001006:8.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x^4+x^3+x^2+x+1:(x-2)^2:-4:-7:4:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6500000000000089:0.0:0.0:5.200000000000071:8.0:0:2:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+7:4*C(2*x)+8:-1:-1:10:20:0:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5553636363636705:0.16666666666666666:1.0:6.109000000000375:11.0:1:6:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+6:4*C(2*x)+8:-1:-1:10:20:0:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5736363636364038:0.0:0.0:6.310000000000442:11.0:0:6:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+5:4*C(2*x)+8:-1:-1:10:20:0:10:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6425454545455177:0.0:0.0:7.068000000000695:11.0:0:6:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+5:4*C(2*x)+7:-1:-1:10:20:0:10:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4818181818181913:0.3333333333333333:1.0:5.300000000000105:11.0:2:6:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+5:4*C(2*x)+7:-1:-1:10:20:0:10:0.2:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5733636363636765:0.0:0.0:6.307000000000441:11.0:0:6:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+5:4*C(2*x)+6:-1:-1:10:20:0:10:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5320909090909354:0.3333333333333333:1.0:5.853000000000289:11.0:2:6:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO

3*S(x/3)+5:4*C(2*x)+6:-1:-1:15:15:2:11:0.1:0.1:0.0010:0.1:0.1	0.66743749999997:0.5:1.0:10.67899999999952:16.0:4:8:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+7:4*C(2*x)+8:-1:-1:15:15:2:11:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6200624999999963:0.25:1.0:9.92099999999994:16.0:2:8:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/2)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:0:4:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4171818181818061:0.45454545454545453:1.0:4.588999999999867:11.0:5:11:5
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/2)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:0:4:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5350000000000272:0.09090909090909091:1.0:5.8850000000003:11.0:1:11:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:0:4:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.42036363636362534:0.2857142857142857:1.0:4.623999999999879:11.0:2:7:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:0:4:0.3:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3631818181817883:0.2857142857142857:0.5:3.994999999999671:11.0:2:7:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:0:4:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.2536363636363622:1.0:1.0:2.7899999999999845:11.0:7:7:7
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:0:4:0.4:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.43909090909090376:0.14285714285714285:0.0:4.8299999999999415:11.0:1:7:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:0:4:0.4:0.4:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4627272727272669:0.0:0.0:5.089999999999936:11.0:0:7:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x/3)+3:4*(C(2*x)-(1/3)*C(6*x)+(1/5)*C(10*x))+4:-1:-1:10:10:2:4:0.4:0.4:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5318181818181745:0.2857142857142857:1.0:5.84999999999992:11.0:2:7:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x+1.570796)+3:4*C(x-3.141592)+5:-10:-1:10:10:0:4:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4593000000000174:1.0:1.0:9.186000000000348:20.0:6:6:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x+1.570796)+3:4*C(x-3.141592)+5:-10:-1:10:10:0:4:0.4:0.4:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6153999999999309:0.0:0.0:12.307999999998618:20.0:0:6:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x+1.570796)+3:4*C(x-3.141592)+5:-10:-1:10:10:0:4:0.01:0.4:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8217999999998552:1.0:1.0:16.435999999997104:20.0:6:6:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x+1.570796)+3:4*C(x-3.141592)+5:-10:-1:10:10:0:4:0.01:0.01:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9154499999999697:1.0:1.0:18.308999999999394:20.0:6:6:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x+1.570796)+4:4*C(x-3.141592)+5:-10:-1:10:10:0:4:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3993000000000005006:1.0:1.0:7.986000000001002:20.0:6:6:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x+1.570796)+4:2*x*S(x/2):-10:-1:10:10:0:4:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6557499999999086:1.0:1.0:13.11499999999817:20.0:4:4:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(x+1.570796)+4:2*x*S(x/2):-10:-1:10:10:0:4:0.1:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7806999999998393:1.0:1.0:15.613999999996786:20.0:4:4:4

HANDOFF DATA COLLECTED FROM USER "C" (133 samples)

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(x-1.6):-5:-7:5:7:-2:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7695000000000904:1.0:1.0:7.6950000000009044:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(2*x-1.6):-5:-7:5:7:-2:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8586000000000681:0.5:1.0:8.58600000000068:10.0:2:4:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(2*x-1.6):-5:-7:5:7:-3:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8888000000000513:0.42857142857142855:1.0:8.888000000000513:10.0:3:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+0.5:4*S(2*x-1.6):-5:-7:5:7:-	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6286000000000433:0.42857142857142855:1.0:6.2860000000000

4:5:0.2:0.2:0.0010:0.1:0.1	0434:10.0:3:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)+0.5:4*S(2*x-1.6):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6164000000000394:0.42857142857142855:1.0:6.164000000000393:10.0:3:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)+0.5:4*S(3*x-1.6):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5903000000000306:0.1111111111111111:1.0:5.903000000000306:10.0:1:9:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+0.5:4*S(3*x-1.6):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5727000000000247:0.0:0.0:5.727000000000247:10.0:0:9:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+0.5:4*S(3*x-1.6):-5:-7:5:7:-4:5:0.15:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5936000000000317:0.4444444444444444:1.0:5.936000000000317:10.0:4:9:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+0.5:4*S(3*x-1.6):-5:-7:5:7:-4:5:0.15:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5819999999999921:0.4444444444444444:1.0:5.81999999999992:10.0:4:9:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+0.5:4*C(x)+4/3*C(3*x)+4/5*C(5*x)+4/7*C(7*x):-5:-7:5:7:-4:5:0.15:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5989999999999917:1.0:1.0:5.989999999999917:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+0.5:4*S(x)+4/3*C(3*x)+4/5*C(5*x)+4/7*C(7*x):-5:-7:5:7:-4:5:0.15:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.39599999999999597:0.4:0.75:3.9599999999999596:10.0:4:10:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+0.5:4*S(x)+4/3*C(3*x)+4/5*C(5*x)+4/7*C(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.47699999999999276:0.2:1.0:4.769999999999928:10.0:2:10:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+0.5:4*S(x)+4/3*C(3*x)+4/5*C(5*x)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.36819999999997055:0.38461538461538464:0.6:3.6819999999997055:10.0:5:13:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x)+4/3*C(3*x)+4/5*C(5*x)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5570000000000195:0.07692307692307693:1.0:5.570000000000195:10.0:1:13:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x-2)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x)+4/3*C(3*x)+4/5*C(5*x)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5807000000000274:0.3:1.0:5.807000000000274:10.0:3:10:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x)+4/3*C(3*x)+4/5*C(5*x)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8242000000000871:0.25:1.0:8.242000000000871:10.0:2:8:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x)+4/3*C(3*x-2)+4/5*C(5*x)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.49699999999999384:0.4:1.0:4.969999999999385:10.0:4:10:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x)+4/3*C(3*x-2)+4/5*C(5*x+2)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6689999999999902:0.15384615384615385:1.0:6.689999999999902:10.0:2:13:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x-1)+4/3*C(3*x-2)+4/5*C(5*x+2)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5109999999999936:0.2857142857142857:1.0:5.1099999999999355:10.0:2:7:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x-1)+4/3*C(3*x-2)+4/5*C(5*x+2)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6188000000000401:0.375:1.0:6.188000000000401:10.0:3:8:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*S(7*x+1)+1:4*S(x-2)+4/3*C(3*x-2)+4/5*C(5*x+2)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6624000000000547:1.0:1.0:6.624000000000547:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x-2)+4/3*C(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5862000000000293:1.0:1.0:5.862000000000292:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(2*x-	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.36839999999997053:0.7142857142857143:0.6:3.68399999999

2)+4/3*C(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	97053:10.0:5:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(2/x-2)+4/3*C(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6079000000000365:0.25:1.0:6.079000000000365:10.0:2:8:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(2/x-2)+4/3*C(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6984000000000667:0.25:1.0:6.984000000000667:10.0:2:8:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(2/x-2)+4/3*C(3/x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7272000000000763:0.2857142857142857:1.0:7.272000000000763:10.0:4:14:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*C(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6133000000000383:0.4:1.0:6.133000000000383:10.0:4:10:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*C(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.05:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6000000000000338:0.4:1.0:6.000000000000338:10.0:4:10:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.05:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6105000000000373:0.5454545454545454:0.6666666666666666:6.1050000000003735:10.0:6:11:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.666500000000056:0.2727272727272727:1.0:6.6650000000005605:10.0:3:11:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*C(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5737000000000251:0.2727272727272727:1.0:5.737000000000251:10.0:3:11:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*S(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.552600000000018:0.2727272727272727:1.0:5.52600000000018:10.0:3:11:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*S(5*x+2)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.3:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5480000000000165:0.2727272727272727:1.0:5.480000000000165:10.0:3:11:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.3:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6930000000000649:0.2727272727272727:1.0:6.930000000000649:10.0:3:11:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+1)+4/3*S(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.3:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5967000000000328:0.6666666666666666:1.0:5.967000000000327:10.0:4:6:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+1)+4/3*C(3*x+2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5598000000000204:0.75:1.0:5.598000000000204:10.0:6:8:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+1)+4/3*S(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6104000000000374:0.42857142857142855:1.0:6.104000000000373:10.0:3:7:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+1)+4/3*S(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x/3)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6440000000000485:0.6:1.0:6.440000000000485:10.0:3:5:3

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+1)+4/3*S(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x/3)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7189000000000736:0.6:1.0:7.1890000000007355:10.0:3:5:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+1)+4/3*S(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x/3)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-5:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.46219999999998784:0.4:1.0:4.621999999999878:10.0:2:5:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*S(2*x+1)+4/3*S(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-5:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8010000000001:0.2:1.0:8.010000000001:10.0:1:5:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/3)+4/3*S(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-5:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7037000000000685:0.0:0.0:7.037000000000685:10.0:0:1:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/3)+4/3*S(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-5:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8096000000000952:1.0:1.0:8.096000000000952:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/3)+4/3*C(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1)+1:4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-5:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6886000000000634:0.0:0.0:6.886000000000634:10.0:0:1:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/3)+4/3*C(3*x/2)+4/5*S(5*x)+4/7*C(7*x+1):4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-5:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8595000000000675:0.3333333333333333:1.0:8.595000000000676:10.0:1:3:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/3)+4/3*C(3*x/2)+4/5*C(5*x)+4/7*C(7*x+1):4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-5:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8069999999999873:1.0:1.0:8.069999999999872:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/3)+4/3*C(3*x/2)+4/5*C(2*x)+4/7*C(7*x+1):4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7149999999999892:1.0:1.0:7.149999999999892:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(2*x)+4/7*C(7*x+1):4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8469999999999864:1.0:1.0:8.469999999999864:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x)+4/7*C(7*x+1):4*S(x/3)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8369999999999866:1.0:1.0:8.369999999999866:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x)+4/7*C(7*x+1):4*S(x)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6509999999999906:0.3333333333333333:1.0:6.509999999999906:10.0:2:6:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x)+4/7*C(7*x+1):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.724999999999989:1.0:1.0:7.24999999999989:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x)+4/7*C(7*x+1):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7379999999999887:0.3333333333333333:1.0:7.379999999999887:10.0:1:3:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7289999999999889:0.25:1.0:7.289999999999889:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1)-3:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8569999999999862:0.3333333333333333:1.0:8.569999999999862:10.0:1:3:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x-1)-2:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8389999999999865:0.3333333333333333:1.0:8.389999999999866:10.0:1:3:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x/2)+4/5*C(x/2)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)-1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.821999999999987:0.3333333333333333:1.0:8.21999999999987:10.0:1:3:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO

4*C(x/2)+4/3*C(3*x/2)+4/5*C(x/2)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	0.5629999999999924:0.25:1.0:5.629999999999924:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(3*x)+4/5*C(x/2)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5559999999999926:0.125:1.0:5.559999999999926:10.0:1:8:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x/3)+4/5*C(x/2)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5779999999999921:0.16666666666666666:1.0:5.779999999999921:10.0:1:6:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x/3)+4/5*C(x/4)+4/7*C(7*x):4*S(x)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6159999999999913:0.25:1.0:6.159999999999913:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x/3)+4/5*C(x/4)+4/7*C(7*x):4*S(x/2)+4/3*S(3*x)+4/5*S(5*x)+4/7*S(7*x)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6149999999999913:0.5:1.0:6.149999999999913:10.0:1:2:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x/3)+4/5*C(x/4)+4/7*C(7*x):4*S(x/2)+4/3*S(x/3)+4/5*S(5*x)+4/7*S(7*x)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5659999999999924:0.5:1.0:5.659999999999924:10.0:2:4:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x/3)+4/5*C(x/4)+4/7*C(7*x):4*S(x/2)+4/3*S(x/3)+4/5*S(x/4)+4/7*S(7*x)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6439999999999907:0.5:1.0:6.439999999999907:10.0:1:2:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x/3)+4/5*C(x/4)+4/7*C(7*x):4*S(x/2-1)+4/3*S(x/3)+4/5*S(x/4)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6599999999999904:0.25:1.0:6.599999999999904:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x/3)+4/5*C(x/4)+4/7*C(7*x):5*S(x/2-1)+5/3*S(3*x)+4/5*S(x/4)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6919999999999897:0.25:1.0:6.919999999999897:10.0:1:4:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x*3)+4/5*C(x/4)+4/7*C(7*x):5*S(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7159999999999892:1.0:1.0:7.159999999999892:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*C(x*3)+4/5*C(x/4)+4/7*C(7*x):5*S(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8059999999999873:1.0:1.0:8.059999999999873:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*S(x*3)+4/5*C(x/4)+4/7*C(7*x):5*S(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7969999999999875:1.0:1.0:7.9699999999998745:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*S(x*3)+4/5*C(x/4)+4/7*C(7*x):5*C(x/2-1)+5/3*S(3*x-3)+4/5*S(x/4)+4/7*S(7*x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6229999999999911:0.2:1.0:6.229999999999912:10.0:1:5:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 4*C(x/2)+4/3*S(x*3)+4/5*C(x/4)+4/7*C(7*x):2*x^2-4:-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6559999999999905:1.0:1.0:6.559999999999905:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3:2*x^2-4:-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.675999999999999:1.0:1.0:6.759999999999999:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*L(x):2*x^2-4:-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8259999999999869:1.0:1.0:8.259999999999868:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*L(x)+S(x):2*x^2-4+C(x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7859999999999877:1.0:1.0:7.859999999999877:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*L(x)+S(x):2*x^3-4+C(x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.36799999999999655:1.0:1.0:3.6799999999999655:10.0:2:2:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3/S(x):2*x^3-4+C(x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6889999999999897:0.6666666666666666:1.0:6.8899999999998975:10.0:2:3:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:0-x:-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8999999999999853:1.0:1.0:8.999999999999853:10.0:1:1:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL x:0-x:-5:-7:5:7:-4:5:0.01:0.01:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9709999999999838:1.0:1.0:9.709999999999837:10.0:1:1:1

Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL S(x):0:-5:-7:5:7:-4:5:0.01:0.01:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.8779999999999857:1.0:1.0:8.779999999999857:10.0:3:3:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL S(2*x):0:-5:-7:5:7:-4:5:0.15:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4939999999999939:0.0:0.0:4.939999999999939:10.0:0:7:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL S(2*x):0:-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3539999999999969:0.8571428571428571:1.0:3.5399999999999685:10.0:6:7:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(2*x):0:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4939999999999939:0.0:0.0:4.939999999999939:10.0:0:7:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x):0:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.49299999999999394:0.0:0.0:4.929999999999939:10.0:0:9:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x):2*C(x/2):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5839999999999992:0.1111111111111111:1.0:5.8399999999999992:10.0:1:9:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x):2*C(x/3):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6339999999999909:0.0:0.0:6.339999999999909:10.0:0:9:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x):2*C(x/3)-2:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5699999999999923:0.0:0.0:5.699999999999923:10.0:0:10:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x-2):2*C(x/3)-2:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5679999999999923:0.0:0.0:5.679999999999923:10.0:0:10:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2):2*C(x/3)-2:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.348999999999997:0.6:1.0:3.4899999999999696:10.0:3:5:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2):2*C(x/3)+2:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.9499999999999842:0.0:0.0:9.499999999999842:10.0:0:3:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2):2*C(x/3)+1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.7879999999999876:0.0:0.0:7.879999999999876:10.0:0:5:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2):2*C(x/3):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.631999999999991:0.0:0.0:6.31999999999991:10.0:0:5:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2):2*C(x/3)-1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3649999999999966:0.4:1.0:3.649999999999966:10.0:2:5:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(3*x):2*C(x/3)-1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.37299999999999645:0.4:1.0:3.7299999999999645:10.0:2:5:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(3*x):2*C(x/3)-1:-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.45899999999999463:1.0:1.0:4.589999999999947:10.0:5:5:5
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(3*x):2*C(x/3)-1:-5:-7:5:7:-4:5:0.1:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.532999999999993:0.6:1.0:5.329999999999931:10.0:3:5:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x):2*C(x/3)-1:-5:-7:5:7:-4:5:0.1:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5199999999999934:0.6:1.0:5.199999999999934:10.0:3:5:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x):2*C(x/3)-1:-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.348999999999997:0.4:1.0:3.4899999999999696:10.0:2:5:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x):2*C(x/3)-1:-5:-7:5:7:-3:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5129999999999935:0.6:0.6666666666666666:5.129999999999935:10.0:3:5:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x):2*C(x*3)-1:-5:-7:5:7:-3:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.44899999999999485:0.75:1.0:4.489999999999949:10.0:6:8:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x):2*C(x*3)-1:-5:-7:5:7:-2:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.48199999999999416:0.6666666666666666:0.75:4.819999999999942:10.0:4:6:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x):2*C(x*3)-1:-5:-7:5:7:-5:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4839999999999941:0.0:0.0:4.839999999999941:10.0:0:9:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-1:-5:-7:5:7:-5:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5309999999999931:0.0:0.0:5.309999999999931:10.0:0:7:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-3/5*C(5*x):-5:-7:5:7:-	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6459999999999907:0.0:0.0:6.459999999999907:10.0:0:5:0

5:5:0.2:0.2:0.01:0.1:0.1	
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-3/5*C(5*x):-5:-7:5:7:-4:5:0.15:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6469999999999907:0.0:0.0:6.4699999999999065:10.0:0:5:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-3/4*C(5*x):-5:-7:5:7:-4:5:0.1:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3749999999999964:0.8:1.0:3.749999999999964:10.0:4:5:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-3/4*C(5*x):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.42799999999999533:0.8:1.0:4.279999999999953:10.0:4:5:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-3/4*C(5*x):-5:-7:5:7:-4:5:0.2:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6459999999999907:0.0:0.0:6.459999999999907:10.0:0:5:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.2:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6199999999999912:0.0:0.0:6.199999999999912:10.0:0:7:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3-4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.15:0.05:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3889999999999961:0.4444444444444444:1.0:3.889999999999961:10.0:4:9:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3-4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.15:0.5:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4369999999999951:0.0:0.0:4.369999999999951:10.0:0:9:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3-4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.15:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3889999999999961:0.4444444444444444:1.0:3.889999999999961:10.0:4:9:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*3-4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.2:0.25:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.43499999999999517:0.0:0.0:4.349999999999952:10.0:0:9:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.2:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.40299999999999586:0.1111111111111111:1.0:4.029999999999585:10.0:1:9:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.1:0.2:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3989999999999959:0.2222222222222222:1.0:3.989999999999959:10.0:2:9:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.1:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5129999999999935:0.3333333333333333:1.0:5.129999999999935:10.0:3:9:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.05:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6369999999999909:0.5555555555555556:1.0:6.369999999999909:10.0:5:9:5
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)-3/4*C(5*x+2):-5:-7:5:7:-4:5:0.2:0.05:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.3129999999999977:0.2222222222222222:1.0:3.1299999999999772:10.0:2:9:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)+3/4*C(5*x+2):-5:-7:5:7:-4:5:0.2:0.05:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.19500000000000015:0.5714285714285714:1.0:1.9500000000000015:10.0:4:7:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)+3/4*C(5*x+2):-5:-7:5:7:-4:5:0.2:0.1:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.2959999999999981:0.42857142857142855:0.6666666666666666:2.959999999999981:10.0:3:7:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4)+3/4*C(5*x+2):-5:-7:5:7:-4:5:0.2:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.30299999999999794:0.2857142857142857:1.0:3.0299999999999794:10.0:2:7:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4-3)+3/4*C(5*x-3):-5:-7:5:7:-4:5:0.2:0.15:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4619999999999946:0.14285714285714285:1.0:4.619999999999946:10.0:1:7:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4-3)+3/4*C(5*x-3):-5:-7:5:7:-4:5:0.05:0.05:0.01:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.6149999999999913:0.7142857142857143:1.0:6.149999999999913:10.0:5:7:5
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4-3)+3/4*C(2*x-3):-5:-7:5:7:-4:5:0.05:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.52870000000001:0.7777777777777778:0.8571428571428571:5.2870000000001:10.0:7:9:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO

3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4-3)+3/4*C(2*x-3):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	0.4509999999999841:0.4444444444444444:0.75:4.509999999999841:10.0:4:9:3
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x-2):2*C(x*4-3)+3/4*C(2*x-3):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5178000000000064:0.2222222222222222:1.0:5.178000000000064:10.0:2:9:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x+2):2*C(x*4-3)+3/4*C(2*x-3):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5632000000000216:0.0:0.0:5.6320000000002155:10.0:0:5:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x+2):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(x):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.5609000000000208:0.0:0.0:5.609000000000208:10.0:0:5:0
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x+2):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(x):-5:-7:5:7:-4:5:0.1:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4491999999999835:0.8:1.0:4.491999999999835:10.0:4:5:4
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x/2)+2/3*S(5*x+2):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(x):-5:-7:5:7:-4:5:0.2:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4500999999999838:0.4:1.0:4.500999999999838:10.0:2:5:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x-2)+2/3*S(5*x+2):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(x):-5:-7:5:7:-4:5:0.2:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4425999999999813:0.16666666666666666:0.5:4.425999999999813:10.0:2:12:1
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x-2)+2/3*S(5*x+2)+C(x):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(x):-5:-7:5:7:-4:5:0.15:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.40409999999996843:0.5:0.4:4.040999999999684:10.0:5:10:2
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x-2)+2/3*S(5*x+2)+C(x):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(x):-5:-7:5:7:-4:5:0.1:0.15:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.30809999999997717:0.5:1.0:3.0809999999997717:10.0:5:10:5
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x-2)+2/3*S(5*x+2)+C(x):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(5*x):-5:-7:5:7:-4:5:0.1:0.1:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.33989999999997367:0.7:0.8571428571428571:3.3989999999997367:10.0:7:10:6
Scenary = N1:N2:X1:Y1:X2:Y2:LT:UT:mDly:mDR:StX:ExL:EvL 3*S(3*x-2)+2/3*S(5*x+2)+C(x):2*C(x*4-3)+3/4*C(2*x-3)-2/3*S(5*x):-5:-7:5:7:-4:5:0.2:0.2:0.0010:0.1:0.1	Results = rTiB:rEHO:rBHO:TiB:ToS:nEHO:ToC:nBHO 0.4010999999999674:0.3:1.0:4.010999999999674:10.0:3:10:3

Glossary of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
3GPP	Third Generation Partnership Project
AAAC	Authentication, Authorization, Accounting, and Charging
ABC	Always Best Connected
AL	Authentication Latency
AMPS	Advanced Mobile Phone Service
ANL	Available Network List
AP	Access Point
AppImpR	Application Improvement Rate
AppT	Application Type
AS	Autonomous System
BER	Bit Error Rate
BL	Battery Load
BLER	Block Error Rate
BS	Base Station
BT	Battery Types (or Bluetooth)
CB	Call Blocking
CCI	Co-Chanel Interference
CD	Call Dropping
CDMA	Code Division Multiple Access
CIR	Carrier-to-Interference Ratio
conB	Consistently Better
DAR	Detected Attacks Rate
DI	Degradation Intensity
DL	Degradation Latency
DLat	Decisions Latency
DR	Degradation Rate
DTiB	Dwelling-Time in the Best Network
DTR	Data Transfer Rate (Goodput)
DVB-SH	Digital Video Broadcasting - Satellite to Handhelds
ECR	Energy Consumption Rate
EDGE	Enhanced Data rates for GSM Evolution
ETSLH	Elapsed Time since Last Handoff

EvLat	Evaluation Latency
ExLat	Execution Latency
FSM	Finite State Machine
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HCE	Handoff Control Entity
HMIP	Hierarchical MIP
HO	Handoff or Handover
HOB	Handoff Blocking
HOL	Handoff Latency
HOR	Handoff Rate
HOSO	Handoff Signaling Overhead
HOType	Handoff Type
IHOR	Imperative Handoff Rate
IL	Interruption Latency
ImpR	Improvement Rate
IMT-2000	International Mobile Telecommunications-2000
IR	Interruption Rate
ISP	Internet Service Provider
LTE/SAE	Long Term Evolution/System Architecture Evolution
MAHO	Mobile Assisted Handoff
MBWA	Mobile Broadband Wireless Access or IEEE 802.20
MCHO	Mobile Controlled Handoff
MIP	Mobile IP
MN	Mobile Node
MOP	Multi-objective Optimization Problem
MT	Mobile Terminal
MTU	Maximum Transmission Unit
NAHO	Network Assisted Handoff
NBW	Network Bandwidth
NCHO	Network Controlled Handoff
ND	Network Delay
nEHO	Number of Executed Handoffs
NGI	Next Generation Internet
NIA	Network Inter-operating Agent
NJ	Network Jitter
NL	Network Load
NT	Network Throughput
OHOR	Opportunist Handoff Rate

OSI	Open Systems Interconnection
OUIR	Online User Interventions Rate
PDA	Personal Digital Assistant
PHOR	Premature Handoff Rate
QoS	Quality of Service
rCP	Rate of Corrupted Packets
rDP	Rate of Delayed Packets
rDuP	Rate of Duplicated Packets
rEHO	Rate of Executed Handoffs
rJP	Rate of Jittered Packets
rLP	Rate of Lost Packets
rOOD	Rate of Out-of-Order Delivered Packets
rTiB	Rate of Time in the Best
RSS	Received Signal Strength
SDR	Software-Defined Radio
SHOR	Successful Handoff Rate
SIP	Session Initiation Protocol
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
SNIR	Signal to Noise and Interference Ratio
SP	Stability Period
SSO	Security Signaling Overload
suffB	Sufficiently Better
SysML	Systems Modeling Language
TermImpR	Terminal Improvement Rate
THOR	Tardy Handoff Rate
TPC	Transmit Power of Current Network
TPT	Transmit Power of Target Network
UF	Utility Function
UMTS	Universal Mobile Telecommunications System
UsrImpR	User Improvement Rate
Wi-Fi	Wireless Fidelity or IEEE 802.11
WiMAX	Wireless Microwave Access or IEEE 802.16
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network
WWAN	Wireless Wide Area Network

List of Figures and Tables

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Extended Summary in Spanish

Transición Cognitiva y Movilidad para la Internet del Futuro

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Introducción

Una transición es un proceso dirigido a preservar las comunicaciones del usuario mientras éstas cambian entre diferentes redes, proveedores, o terminales. La principal característica deseable de una transición ha sido la transparencia [a]; sin embargo, para hacer frente a las futuras redes móviles, la transición debe además, ser autónoma, segura, correcta, y adaptable [b]. Esta transición es llamada multipropósito o cognitiva, pues busca optimizar múltiples objetivos posiblemente en conflicto; utiliza una gran variedad de información para tomar sus decisiones; y se desempeña correctamente en cualquier escenario posible de movilidad. Este trabajo crea una base de conocimiento para comprender, desarrollar y evaluar transiciones cognitivas.

Métodos

Inicialmente, usamos un enfoque holístico para desarrollar una taxonomía de escenarios de movilidad, una clasificación de variables del ambiente externo e interno de la transición y la definición de múltiples características deseables. Posteriormente, usamos la teoría de solución de problemas, el método de descomposición funcional y el paradigma de diseño basado en modelos para crear una metodología para construir transiciones cognitivas. Al aplicar los primeros pasos de la metodología propuesta, obtuvimos una arquitectura funcional de la transición cognitiva y una estrategia para evaluar el desempeño de transiciones multi-objetivo.

Resultados

Para validar y verificar los modelos de la arquitectura funcional, cambiamos a un enfoque reduccionista y tomamos como caso de estudio, el modelo de estados del proceso de control de una transición. Considerando solo dos objetivos en conflicto: maximizar la razón de permanencia en la mejor red (rTiB) y minimizar la tasa de transiciones ejecutadas (rEHO), construimos un algoritmo de control basado en optimización heurística. Asimismo, creamos un instrumento virtual que permite probar el algoritmo en una diversidad de escenarios. Dicho instrumento produce un valor bidimensional (rTiB, rEHO) por cada prueba realizada. La figura 1 muestra un diagrama de dispersión de resultados para un total de 249 pruebas aleatorias. La tabla 1 presenta diferentes clases de resultados obtenidos por cada experimento realizado.

Conclusiones

Construimos un marco de trabajo basado en modelos orientados a comprender la funcionalidad de una transición cognitiva, una metodología que describe su proceso de desarrollo, y un caso de estudio que demuestra la factibilidad de desarrollar transiciones multi-objetivo. Análisis estadísticos y modelos probabilísticos son desarrollados para evaluar su desempeño.

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Tabla 1. Resultados del experimento

Experimentos / Resultados	32 muestras - usuario A	84 muestras - usuario B	133 muestras - usuario C	249 muestras - usuarios A, B, C	Metas de desempeño
Muy buen balance y resultados	34.48%	14.29%	12.78%	16.06%	>10%
Buen balance y resultados	87.5%	54.76%	71.43%	67.87%	>50%
Buenos resultados	90.63%	92.86%	90.98%	91.57%	>90%
Malos resultados	9.37%	7.14%	9.02%	8.43%	<10%

Figura 1. Diagrama de dispersión de datos (249 muestras de tres diferentes usuarios)