Doctoral Thesis

Autonomic Management for Personalized Handover Decisions in Heterogeneous Wireless Networks

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by

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ABSTRACT

In this thesis, we present an approach that uses autonomic management principles to provide personalized handover decisions for customized mobility management in heterogeneous wireless networks. The computation of good and optimal handover decisions is a significant problem, especially in a heterogeneous network environment. This is exacerbated when the goal is to provide personalized services for mobile users, since "good" is now dependent on specific user needs, as opposed to generic device metrics such as received signal strength. Personalized handover decisions should not only consider received signal strength, which is a traditional handover decision factor, but also context information, user preferences, user profiles, and other non-functional requirements. In this thesis, we propose a novel autonomic management for personalized handover decisions, called AUHO, for satisfying end user's demands in heterogeneous wireless networks

The organization of this thesis is as follows. First, we review previous work on autonomic computing, autonomic networking, and handover decision management as related work. We compare previous handover decision approaches to our proposed AUHO method. Then, we present our hypothesis, assumptions, motivating scenarios, and research methodologies for approaching personalized handover decision problems. Next, we introduce context information for handover decisions which is available from mobile devices, networks, users, and services. Then, we present our

design of an information model that represents mobile and network devices, policy rules, user preferences, and user profiles for heterogeneous devices that are based on the DEN-ng information model, which is a technology-neutral information model. We then show how this model is used in our autonomic architecture to support handover decisions.

Then, we present our novel decision making algorithm for personalized handover decisions. For supporting it, we define two objective metrics for evaluating the suitability of choosing a specific access point of an access network: access point acceptance value and access point satisfaction value. The former represents suitability of an access point for an end user based on a set of preference metrics for that user (i.e., received signal strength, quality of service, cost, or battery lifetime) and his or her application requirements. The latter represents how well a particular access point satisfies the needs of the end user based on his or her user profile(s) which include weights of each user preference.

Our algorithm uses a combination of functional and non-functional metrics to select the access point that best meets the needs of the user. Our algorithm supports the best access point (horizontal handover decisions) as well as the best access network (vertical handover decisions) to use, based on the current set of user preferences, application requirements, and context information.

We have designed a new network simulator for testing and verifying the performance of handover decision algorithms in heterogeneous wireless networks. In our simulation study, we show that our decision algorithm selects access points and networks that support the needs of the user better than other decision algorithms.

In this thesis, our main contributions are: (1) a novel decision making algorithm for personalized handover, (2) an enhanced autonomic architecture to apply to personalized mobility management, and (3) an extensible and user-friendly test platform for implementing and evaluating handover decision algorithms. These contributions also provide robust cognition mechanisms to support cognitive radio technology.

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Chapter I

INTRODUCTION

This chapter provides a brief introduction to heterogeneous wireless networks and network handover concepts. The problems in current handover decision-making are listed and the approaches this thesis takes to solve them are outlined.

1.1 Background

Growth in ubiquitous and mobile computing systems has led to the early introduction of a wide variety of new access networks and Internet-capable devices [1]. Moreover, the network trend towards next-generation networks has been moving towards an architecture that supports different wireless technologies, mobile users, multiple radio access technologies, heterogeneous networks, and network convergence. Wireless networks have been emphasized due to their ability to provide Internet connection regardless of location [2, 3].

As shown in Figure I.1, multiple heterogeneous wireless access networks can

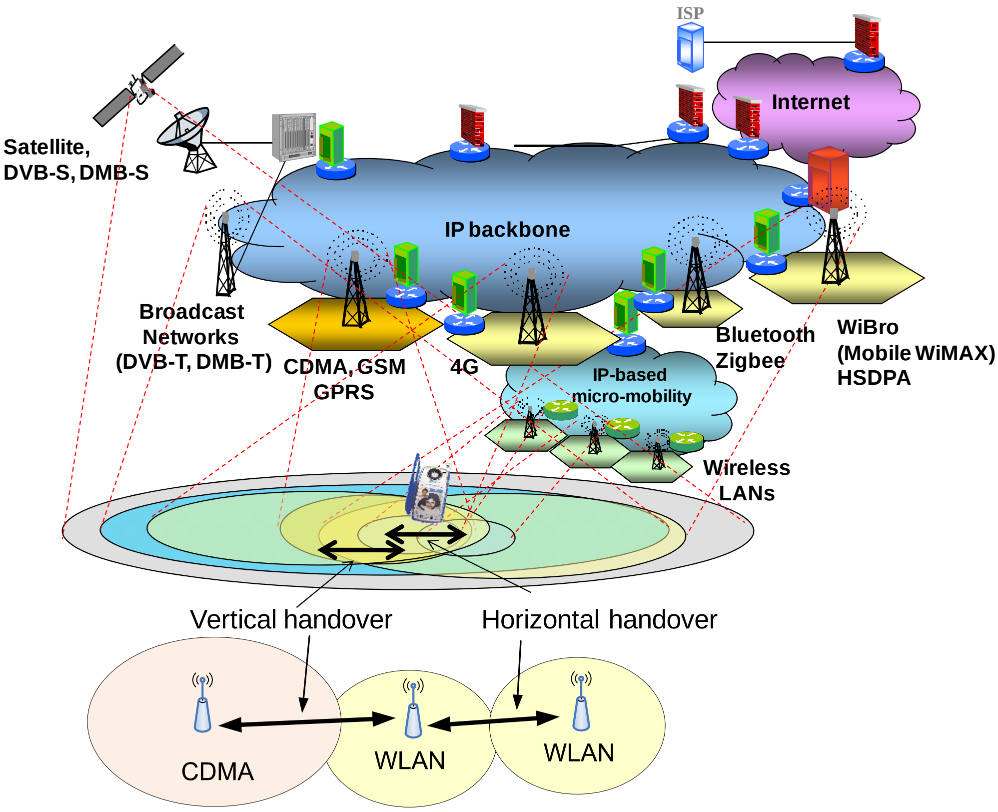


Figure I.1: Horizontal and vertical handover in heterogeneous wireless networks

be used at the same place. For example, *Code Division Multiple Access (CDMA)* networks based on cellular communication and IEEE 802.11-based *Wireless LAN (WLAN)* networks can coexist, since they can provide their own services without any interference because they use different technologies. In a future network environment, users will increasingly use mobile devices that support multi-mode and multi-access functionality, which means that a single mobile device will be able to provide services by accessing different access networks (e.g., CDMA, *High Speed Downlink/Uplink Packet Access (HSDPA/HSUPA)*, WLAN, Bluetooth, *Global System for Mobile Communications (GSM)*, *General Packet Radio Service (GPRS)* and IEEE 802.16 based Mobile *Worldwide Interoperability for Microwave Access (WiMAX)*) provided by one or more network providers [4, 5, 6].

Therefore, mobility management is very important when trying to achieve *seamless mobility* in a heterogeneous network environment. The goal of seamless mobility is to provide simple, uninterrupted access to any type of information desired at any time, independent of place, network, and device [7, 8]. For example, it could enable access to mobile multimedia content by automatically switching between protocols, networks, frequencies, and physical environments. This allows the user to be continuously connected to relevant content that is automatically synchronized, while individual content preferences are used to provide an environment that conforms to the needs of the user.

In cellular-based networks, "*handover*" (or "*handoff*") is a well-known term, which refers to the process of transferring an ongoing call or data session from one channel connected to the core network to another [9]. There are two kinds of handover: horizontal and vertical. *Horizontal handover* occurs when the user switches between different base stations of the same access network, whereas vertical handover involves two different network interfaces that usually represent different access networks. In Figure I.1, horizontal handover occurs between WLAN and WLAN, whereas *vertical handover* occurs between WLAN and CDMA. As a result, an interesting problem has developed, which is how to decide the "*best*" access network and access point vs. base station to use for a given service at a given moment. This thesis hypothesizes that the optimal handover decision for personalized services must include one or more metrics that express the needs of the user and the current status of existing networks.

1.2 Motivation and Problem Statements

Our research motivation is determining what problems can occur during handover to achieve seamless mobility in the heterogeneous wireless networks, as described in Section 1.1. There are two major research topics for achieving seamless mobility: the handover decision making algorithm and the handover protocol design. In this thesis, we focus on handover decisions. Traditionally, horizontal handover decisions have been based on the manual evaluation of the *Received Signal Strength (RSS)* at the mobile device to support *Always-Best-Connected (ABC)* communication [10, 11, 12]. Whereas, vertical handover decisions have been performed by end user's manual selection.

The handover decision is more simple in a homogeneous than a heterogeneous environment. In a homogeneous environment, it determines whether or not to initiate the handover, and (in cellular networks) the specific cell for the handover. As we mentioned earlier, it is pointed out that the need for horizontal handover arises when the RSS of the serving *Base Station (BS)* deteriorates below a certain threshold value. In a heterogeneous environment users can move between different access networks that have different functionality. They can potentially benefit from different network characteristics (coverage, bandwidth, latency, power consumption, cost, etc.) that cannot be directly compared. The handover process is more complex in such an environment when compared to a homogeneous one. For example, we can use our mobile devices at different locations, such as at the home or office. Furthermore, we can use our mobile devices in different countries by roaming.

End users require different user profiles for many reasons. For example, different locations provide different services and environmental conditions for the handover decision. Furthermore, there are a number of access network operators, Internet service providers, application service providers, and device manufactures that provide different service and device capabilities. There are many different types of users that have different preferences. In addition, mobile devices increasingly are continuously adding more functions, and end users use their mobile devices during different types of mobility such as walking, driving, or using the train or bus. Because the heterogeneous wireless networks have such characteristics, the traditional approach, RSS-based handover decision, is not appropriate to support handover. Therefore, the more challenging problem is the handover decision [13]. Moreover, end users want to use mobile services simply, conveniently, and with high performance, regardless of any technical aspect such as access networks or handover, since the average users do not have much knowledge about access network technologies and mobile services. For example, one of the problems of seamless mobility is that seams are produced when the user switches between devices or technologies. This is usually not desired, as this interrupts the continuity of the user experience.

The current handover decision methods based on RSS or pre-defined simple policies do not provide good solutions for simple cases, let alone for seamless mobility, because they do not take into account services that satisfy the preferences of a user at a given time, location, and/or application context. Therefore, handover decisions should be based on additional considerations, such as the capacity of each network link, usage charge of each network connection, power consumption of each network interface, battery status of the mobile device, and user preferences. We call these and similar data *context* information. The approach in this thesis is to develop a rich contextual understanding of the operating environment of the user's mobile, including networks, systems, services, and user aspects. We will use the contextual data to develop a more intelligent and novel method to manage handover decisions in terms of the end user's personalized requirements.

One scenario for motivating our research is as follows. When we use our mobile device in heterogeneous wireless networks, we encounter many situations where we should select a potentially different access network for different types of applications such as voice calls, streaming services and file transfer applications. Assume that we have a unique user profile based on our own user preferences, and that there is context information available from networks, mobile nodes, and users for deciding handover for mobile services [14]. In this environment, when a user wants to use a voice call application, which access network is best suited for that application? For example, is the access network that has the highest quality best? In this context, the term "best" means that the "best" access network is the network that best satisfies the functional and non-functional requirements of the user. The novelty of our approach is in using a combination of functional and non-functional requirements, filtered by the particular context. Hence, if the only consideration is high quality, then the network *with the highest quality* is the best one. However, if the user wants to use a voice call *with high quality and low price*, the network with the highest quality many no longer be the best one, since its price may be too high.

Our proposed method in this thesis is differentiated from other approaches by focusing on *satisfying the end user's personalized needs.* We provide an answer to the question "*Are you happy? (RUH)*" when end users use services on their mobile devices in different environments. We propose a way to determine the *Access*

Network (AN) and *Access Point (AP)*[1] that best satisfy for the current service with RUH scores based on context information, application requirements, *Service Level Agreement (SLA)* data, and user profile and user preference information. RUH scores measure the user's personalized satisfaction with their services based on their own preferences in a given environment.

As we mentioned before, when a user wants to use a voice call application with high quality and low price, traditional approaches can only provide *high quality or low price* because they typically only optimize one parameter. Hence, this thesis focuses on multiple parameter optimizations, and recommends the AN and AP which has *both high quality and low price* by determining RUH scores.

In this thesis, we concentrated on the following key questions.

- What are the limitations of the current handover decision management approaches for personalization?
- How can we provide intelligent decision making for personalized handover?
- How can we manage and represent different types of context data from different sources?
- How can we combine different context data from different sources and develop a single comprehensive understanding of context?
- How can we efficiently rank target access networks and access points according to user preferences and mobile application requirements?

[1]An AP or a Wireless Access Point (WAP) is a term of WLANs. In this thesis, an AP is a general term which represents a device that allows wired communication devices to connect to a wireless network using Wi-Fi, Bluetooth, CDMA, HSDPA, Bluetooth or related standards. That is, an AP includes a WAP for WLAN, a BS for CDMA, a Radio Access Station (RAS) for mobile WiMAX, and so on.

- How can we provide a user-friendly mechanism for determining the best access network and access point to use to meet the personalized needs of a user of a particular service, independent of location?

1.3 Objectives and Scope

This thesis proposes a novel autonomic handover decision method for satisfying the end user's demand for different types of services in converged networks by using fuzzy logic and utility functions as part of the decision-making process. We call it *AUHO*, which is an abbreviation for ***AU****tonomic* ***H****and****O****ver*. Our approach proposes a handover decision process based on a three-phased process to find the network that can best fulfill the user's requirements. The three phases are *Network Detection*, *Network Evaluation*, and *Handover Execution* [15, 16]. Network detection is used to discover available access networks and collect appropriate metrics to evaluate them. Handover evaluation uses the collected information as input to evaluate the available access networks and to select the network best capable of satisfying the user's request at a particular time. We name such a network an "*Always-Best-Satisfying (ABS)*" network. As we mentioned earlier, previous handover management has focused on *Always-Best-Connected (ABC)* networks. However, current and future applications that wish to offer intelligent handover decisions for personalized services should consider ABC as well as ABS. The ABS network provides both always-on-connectivity as well as the best service according to the user's preference at any time or place. Our proposed method supports "Context-aware ABS (CABS)" to satisfy user preferences with available context information, and uses fuzzy logic inferencing to evaluate different types of context information. This is an important factor for providing personalized services, since context can affect the resources and services available to a mobile. In this thesis, we focus on not handover execution but handover decisions. Handover execution is beyond scope of this thesis.

First of all, we review previous work on autonomic computing and autonomic networking for building our autonomic management architecture for handover decisions. We design an adaptive control loop and autonomic architecture based on the FOCALE, which is the abbreviation of *Foundation, Observation, Comparison, Act, Learning*, and *rEasoning*, autonomic architecture [17], because it is well-defined and widely adapted for autonomic network management. Then, we compare previous approaches for handover decision management, which is called access network selection, cell selection, and vertical handover decision strategies, to our AUHO. We then present our hypothesis, assumptions, motivating scenarios, and research methodologies for solving the problems mentioned. Then, we introduce context information for handover decisions that are available from mobile devices, networks, users, and services. Then, we present our design of an information model that represents mobile and network devices, policy rules, user preferences, and user profiles for heterogeneous devices. This enables us to integrate different data sources, and also supports developing different data models to suit the needs of different applications. We then show how this model is used in our autonomic architecture to support handover decisions.

Then, we present our novel decision making algorithm for personalized handover decisions. For supporting it, we define two objective metrics for evaluating performance of APs: a) "Access Point Acceptance Value (APAV)" and b) "Access

Point Satisfaction Value (APSV)". The former represents the degree of accepting an AP by end users based on the given user preference metrics (i.e., received signal strength, quality of service, cost, or battery lifetime) and application requirements. The latter represents the degree that an AP satisfies the end user based on his or her user profile which include weights of each user preference item. Our algorithm supports the selection of the best AP (horizontal handover decisions) as well as the best access network (vertical handover decisions) using current user preferences and profile data, application requirements, and context information.

We then present an autonomic architecture that uses a control loop based on the FOCALE autonomic architecture [17]. We evaluated our proposed method using some case studies that we created on our own network simulator which was developed for testing mobile communications and performance of handover decision algorithms in a heterogeneous wireless network environment. The simulator can incorporate external traffic data from ns-2 [18]. The results of our simulation show that our proposed method outperforms other decision algorithms, which are Random, RSS-based, Cost-based, QoS-based, and Lifetime-based decision-making algorithms, when using end user satisfaction as the main criterion.

In this thesis, we recommend one access point for a specific application based on user preference and profile data. We do not focus on the total handover process, but rather on the handover decision. Our handover decision algorithm is one of the core modules in handover systems, and it is flexible and scalable enough to incorporate into most handover systems.

1.4 Contributions

The main contributions of this thesis are summarized as follows.

We introduce extensions to the DEN-ng information model to support *autonomic management of personalized handover decisions* because the current DEN-ng information model lacks detailed mobile devices and handover decision information. Our method enables users to easily select the optimal access network and access point for each service based on a set of preferences.

Our approach provides a concrete guide for developing an autonomic management system by using the FOCALE autonomic architecture to be used for intelligent handover decisions in heterogeneous wireless networks.

Our proposed method is differentiated from other approaches by its attention to end user satisfaction. Our method provides the answer to the question "*Are you happy?*" when an end user uses applications on his or her mobile device. We calculate which access network and access point best satisfies the current service needs by using RUH scores, which are evaluated using context and application requirements. We define the RUH scores in terms of APSVs in this thesis.

Our proposed method provides *seamless roaming* based on personalization by monitoring the current context (e.g., location, time, or tasks performed) of the user and *adjusting* the access network and/or access point based on changes in context *without requiring any direct user actions.*

Our proposed method calculates the APAV using fuzzy logic inferencing, and calculate the APSV by evaluating utility functions. This enables our method to *personalize* the access network selection by weighting the contribution of user-centric, context-aware, fuzzy-logic based, and utility-function based approaches to best suit the needs of the user and the applications being used for *that particular context.* We provide a proof of concept for *seamless mobility.*

We describe *real-world use cases*, and how autonomic management mechanisms are used to provide a good solution. We present how common end users can use a mobile services at their mobile devices simply, conveniently, with high quality based on their own preferences without complex manual settings.

Our proposed method provides a *more robust cognition to the Cognitive Radio (CR)* domain than current implementations. Current CR technology is not focused on the cognition process as defined in psychology and cognitive science (i.e., the process of understanding data in order to make an intelligent decision based on those data), but instead focuses on utilizing radio spectrum flexibly. Our method provides context information for making a cognitive decision, and a feedback control loop for selecting and managing the best (or optimal) radio parameters for that context.

We provide an *extensible network simulator* for validating the work of this thesis; this simulator can be reconfigured for testing other handover decision algorithms as well. Most network simulators focus on low-level network protocol implementation, and do not address handover decisions in a heterogeneous network environment. Our simulator is used to evaluate different aspects of handover decisions. Anyone can use this simulator for testing and comparing other handover decision algorithms without implementing low-level protocols. We have implemented six handover decision algorithms (including our own), and hope that this can be used to contribute to future research for handover decisions.

1.5 Thesis Organization

The organization of this thesis is as follows. Chapter II describes autonomic management and handover decision management as related work. Chapter III introduces our research hypothesis, assumption, and methodologies for designing and implementing our solution for autonomic management of personalized handover decisions; it also includes some useful use cases. Chapter IV first presents our decision making algorithm and autonomic management architecture, and then describes our proposed AUHO based on fuzzy logic and utility functions. In Chapter V, we present our implementation of AUHO and a network simulator tool for testing handover decisions in heterogeneous wireless networks. In Chapter VI, we present an evaluation and its results for validating our proposed method with case studies. Finally, Chapter VII concludes the thesis with a summary, hypothesis validation, and contributions and suggests possible future work to extend AUHO.

Chapter II

RELATED WORK

In this chapter, we introduce autonomic computing and networking which are important for supporting the concept of autonomic management. We then describe the FOCALE autonomic architecture and DEN-ng information model, which are used to support our handover decision management architecture. We then review some exemplary work on handover decision strategies used by mobile devices for access network selection or vertical handover. Finally, we compare our proposed method with previous approaches.

2.1 Autonomic Computing

Advances in computing and communication technologies have resulted in explosive growth in computing systems and applications that impact all aspects of our lives. However, as the scale and complexity of these systems and applications grow, their development, configuration and management challenges are beginning to break current paradigms, overwhelm the capabilities of existing tools and methodologies, and rapidly render the systems and applications brittle, unmanageable and insecure [19]. This has led researchers to consider alternative approaches based on strategies used by biological systems to successfully deal with similar challenges of complexity, dynamism, heterogeneity and uncertainty [19, 20, 21, 22, 23, 24, 25].

In 2001, IBM proposed "*Autonomic Computing*" as a systematic approach for achieving computer-based systems to manage themselves without human interventions based on the autonomic nervous system [26, 27, 28, 29, 30, 31]. It is emerging as a significant new strategic and holistic approach to the design of complex distributed computer systems. Inspired by the functioning of the human nervous system, the goal of Autonomic Computing is to manage the complexity, heterogeneity, and uncertainty of the system.

More specifically, an autonomic system is a self-managing system that hides its complexity, to users and operators of the system with an interface that exactly meets her/his *needs*. The system will make decisions on its own, using high-level guidance from humans. It will constantly check and try to optimize its status, and automatically adapt itself to changing conditions. Self-management is achieved through key functions such as *self-governance, self-adaptation, self-organization, self-optimization, self-configuration, self-diagnosis, self-protection, self-healing*, and *self-recovery*. This is done by using policy rules based on self-* functions and environmental-awareness and knowledge. Meeting these challenges of autonomic computing requires scientific and technological advances in a wide variety of fields, and new architectures that support effective integration of the constituent technologies.

An autonomic computing system is based on knowledge, both of itself and of its environment. It uses these sources of knowledge to provide *self-configuring, self-healing, self-optimizing*, and *self-protecting* functions that constitute self-management. Many studies based on this concept have explored different types of autonomic systems [19, 32, 33, 34, 35]. These four self-properties all have the objective of reducing the amount of work required by people; the reduction of this work is achieved by either the system directly doing the work, or by the system gathering, analyzing, and correlating results to simplify decisions that must be made by end-users and operators.

IBM proposed a control loop called *MAPE (Monitor, Analyze, Plan, and Execute)* which dissects the loop into four parts that share knowledge as shown in Figure II.1. The MAPE control loop represents an *Autonomic Element (AE)* which consists of a managed element and an *Autonomic Manager (AM)*. An autonomic manager is responsible for governing a set of components. It automates some management functions and externalizes those functions using a set of management interfaces. This provides a consistent management interface to the external world, and also enables different AEs to communicate.

The AM's functions are as follows: [26]

- **Monitor** function provides the mechanisms that collect, aggregate, filter, and report details collected from managed resources by sensors.

- **Analyze** function provides the mechanisms that correlate and model complex situations. These mechanisms allow the autonomic manager to learn about the environment and help predict future situations.

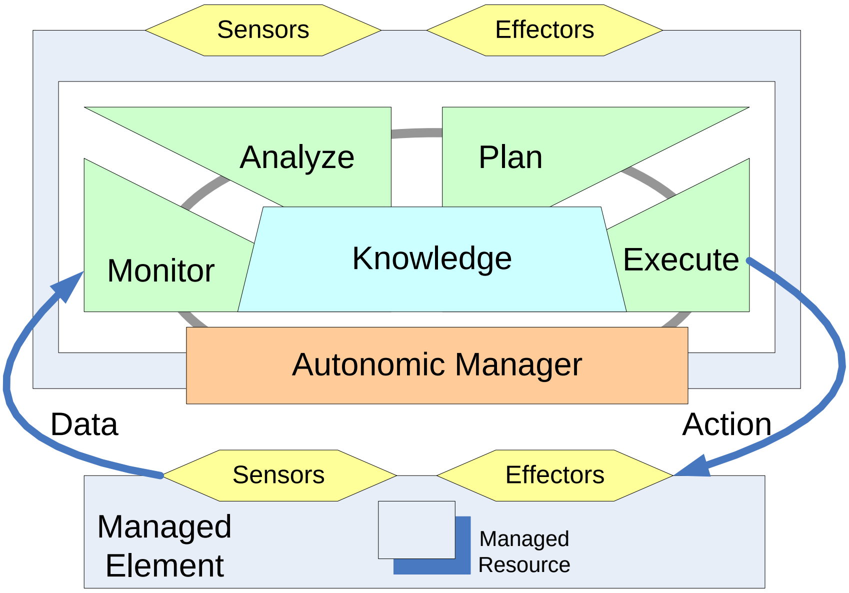


Figure II.1: The architecture of autonomic element by IBM (MAPE)

- **Plan** function provides the mechanisms that construct the actions needed to achieve goals and objectives. The planning mechanism uses policy information to guide its work.

- **Execute** function provides the mechanisms that control the execution of a plan with considerations for dynamic updates by effectors.

These four parts communicate and collaborate with one another and exchange appropriate knowledge and data to achieve autonomic management. However, self-* functions, which we mentioned previously, cannot define an autonomic system [36]. These are benefits resulting from an autonomic system. An autonomic system is rooted in the following capabilities: 1) we need self-knowledge because we cannot configure what we do not know; 2) we need the ability to understand what is happening to our surroundings by learning from and reasoning using sensed data; 3) we need new ways to build and organize management functionality by inspiration from biology, sociology, economics, and so on.

2.2 Autonomic Networking

Autonomic Networking follows the concept of Autonomic Computing. Its ultimate aim is to create self-managed networks to overcome the rapidly growing complexity of the Internet and other networks and to enable their further growth, far beyond the size of today [36]. Many researchers and research projects are now investigating how the principles and paradigms of nature can be applied to networking [37]. Instead of a layering approach, Autonomic Networking targets a more flexible structure termed *compartmentalization*. The goal is to produce an architectural design that enables flexible, dynamic, and fully autonomic formation of large-scale networks in which the functionalities of each constituent network node are also composed in an autonomic fashion. Functions are divided into atomic units to allow for maximal re-composition freedom. A fundamental concept of Control Theory, the closed control loop, is among the fundamental principles of Autonomic Networking. A closed control loop maintains the properties of the controlled system within desired bounds by constantly monitoring target parameters.

2.2.1 FOCALE Autonomic Architecture

FOCALE was proposed as a novel Autonomic Networking architecture. It is the abbreviation of *Foundation, Observation, Comparison, Act, Learning*, and *rEasoning*, which is based on the observation that business objectives, user requirements, and environmental context changed dynamically [17, 36, 38]. Therefore, a single, statically defined, management control loop is insufficient; FOCALE uses a set of adaptive control loops.

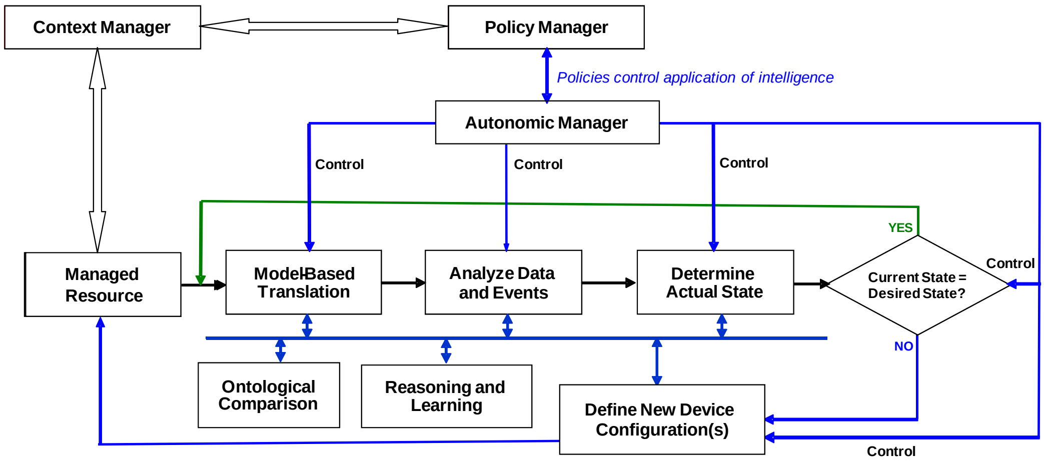


Figure II.2: Simplified FOCALE autonomic architecture

Figure II.2 shows a simplified version of the FOCALE autonomic architecture, which we used for making handover decisions with our autonomic architecture. Multiple networks and network technologies require multiple control planes that can use completely different mechanisms; this makes managing an end-to-end service difficult, since different management mechanisms must be coordinated. FOCALE addresses this through model-based translation, which uses a combination of models and ontologies to translate disparate sensed data into a *lingua franca*. In current environments, user needs and environmental conditions can change without warning. Therefore, the system, its environment, and the needs of its users must be continually analyzed with respect to business objectives. FOCALE uses inferencing to instruct the management plane to coordinate the (re)configuration of its control loops in order to protect the current business objectives of the organization.

The key to the FOCALE adaptive control loops is the interaction between the context manager, policy manager, and autonomic manager. Conceptually, the context manager detects changes in the network, or in user needs, or even in the business; these context changes in turn trigger a new set of policies to take over control of the autonomic system, which enables the services and resources provided by the autonomic system to adapt to these new needs given that appropriate policies are available for the new context. The autonomic manager uses these policies to govern each of the architectural components of the control loop, enabling the different control loop components to change the type of algorithm used, the type of function used, and even the type of data used as a function of context. A system built in accordance with FOCALE is self-governing, in that the system senses changes in itself and its environment, and determines the effect of the changes on the currently active set of business policies. In general, those changes could either cause a new set of business policies to be activated, or endanger one or more goals of the currently active set of business policies. In the latter case, FOCALE reconfigures the system to ensure that the currently active set of business policies is not violated and observes the results. FOCALE responds to both changing user needs as well as changing conditions in the business and the network infrastructure through the use of a Policy Continuum [39, 40], which is a mechanism to translate policies for one constituency (e.g., business people) to a form for another constituency (e.g., network administrators).

FOCALE implements two control loops: a maintenance control loop is used when no anomalies are found; an adjustment control loop is used when one or more policy-based reconfiguration actions must be performed, and/or new policies must be deployed. Because it is unreasonable to assume that a single entity can maintain all the information required to realize the FOCALE control loops for large scale networks containing large numbers of heterogeneous devices (in terms of available functionality, vendor-specific programming model, and specific configuration), FOCALE is implemented as a distributed architecture, to the degree that even individual network devices may incorporate autonomic management software, implementing the maintenance and adjustment control loops. FOCALE assumes that any managed resource (which can be as simple as a device interface or as complex as an entire system or network) can be associated with an *Autonomic Management Element (AME)*, by interfacing the functionality of the managed resource to the functionality of an *Autonomic Manager (AM)* in Figure II.2 using a *Model Based Translation Layer (MBTL)* in Figure II.2.

AMEs can be modularized to first form a uniform *Autonomic Management Domain (AMD)* and then to an AME; with each level containing policy, security, discovery, context, and analysis services that serve to harmonize the operation of the AMEs/AMDs. The autonomic management architecture contains two main functional components: the AM and the MBTL. The AM is independent of the vendor-specific functionality/data of the underlying managed resource(s), which facilitates easier communication between AMEs for coordination of management decision making. Each AM realizes the autonomic management functionality described in the previous section via an event manager, a state manager, an action manager, a reasoner, a learner, and a policy analyzer/ policy decision point (PDP). All these subcomponents can communicate with each other using an event bus. Communication is done by representing entities as objects from the DEN-ng information model [41] which we will present in Section 2.2.2. This is done to represent the current state of the AME's managed resource(s) in a uniform way. This set of data constitute *facts*; ontologies are used to *reason* about the facts and take action using the context-aware policy rules defined in DEN-ng to govern the AME's managed resource(s). When the AM receives context information via the MBTL, the policy analyzer/PDP ascertains if the conditions of any deployed policies are satisfied; if they are, then the corresponding actions are executed by transforming them into device-specific commands via the MBTL.

If the policy analyzer/PDP determines that the context is changed, then it examines the set of active policies, unloads those that are no longer applicable, and loads any new policies that pertain to the new context. If the policy analyzer/PDP does not recognize the context, then either a new context has been found that was not previously modeled, or an error has occurred. In either case, it contacts the event and state managers, which use the models/ontologies to try to match the newly found context (either by structural matching or through inference) to context descriptions/definitions in either the model and/or the ontology. The system then determines if the system is in a known state in the state machine. If it is not, then the state machine is modified; this is beyond the scope of this thesis. Otherwise, the system checks to see if the newly identified state is equal to an acceptable state. If it is not, the state manager employs the reasoner to identify actions that will lead the system back toward its desired state. Once identified, the action manager coordinates the enforcement of these actions by the policy analyzer/PDP. Subsequently, the learner monitors the effectiveness of actions identified in this manner;

if successful, these actions are codified as one or more policies that then are added to the set of system policies.

AMs also have the ability to communicate with other AMs to complete management operations, or to coordinate activities such as analyzing the global network state or introducing new policies. One of the fundamentally important ways that FOCALE distributes its management functionality is through collaboration. That is, instead of assuming that a single AM has the power to finish a task, FOCALE supports using multiple AMs to self-organize to form a new, more powerful, AM that can complete the task.

The AM uses a single internal language to represent data and commands. The function of the MBTL is to translate vendor-specific data and commands to and from this internal language. Therefore, unlike the AM, the MBTL must have in-depth knowledge of the managed resource(s) to enable it to translate normalized vendor-specific data gathered from the managed resource(s) into DEN-ng compliant vendor-neutral data (context information) to pass to the policy analyzer/ PDP and vice versa for configuration commands. As alluded to in the previous section, DEN-ng can be readily extended with vendor specific information and data models (e.g., relating to new releases of *Command Line Interface (CLI)* command sets for a family of network devices). Assuming that the DEN-ng information model is extended in this manner for all the managed resource(s), and furthermore, that the system ontology is extended to incorporate semantic information detailing the meaning of various vendor specific data/commands, the MBTL can employ ontological engineering techniques, including semantic similarity matching, to map between DEN-ng vendor neutral representations and vendor specific representations.

In this section, we described the concept of autonomic computing and autonomic networking for supporting which we will use for supporting autonomic management of handover decisions. We will use a maintenance control loop and an adaptive control loop for dynamically determining the best AP for the end user based on the autonomic concept.

2.2.2 The DEN-ng Information Model

The DEN-ng [41] is an object-oriented information model that describes different entities of interest in the managed environment. We use it to build a technology-neutral information model (i.e., a model that is independent of technology, platform, and protocol) describing important concepts and mechanisms to represent, measure, and manage networks. The DEN-ng model uses software patterns [42] to more efficiently describe complex architectures and make the model more understandable and extensible. A pattern defines a generic, reusable solution to a commonly occurring problem. When we design a model, we can improve our model's readability by defining software patterns and repeatedly using them in solving similar problems. Two common patterns are the composite pattern [42] and the role-object pattern [43]. The composite pattern is used to define bundles, groupings, and other hierarchical and network-oriented structures that represent part-whole hierarchies. The role-object pattern enables a component object to be adapted to different needs through transparently attached role objects. This pattern is especially useful in separating the intrinsic and contextual characteristics and behavior of an entity. A person is thus modeled as an object that can have multiple roles attached; each role defines different responsibilities and functions of that person. This avoids the trap of altering the definition of a person due to changing responsibilities. The role-object pattern is also useful for other types of entities, and is used extensively in the DEN-ng model. The policy pattern is an example of a novel DEN-ng pattern. It provides policy-based management governance. In this pattern, policy rules are used to determine the characteristics and behavior of an association using an association class. The association class represents the semantics of a relationship as a class, which enables the relationship to have a set of associated attributes, relationships, and other model elements as required. The attributes (and possibly additional relationships) of the association class are then modified by the policy rules. In DEN-ng, this enables changing context to select new applicable policy rules, which then change the attributes and/or relationships of the selected association accordingly.

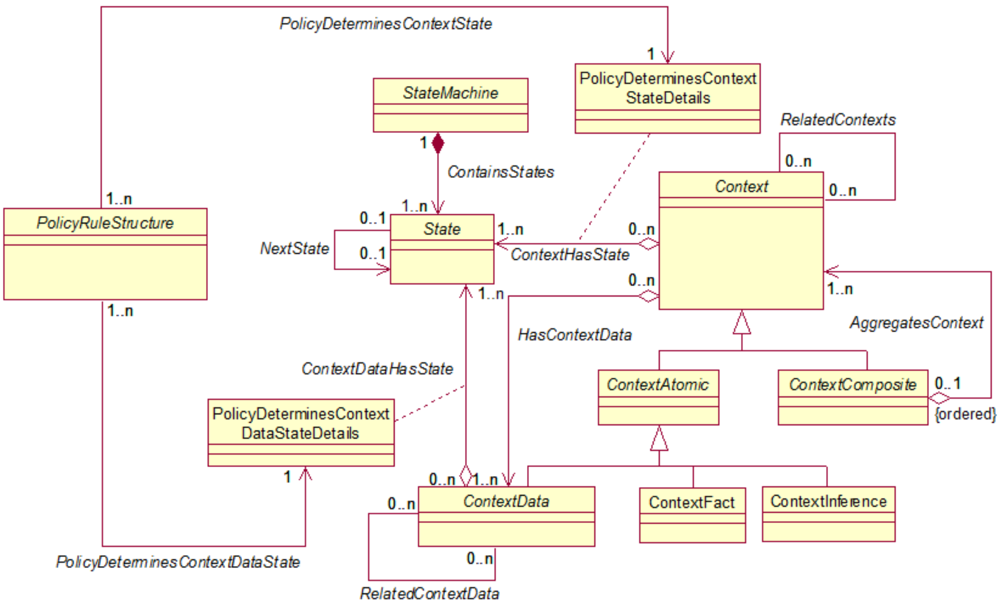


Figure II.3: Simplified extract of the DEN-ng context model

Figure II.3 shows a simplified extract of the DEN-ng Context model. The Context object models the complete context of a situation, and can be made up of a set of ContextData objects, which each represent a unique aspect of the overall context. The Context and the ContextData objects are implemented as intelligent containers, and contain metadata as well as content to describe their information. The composite pattern is used to enable hierarchies of Context and ContextData objects to be created in a consistent manner. In this approach, a ContextAtomic (or ContextDataAtomic) object represents Context (or an aspect of Context) when it can be modelled as a single, stand-alone object. In contrast, the ContextComposite (or ContextDataComposite) objects represent objects that are made up of multiple distinct Context (or ContextData) objects that can be separately managed. For example, when modeling a phone call that can involve handover between two different technologies, we instantiate two different aspects of context, each consisting of a collection of ContextData object instances that is bound to a particular technology. This enables us to better manage the phone call (which is modelled as an instance of the Context object), since the underlying technologies are themselves fundamentally different. Sensor data describing each ContextData is retrieved from a set of device converters, which translate vendor-specific data into a normalized form. The normalized form of each sensor data object is then analyzed to determine if it is a valid Context or ContextData object. If not, it is discarded; if so, it is added to the appropriate data model. The set of ContextData objects are then analyzed to determine the current state of the managed entity; this information is then sent to the next module.

In this section, we presented the DEN-ng information model which will support our AUHO, and the role that its Resource, Service, Context, Profile, Preferences, and Policy sub-models will play. We will use the DEN-ng information model for designing context information, policy rules, user profile, and preferences for handover decisions.

2.3 Handover Decision Management

Handover is the process of maintaining a user's active session(s) when a mobile device changes its connection point to an access network, (e.g., a base station or an access point) [44]. Depending on the access network that each point of attachment belongs to, the handover can be either *horizontal* or *vertical* [45]. A horizontal handover takes place between points of attachment supporting the same network technology, (e.g., between two neighboring base stations of a cellular network). On the other hand, a vertical handover occurs between points of attachment supporting different network technologies, (e.g., between an IEEE 802.11 access point and a cellular network base station). A handover process can be split into three stages: handover decisions, radio link transfer, and channel assignments. A handover decision involves the selection of the target point of attachment and the time of the handover. Radio link transfer is the task of forming a link to the new point of attachment, and an channel assignment deals with the allocation of channel resources [46].

Handover decision algorithms choose the best access point (horizontal) or access network (vertical) for a mobile to connect to among all the available candidates. Handover decision strategies are very important for achieving seamless mobility

[47, 13, 48, 46]. In this section, we present previous approaches for handover decision strategies proposed in the literature. We divide these studies into six categories based on the metrics or techniques to use for handover decisions [13]: 1) RSS-based, 2) cost function-based, 3) user-centric, 4) Artificial Intelligence (AI) approaches, 5) multiple-criteria decision-based, and 6) context-aware approaches. In general, compared to our AUHO approach, none of these approaches provide sufficient flexibility in satisfying user needs, and most cannot adapt to changing context. Additional details on each algorithm are provided in the following sub-sections.

2.3.1 RSS-based Approaches

In this group of approaches, RSS is used as the main handover decision criterion. Various strategies have been developed to compare the RSS of the current point of attachment with that of the candidate point of attachment [49, 50, 51]. In [52], RSS based horizontal handover decision approaches are classified into the following five subcategories: relative RSS, relative RSS with threshold, relative RSS with hysteresis, relative RSS with hysteresis and threshold, and prediction mechanisms. For vertical handover decisions, relative RSS is not applicable, since the RSS from different types of networks cannot be compared directly due to the disparity of the technologies involved (e.g. separate thresholds are required for each technology). Furthermore, other network parameters such as bandwidth are usually combined with RSS in the vertical handover decision process. In this thesis, we also consider the RSS as a handover decision metric.

In summary, these approaches have been used widely for handover decisions due to simple measurement, but it lacks to apply to vertical handover decisions because of different characteristics of the heterogeneous wireless access networks. So, we need to consider other information as well as RSS.

2.3.2 Cost Function-based Approaches

A vertical handover decision cost function is a measurement of the benefit obtained by handing over to a particular network. It is evaluated for each network n that covers the service area of a user. It is a sum of weighted functions of specific parameters. The general form of the cost function f_n of a wireless network n is Equation II.1 [53].

$$f_n = \sum_s \sum_i w_{s,i} \cdot p^{n_{s,i}} \tag{II.1}$$

$p^{n_{s,i}}$: the cost in the ith parameter to carry out service s on network n; $w_{s,i}$: the weight (importance) assigned to using the ith parameter to perform services (with $\sum_i w_i = 1$). Wang et al. [54] proposed a policy-based handover scheme, where the authors designed a cost function to decide the "best" moment and interface to execute a vertical handover. The parameters used are bandwidth B_n that network n can offer, power consumption P_n of using the network device for n and monetary cost C_n of n. The cost of using a network n at a certain time, with $N(i)$ as the normalization function of parameter i is defined as:

$$f_n = w_b \cdot N(1/B_n) + w_p \cdot N(P_n) + w_c \cdot N(C_n) \tag{II.2}$$

The network that is consistently calculated to have the lowest cost is chosen as the target network. However, the cost function presented in the paper is very simple and cannot handle sophisticated configurations. The logarithmic function used in the cost function also has difficulty in representing the cost value when the value of the constraint factor is zero (i.e., the connection is free of charge) .

A number of papers use similar cost functions in the handover decision process. Chen et al. [55] proposed an adaptive scheme based on the handover decision process described in [54]. The authors use the utility function (higher utility == target network), to evaluate the reachable wireless networks discovered (bandwidth and movement speed as factors) and to quantify the Quality of Service (QoS) provided by the wireless network on the mobile terminal. However, it did not consider user's needs and application requirements for handover decisions.

Angermann and Kammann [56] proposed another scheme to model the handover with HTTP traffic, but it has problems with other types of traffic, such as video and audio streaming, where the bandwidth demand is much higher than HTTP traffic.

Chen et al. [57] proposed a smart decision model to perform vertical handover to the "best" network interface at the "best" moment; this was tested on the *Universal Seamless Handover Architecture (USHA)*. The smart decision model is based on the properties of available network interfaces (e.g., link capacity, power consumption and link cost), system information (e.g., remaining battery) and user preferences. Although the model presented a detailed example on the USHA test-bed, it did not describe, in enough detail to reproduce results how to calculate the properties and the meaning of cost value.

In [58], an optimized cost function is used to evaluate the target network (based on QoS factor) establishing a tradeoff between user satisfaction (gains in QoS) and network efficiency. The cost function is applied on two vertical handover policies, one for all the user's active sessions collectively (i.e., all are handed over to the same target network) and one for each of the user's active sessions independently (with prioritization). All the described decision approaches were evaluated on two types of networks: WLAN and GSM (or GPRS). However, these approaches do not evaluate user satisfaction, which is the main purpose of the user-centric approaches presented in the following section.

2.3.3 User-Centric Approaches

Among the different criteria that a vertical handover decision takes into account, user preferences, in terms of cost and QoS, are the most interesting policy parameter for a user-centric strategy. In [59], a model is proposed based on a handover decision evaluated, from the user point of view, as the most convenient handover to his specific needs (cost and QoS). The authors propose two handover decision policies (fixing a threshold value) between GPRS and WiFi networks: a) the mobile terminal will never abandon GPRS connection without connections and b) the algorithm searches for just WiFi access points with connection. In order to find the optimum handover decision policy maximizing performance, they define a cost function as follows:

$$C = T_{WiFi} \cdot c_{WiFi}(h) + T_{GPRS} \cdot c_{GPRS}(h) \tag{II.3}$$

T_i: the time spent by the user in the ith access network;
$c_i(h)$: the fee per unit of time (second) that the operator of the ith access network charges to the user;
C: the monetary cost faced by the user for a given communication session.

This work proves that the willingness to pay expressed by the user can be satisfied when adopting a suitable handover decision policy. However, this approach did not use a feedback control loop; therefore, it is unable to adapt to changes in the environment or in policies.

Hasswa et al. [60] proposed a vertical handover decision function to allow the user to strategically prioritize the different network characteristics such as network performance, user preference, and monetary cost. This function is simple and can be easily applied to any vertical handover approach. The authors presented some characteristics for creating a decision function such as the cost of service, security, power requirements, proactive handover, quality of service and velocity of the mobile device. However, this study did not describe in enough detail how to define each characteristic property in order to reproduce its results. In addition, it did not provide a detailed example to validate the decision function. Finally, it did not consider the cost function in terms of the service or the application.

Ormond et al. analyze only user satisfaction by using a utility function for non-real-time data services (i.e., an FTP application) [47, 61]. The network selection decision algorithm is based on consumer surplus value, which is the difference between the monetary value of the data transferred and the actual price charged, within a predicted transfer completion time. Thus, if the price that the user pays for the transfer is less than the value they were willing to pay it is useful for the user to save money. In order to choose the appropriate utility function, the decision metrics are the user's risk attitudes: neutral (user prefers paying less and experiencing less delay equally), seeking (user prefers less delay to assured money saving) and adverse (user prefers to be certain of paying less). However, the authors do not consider other factors for user satisfaction.

Nguyen-Vuong et al. proposed user-centric network selection, power-saving interface management, and adaptive handover initiation solutions at the terminal side to support seamless terminal-initiated and terminal-controlled vertical handover [62]. The authors employed a novel multiplicative aggregate utility approach to best evaluate the candidate access networks in terms of user-centric decisions. However, the authors do not consider how to evaluate different types of context data for decisions.

The described user-centric functions propose handover decision policies and criteria mainly for user satisfaction and non-real-time applications. In order to determine the most appropriate network for user satisfaction and network efficiency, more network criteria and more advanced mechanisms have to be considered.

2.3.4 Multiple Attribute Decision-based Approaches

The handover decision problem selects among a limited number of candidate networks from various service providers and technologies with respect to different criteria. This is a typical *Multiple Attribute Decision Making (MADM)* problem, which deals with choosing from a set of alternatives which are characterized in terms of their attributes. These are four popular classical MADM methods: *Simple Additive Weighting (SAW)*, *Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)*, *Analytic Hierarchy Process (AHP)*, and *Grey Relational Analysis (GRA)* [63, 16]. In SAW, the overall score of a candidate network is determined by the weighted sum of all the attribute values. In TOPSIS, the chosen candidate network is the one which is closest to the ideal solution and the farthest from the worst case solution. AHP divides the network selection problem into several sub-problems and assigns a weight value for each sub-problem. GRA is then used to rank the candidate networks and selects the one with the highest ranking.

A comparison of three of these models was established in [16], using four attributes (bandwidth, delay, jitter, and BER). It showed that SAW and TOPSIS provide similar performance to the traffic classes used. GRA provides a slightly higher bandwidth and lower delay for interactive and background traffic classes. AHP was used to determine the weights for the three models requiring information about the relative importance of each attribute. Results also showed that all four algorithms depend on the importance weights assigned to the parameters.

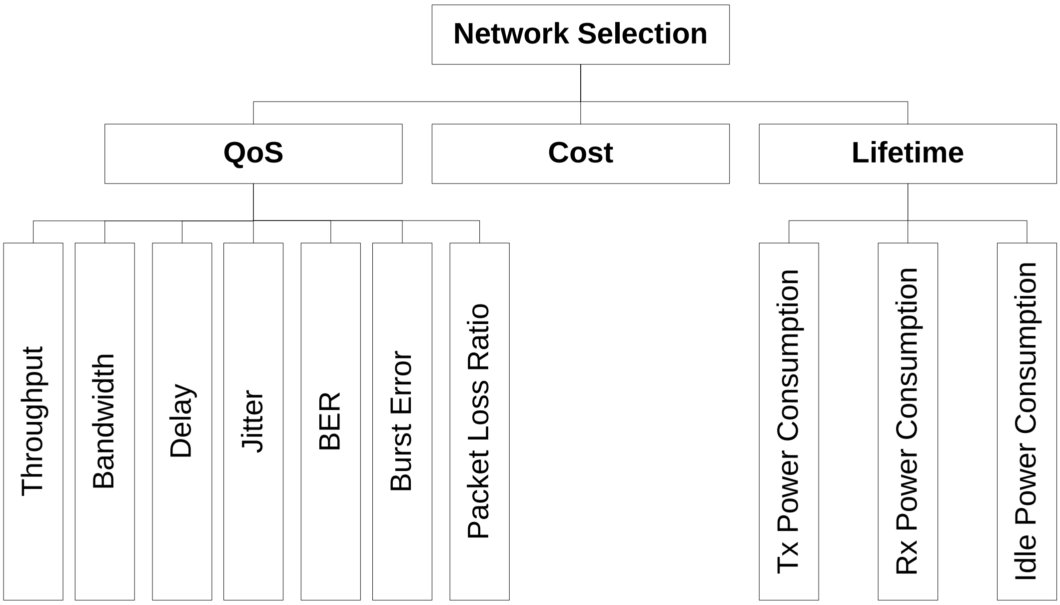


Figure II.4: AHP hierarchy for network selection algorithm

A network selection mechanism has been proposed combining AHP (to achieve weighting of QoS parameters based on user preferences and service application) and GRA (to rank the network alternatives) mechanisms in order to find a tradeoff between user preferences, service application, and network conditions [63, 64, 65]. The mechanism is divided into three logical function blocks: "collecting data"(which collects user preferences and network conditions), "processing data" (which processes user-based data by AHP and normalizes network-based data by GRA), and "making decision block" (which finalizes the process of balancing user preference, service applications, and network conditions). The structure of the AHP hierarchy for the decision algorithm is shown in Figure II.4. It used three global factors for network selection and two global factors, QoS and Lifetime, have local factors for network selection. The results revealed that it can work efficiently for an UMTS/WLAN/WiBro system and also reduce the complexity of implementation significantly. Whereas this approach presents multiple global factors for network selection and selects the best access network based on only one global factor, our AUHO determines the best access network and access point based on multiple global factors.

A QoS-guaranteed cell selection strategy in heterogeneous cellular systems was proposed based on a fuzzy multiple-objective decision method [66]. This cell selection algorithm includes the evaluation matrix definition, weight vector calculations, and a consistency check for the contrast matrix. The appropriate weight vector is selected according to the decision algorithm in the fuzzy multiple-objective decision cell selection. However, this method only considered QoS instead of user centric goals.

MADM is considered a well-known and proven mathematical process. However, MADM remains insufficient to handle a decision problem that exhibits inherent imprecision in its decision criteria. We require advanced methods, or a combination of classical and advanced methods, to get more efficient decision strategies. The following section discusses the application of these advanced AI mechanisms to handover decisions.

2.3.5 AI-based Approaches

The concepts of *Fuzzy Logic (FL)*, *Neural Networks (NN)*, Expert Systems, and *Genetic Algorithms (GA)* from AI can be used to choose when handover occurs and which network to choose among different available access networks. These AI mechanisms are combined with multiple criteria or attribute concepts in order to develop advanced decision algorithms for both non-real-time and real-time applications. Classical MADM methods cannot efficiently handle a decision problem that has inherently the imprecise data in its decision criteria. For such a decision problem, the use of FL not only deals with imprecise information but can also be used to combine and evaluate multiple criteria simultaneously. Hence, the FL concept provides a robust mathematical framework in which vertical handover decisions can be formulated; this is referred to as a Fuzzy MADM [67].

In [15, 68], Chan et al. proposed a solution incorporating FL in which terrestrial (GPRS and UMTS) and satellite mobile networks operate alongside each other. The handover decision algorithm aims at selecting a segment or network for a particular service that can satisfy objectives based on criteria such as low cost, good RSS, optimum bandwidth, low network latency, high reliability and long battery life and takes into account the preferred access network. It is defined as a *Multiple Objective Decision Making (MODM)* algorithm, which requires inputs from the system (e.g., link quality, network characteristics and user profile) and the user (e.g., user preferences and application type). The input from the user is used to determine the weight given to each of the criteria used from the system such as the importance of the cost compared to the importance of the received QoS. The segment selection has two stages:

The first stage consists of *Fuzzification* and *weighting* procedures. Data from the system are converted into fuzzy sets in which each comparative criteria (such as cost) can be represented by a value between 0 and 1, where the value is provided by an appropriate membership function. These representative values (known as membership values) for the fuzzy sets are obtained by mapping the measurements for a particular parameter onto a membership function. The weight evaluates the importance of each criteria based on instructions received from the network provider and the user.It uses the AHP method influenced by user preferences (cost, quality and application used).

The second stage consists of *decision making*, which involves the application of the weights to each criterion according to the define objectives in a decision function. The chosen segment is the segment with the highest membership values of the decision function.

Whereas this approach lacks consideration of user's needs, our AUHO apply a user profile to assign weights of each criterion.

In [69], a combined FL and GA approach has been proposed to solve access network selection in heterogeneous wireless networks. Their proposed scheme is shown in Figure II.5. The scheme's decision phase consists of three main components. The first component contains a set of small parallel FL-based subsystems; the second component is a *Multiple Criteria Decision Making (MCDM)* system; and the third component is a GA based component to assign suitable weights for the criteria in the second component. The authors considered user, operator, and the QoS view

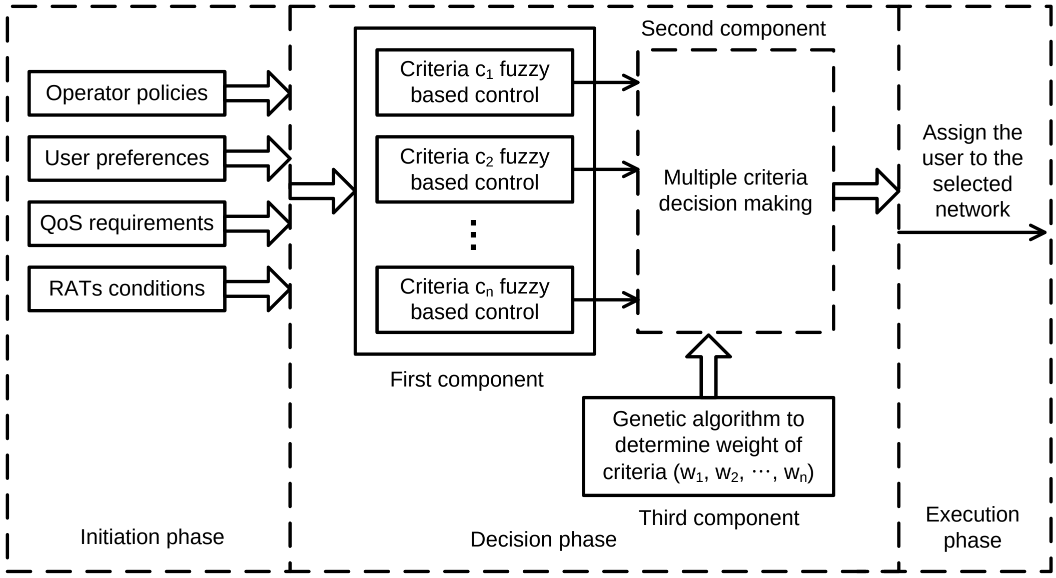


Figure II.5: Access network selection based on FL, MCDM, and GA

points for access network selection.

Whereas this approach lacks a feedback control loop for dynamically adapting to context changes, our AUHO has a feedback control loop for maintaining handover decisions.

2.3.6 Context-aware Approaches

The context-aware handover concept is based on knowledge of the context information of the mobile terminal and the networks in order to make intelligent and better decisions [70]. Thus, a context-aware decision strategy is used to manage this information and evaluate context changes to compute whether a handover is necessary and to choose the best access network. Context information, relevant for the handover decision algorithm is considered for handover decision criteria. Context information consists of the terminal or device (e.g., its capabilities and location), the user (e.g., its preferences), the network (e.g., QoS and coverage) and the application (e.g., QoS requirements, service type such as real-time, interactive or streaming). Two context-aware decision solutions, [70] and [71], are based on the AHP method. These methods identified the most suitable choice (interface for a given application) among multiple alternatives that would satisfy primary set of objectives based on the values of appropriate context parameters.

In [71], Ahmed et al. developed and analyzed an intelligent handover decision algorithm (also based on AHP) that includes session transfer (i.e., application management) which was lacking in [70]. They considered a mobile-initiated and controlled solution. The context-aware decision algorithm processes each service type currently running on the device. Primary objectives were defined in terms of *Lowest Cost, Preferred Interface* and *Best Quality* (maximizing throughput, minimizing delay, jitter, and BER). The algorithm has five stages (see Figure II.6): two stages of pre-configuration and three stages of real-time calculations: The five stages are: 1) taking user inputs, 2) mapping limit values from discrete preferences, 3) assigning scores to available networks, 4) calculating network ranking, and 5) managing the session.

Whereas this approaches lacks to apply user's needs for network selection, our AUHO selects the access network based on user preferences for satisfying user's needs.

In [72], the user perceived quality of service was considered in addition to traditional contexts such as user preferences, application requirements, network parameters and link quality for decision making. *User Perceived Quality (UPQ)* was employed as a trigger source, in addition to link layer triggers which emerged using

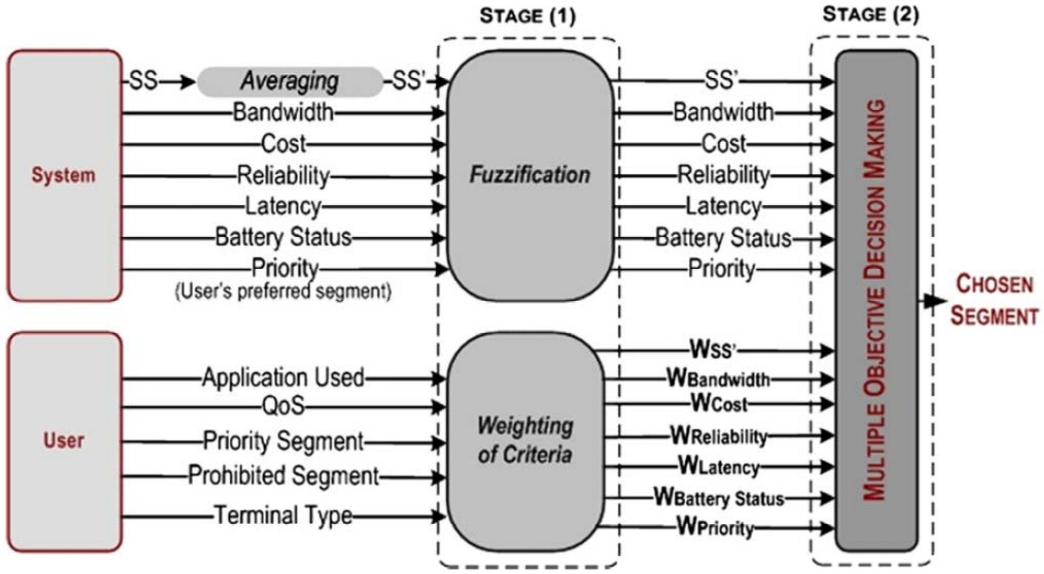


Figure II.6: Context-aware decision algorithm for access network selection

the *Media Independent Handover (MIH)* event service.

Whereas this approach only considers multimedia streaming service by evaluating UPQ, our AUHO supports multiple types of services for handover decisions.

2.3.7 Comparison

Our comparative study shows different issues related to the handover decision problem: good network performance, user satisfaction, flexibility, efficiency, and multi-criteria solution. In a heterogeneous environment, we see that traditional handover decision strategies (RSS-based) are not sufficient to make a vertical handover decision. They do not take into account the current context or user preferences. So, a vertical handover decision strategy involves complex considerations and tradeoffs. It needs to be flexible and efficient considering the useful criteria and reasonable policies or rules applicable to both the user's professional and personal communications.

In Table II.1, we summarize the given approaches compared using different characteristics such as multi-criteria choice, efficiency, or service types supported, and add our proposed AUHO in the last column based on the comparison result in [13]. The *multi-criteria* solution is an essential part of the vertical handover decision process. For instance, a NN-based strategy, compared to the other strategies, is based on only one parameter (i.e., RSS measurements) and on one type of handover policy (i.e., keeping a WLAN connection when it is available). *User consideration* is also a very interesting characteristic in vertical handover decisions. It can include user intervention (e.g., according to user preferences), user interaction (e.g., with automation) and/or user satisfaction.

We also compare the different strategies regarding the following common characteristics: efficiency, flexibility, complexity, service type supported, information model definition, personalization, and feedback control loop. Efficiency means obtaining a precise decision with good performance. Flexibility is the degree of separation of the handover decision mechanism from the whole handover management process, and its adaptation to additional parameters or functions. The implementation of utility functions (DF) is more flexible for the use of vertical handover policies but less efficient for real-time applications due to dynamical context changes.

The use of AI-based algorithms enables analyzing complex problems. It is well-suited for the vertical handover decision problem, since it can give accurate solution with regrouping all the decision factors.

CA strategies try to ensure that high flexibility is treated as important as a high efficiency in a heterogeneous environment. Concerning implementation complexity,

Table II.1: Comparison between handover decision approaches with our proposed algorithm

Handover Decision Approach	**Traditional RSS-based**	**CF**	**UC**	**MAD**	**AI**	**CA**	**AUHO (Proposed)**
Multi-criteria	No	Yes	Yes	Yes	Yes (FL) No (NN)	Yes	**Yes**
User consideration	No	Low	High	Medium	Medium	High	**High**
Efficiency	Low	Medium	Medium	High	High	High	**High**
Flexibility	Low	High	High	High	Medium	High	**High**
Implementation complexity	Low	Low	Low	Medium	High	Medium	**High**
Service type supported	Non-real-time	Non-real-time Real-time	Non-real-time	Non-real-time and real-time	Non-real-time real-time	Non-real-time real-time	**Multiple types of services**
Information model	No	No	No	No	No	No	**Yes**
Personalization	No	No	Yes	No	No	No	**Yes**
Feedback control loop	No	No	No	No	No	Yes	**Yes**
Objective	FR	FR	NFR	FR	FR	FR	**FR and NFR**

CF: cost function; UC: user-centric; MCDM: multiple attribute decision;

AI: AI-based, CA: context-aware, AUHO: Proposed autonomic handover decision

FR: Functional Requirements, NFR: Non-Functional Requirements we focus on the fact that the decision mechanism can be complex in itself. A NN-based strategy is the most complex one due to its complicated topology and, hence, it is difficult to implement in practice. However, FL and NN based strategies together typically consider only a few context parameters and can be too complex for practical multimode mobile terminal with limited resources. Otherwise, some CA strategies, compared to FL/NN strategies, apply classical MADM methods that use simpler calculations. One of the advantages of MADM, FL and CA strategies is combining and evaluating multiple decision criteria simultaneously. But, some decision criteria or contextual information can be imprecise or unavailable. FL is the tool involved in decision strategies to cope with imprecision. It is proved by the use of Fuzzy MADM approaches [67, 73].

Regarding service types, non-real-time applications (file transferring, web browsing, etc.) are supported by all strategies. Only traditional RSS-based and user-centric (UC) strategies do not support real-time applications (streaming, video or voice conferencing, etc.) because these approaches do not consider network traffic conditions or service requirements. Whereas most approaches categorized an application type in two, real-time and non-real-time, our AUHO considers requirements of each application for handover decisions.

Some other characteristics such as stability and handover performance (in terms of throughput, handover delay and packet loss) do not appear in Table II.1. Only DF strategies evaluate the stability aspect which, on one hand, ensures that a handover is worthwhile for each mobile and, on the other hand, copes with handover synchronization when simultaneous decisions are taken by many terminals. Compared to other approaches, our AUHO synthesizes all advantages of the previous approaches, but also focuses on personalization and provides a feedback control loop for maintaining optimal handover decisions. It should be noted that the previous work does not have a feedback control loop, and hence, cannot adapt to changing environmental and terminal conditions. The objectives of other previous approaches is to achieve functional requirements or non-functional requirements, but our AUHO achieves both requirements.

Some recent studies [46, 74, 62, 70, 75, 76] have focused on user-centric, context-aware, and utility-function based approaches. However, to the best knowledge of the authors, none of these context-aware handover decision methods considers how to measure end user satisfaction using a feedback control loop. Thus, we added our AUHO to the previous approaches as shown in Table II.1. We also added information modeling, end user satisfaction, and a feedback control loop as comparison metrics. Our approach provides context-aware handover decisions with FL and utility functions to compute end user satisfaction, and hence provides novel benefits that are not offered by the other approaches.

There has been less work based on an autonomic approach [77, 78]. [77] introduces a novel design approach based on autonomic components and cross-layer monitoring and control for a seamless and efficient vertical handover by handling mobility at the application layer. However, this approach only presented the design concept and simple examples.

Another context-aware handover decision management technique was described in our previous work [78]. We proposed a management solution located in a management plane that controls and monitors the data and control layers. The management plane contains an autonomic handover manager that cooperates with other entities such as a system monitor, a user profile, a network interface, a service, or a session manager. It decides on an appropriate policy by using context information obtained through monitoring, analyzing, planning, and executing the results in a closed control loop. Our previous work provided a unique solution approach for the handover decision but did not provide concrete evaluation results. This thesis not only enhances our previous work but also provides detailed evaluation results. In this thesis, we will apply and unify these handover decision strategies as a set of decision methods that can be used for the autonomic management of mobile devices.

2.4 Chapter Summary

In this chapter, we briefly introduced autonomic computing and networking as the background of autonomic management. We also presented the FOCALE autonomic architecture which is the basis of our autonomic management architecture. We described the DEN-ng information model, which we use for representing technology-neutral knowledge for handover decisions. Finally, we reviewed the state of the art on handover decision management and compared our approach with others. In the next chapter, we will present solutions to some of the problems described in this chapter, as well as our hypothesis, methodologies, and the definition of context for handover decisions.

Chapter III

SOLUTION APPROACH

In this chapter, we present our solutions to the problems mentioned in Section 1.2. First, we present our hypothesis and assumptions. Then, we describe our methodologies and motivating scenarios for personalized handover decisions. We then present context information for making handover decisions, and information models using the DEN-ng.

3.1 Hypothesis and Research Approach

We propose a novel approach to calculating personalized handover decisions for maximizing end user satisfaction. This approach uses context information to overcome the limitations of the previously proposed methods. Our research hypothesis is as follows:

> **Research Hypothesis.** Our proposed AUHO algorithm always *maximizes end user satisfaction* by computing the optimal handover decision for different types of mobile services in heterogeneous wireless networks based on user preferences.

Assumptions For validating the hypothesis, we assume that our target mobile devices have multiple active network-enabled applications and multiple network interfaces for connecting to multiple available access networks and APs. Currently, we can select APs in WLAN manually. We assume that a mobile device can select any AP in any access network. We also assume that we can use any mobile service regardless specific network operators or service providers, and network operators will cover all the expenses for charging data used in transferring networks as dictated by our handover decisions. Especially, it is difficult to deploy the unified *Operations and Supported Systems (OSS)* and context servers to gather all available context information due to the federation problems in network operators and service providers. Federation or contracting issues among different network operators and service providers are beyond the scope of this thesis. We assume that end users can their own preferences by setting policies manually.

Methodologies Our approach is as follows. First, we define and categorize context information for handover decisions. The categorization is based on surveying available context information from mobile devices, networks, application, and users, and comparing this information to that in the DEN-ng information model [41]. Second, we construct an information model to represent different data models of mobile devices, access networks, application, policies, users, and context, because data from each of these entities come from different sources and are defined using different languages. These two efforts take the form of extending the current version of the DEN-ng model, due to the absence of detailed models of mobile device data in the DEN-ng model. Third, we develop a decision making algorithm by evaluating each access network using a *weighted* combination of context information, user preferences, and service requirements. Note that the weighting enables the decision method to be adjusted to better suit the needs of the end user. We define how to measure and evaluate the quality of each AP and then calculate the end user satisfaction for achieving our hypothesis. We define the concept of an "*acceptance value*" using a fuzzy logic-based classifier to process all relevant context information, regardless of whether different languages and formats are used. We then define the concept of a "*satisfaction value*" using a utility function based on user preferences. We then select the "*best satisfying*" AP for supporting *Context-aware Always-Best-Satisfying (CABS)* based on a utility function that maximizes user preferences. Fourth, we evaluate the performance of the proposed method using a network simulator that we developed for testing handover decisions in heterogeneous wireless networks. Finally, we compare our method with other decision making algorithms, and show that our algorithm supports a CABS service, which other methods do not support.

3.2 Motivating Scenario

Our first scenario is very common. When a user wants to use a voice call service in a high quality and low price network, traditional approaches only operate in terms of one functional parameter, such as quality or power consumption. This parameter is optimized, but its interaction with other parameters is *excluded*. Our approach optimizes multiple parameters as a *tuple*, thereby ensuring that interdependencies among them are taken into account. For example, we can recommend one AP that has *high quality and low price* by determining satisfaction scores. This can be further refined by using user preferences, which can differentiate APs by their available context data, such as time or location.

Our second example is related to seamless roaming. Power consumption of mobile devices (battery lifetime) is very important to end users. However, this is very sensitive to context data. For example, when a Korean user can use his or her mobile device in Korea, the user can use it with low power consumption without considering cost, because that user can use a 3G network at a flat rate. However, when that user roams in another country, that user may instead have to use a 3G network at a usage-based rate, which is more expensive. Since the power consumption of a 3G network is lower than that of a WiFi network, we can define a policy to represent this choice as "*Lifetime is important*". Although the user is roaming in another country, certain calls are very important to the user. For example, when the user talks with his or her boss, the quality of service is also important. In that case, we can define another policy as "*If a caller is my boss, quality of service is important*". In this second example, although the quality of service is important, we cannot ignore high costs. We can therefore define a third policy as "*If location is home country and caller is my boss, quality of service and cost are important*". We can apply different weights for each user preference metric with a User Profile (UP). For example, we could assign the following weights, the weight of quality is 0.7 and that of cost is

0.3, where the sum of them is 1.0. This means that in this example, the quality is more important than the cost by a 7 : 3 ratio.

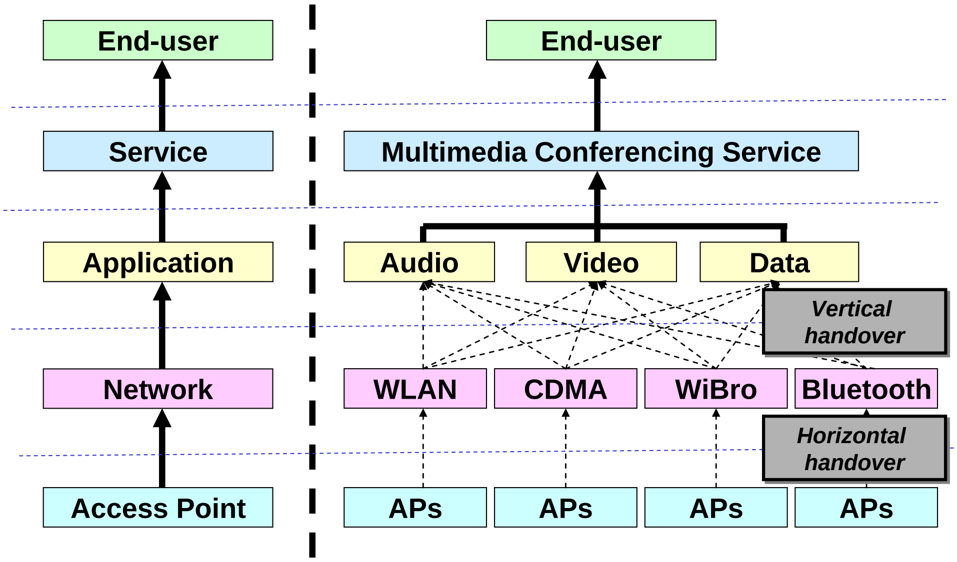


Figure III.1: Layering for general service and multimedia conferencing service

An interesting scenario for future mobile services involves dynamic access network selection. Figure III.1 shows how default services are provided on the left, and how multimedia conferencing services are provided on the right. This figure is generic, and assumes that applications, networks, and AP(s) can all be different, forming a heterogeneous mobile network environment. For instance, an end user is using a multimedia conferencing service on a mobile terminal which can access multiple radio networks using multiple network interfaces. The service is composed of multiple applications such as audio, video and data applications. Each application succeeds in establishing a session with one of several available access networks (e.g., WLAN, CDMA, Mobile WiMax, or Bluetooth). Then, the mobile terminal connects with one of the APs. There are two kinds of handover; vertical handover, which occurs when a different type of access network is selected, and horizontal handover, which occurs when another AP is selected within the same type of access network. As mentioned earlier, the selections of access network and AP have traditionally been based on the RSS. In this example, we are taking into account more parameters (e.g., those that are related to QoS, battery and service pricing), because end users have different needs that can conflict with the selections of an access network and AP.

3.3 Context Information for Handover Decision

We surveyed context information for handover decisions from mobile devices and networks [78]. The context information was classified into static and dynamic data, depending on the frequency and causes of changes. In this section, we present possible context information for our personalized handover decisions based on the previous context-aware approaches [62, 70, 71, 72, 78, 79].

- User Context
  - User Preferences
    - Network values: Bandwidth, Network Type, Power Consumption, Security, Received Signal Strength (RSS), Power,
    - Network-independent values: Quality, Lifetime, Cost
  - Subscription Information, User Profile, User's Current Status (mobility, location, etc.)

- Application Requirements
  - Bandwidth
  - Packet Error Rate (PER)
  - Delay
  - Jitter
  - Packet Loss Ratio (PLR)
- Service Classification
  - Conversational
  - Streaming
  - Interactive
  - Background
- Network Context
  - Network Traffic Load
  - Network Cost
  - Coverage
  - Supported Classes of Service
  - Bandwidth
  - Delay
  - Jitter
- Link Context (Network Interface)

  - Received Signal Strength (RSS)
  - Signal-to-Noise Ratio (SNR)
  - Signal-to-Inference Ratio (SIR)
  - Bit Error Rate (BER)
  - Throughput
  - Burst Error
  - Packet Loss Ratio (PLR)

- Device Capabilities
  - Current Battery Power Level
  - Power Consumption Rate (Tx (Transmitter) Power Consumption Rate, Rx (Receiver) Power Consumption Rate, Idle Power Consumption Rate)

3.4 Information Modeling of Mobile Devices

In general, a network consists of heterogeneous devices that use different technologies. Device functionality, as well as the management and operational data that they produce, are usually represented by different data models that are specific to a vendor, platform, and/or device operating system. Hence, two different vendor devices typically use different data structures, formats, and even languages to define their management and operational data. Therefore, we use a technology-neutral information model as a unifying metaphor to equate differences in each data model; this enables us to combine different data from different sources into a single cohesive whole. As we presented in Section 2.2.2, DEN-ng is an object-oriented information model that describes different entities of interest in the managed environment. However, the current DEN-ng information model does not include detailed mobile devices and handover decision information. Therefore, we extended DEN-ng to support handover decisions for mobile devices.

An example of a simplified DEN-ng model for a mobile device that has network interfaces is shown in Figure III.2; note that a number of classes and associations have been elided for the sake of simplicity.

A mobile device is a PhysicalDevice, which is a type of PhysicalResource. It consists of one main component – the phone (which is a subclass of a mobile device) and a set of physical components, such as the display and keypad. These components are all various subclasses of Hardware or ManagedHardware. The PhysicalPort is one of the extended subclasses of the ManagedHardware class. The MobileDevice has zero or more PhysicalPorts. Each PhysicalPort binds to zero or more DeviceInterfaces. The MediaInterface class, which represents network interfaces that are based on a physical medium, is one of the extended subclasses of the DeviceInterface class that we extended, and defined different kinds of network interfaces for use in the development and testing of AUHO. Using this information model, we can use a single vendor-neutral description of data as inputs to the handover decisions, and define appropriate transformations to data model using a number of model-driven mechanisms [80, 81].

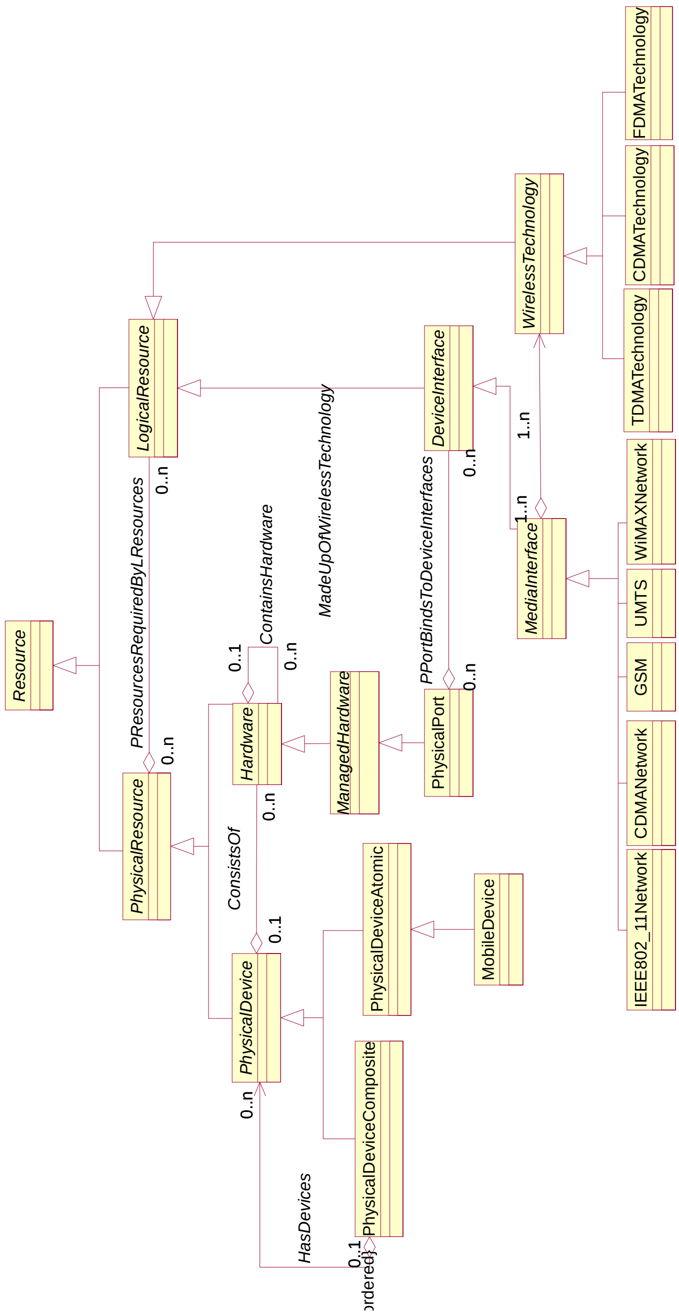


Figure III.2: Simplified extract of the DEN-ng model for network interface management in mobile devices

3.5 Chapter Summary

To conclude, we have presented our hypothesis and research approaches for this thesis. We described three interesting scenarios for motivating personalized handover decisions. We also presented context information for personalized handover decisions. We briefly described the design of information models for mobile devices based on DEN-ng. In the next chapter, we will detail our proposed decision algorithm and concrete architecture.

Chapter IV

AUTONOMIC PERSONALIZED HANDOVER DECISION

In this chapter, we present our proposed *AUHO*, which is an algorithm to help select access networks (vertical handover) and APs (horizontal handover) for applications based on a weighted combination of different preferences for end users who are using mobile devices that have multiple network interfaces. Our AUHO algorithm helps select the best AP using available context information and service requirements based on the user's preferences. In this chapter, we first define some terms for describing our method. Then, we introduce our policy language definition, and provide examples for computing handover decisions. Finally, we present our decision algorithm including how to calculate the APAV and the APSV, and our system architecture for implementing the algorithm.

4.1 Terminology

In this section, we introduce and define the following terms for describing our method as follows:

- ***User Preferences (UPref)*** is a set of attributes of a sender or receiver that indicates particular information or behaviors that he or she would choose instead of others that are available. If multiple options are possible, then it optionally orders them in terms of the most desired to the least desired. Preferences can also be used to indicate default behavior. In this thesis, we use "*RSS (R)*", "*Cost (C)*", "*Quality (Q)*", and "*Lifetime (L)*" as exemplary UPrefs for calculating a handover decision. Note that AUHO is not limited to using a particular number or type of UPrefs.

- ***User Profile (UP)*** describes a specific set of user-programmable attributes that controls how the owner of the profile interacts with the environment using a specific device. This enables some or all of the functionality of the entity to be programmed. One or more UPrefs can select a specific UP in our approach. User profiling is typically either knowledge- or behavior-based. The former creates static models of users and dynamically match users to the close model. The latter uses the user's behavior as a model, typically using machine-learning techniques to discover useful patterns in the behavior. In this thesis, we used weights of user preferences as a user profile for personalization.

- ***Policy (P)*** is typically described as a set of principles or rules to guide decisions and achieve a set of rational outcome(s). We define policies to select a specific UP according to context and the end user's UPrefs.

- ***Service Level Agreement Filter (SLAF)*** represents a filter to select access networks by their service contracts, which are available in their associated subscription information.

- ***Speed Filter (SF)*** represents a filter to select access networks by their supported speed.

- ***AP Acceptance Value (APAV)*** represents the suitability of a particular AP for an end user based on a given set of UPrefs (e.g., RSS, Quality, Cost, and Lifetime) for that user. The range of an APAV is from 0.0 to 1.0. APAVs are not absolute values but relative values. For example, if the APAV of AP_1 is greater than that of AP_2 in terms of the specific UPref, AP_1 is better than AP_2 for selecting the optimal AP.

- ***AP Satisfaction Value (APSV)*** represents how well a particular AP satisfies the needs of the end user based on his or her user profile, as used in this context. We calculate *RUH (Are You Happy)* scores with APSVs. The range of an APSV is from 0.0 to 1.0. APSVs are also relative values. For example, if the APSV of AP_1 is greater than that of AP_2 in terms of an user's UP, AP_1 is preferred (i.e., has a higher user satisfaction) than AP_2.

4.2 Policy Definition for Handover Decisions

This section describes the policy definition for our AUHO method. We define our policy based on the DEN-ng policy model [41]. We design a grammar for our policy language using *Extended Backus-Naur Form (EBNF)* as shown in Listing IV.1. We implement our policy language using an *Extended Markup Language (XML)* which is presented in Listing IV.2.

Listing IV.1: Extended BNF Definition of the handover decision policy syntax

```
rulebase := rule*;
rule := NAME event condition* action;
event := VOICE CALL | STREAMING | FTP | VIDEO CALL | WEB BROWSER | SMS
    ;
condition := atom*;
atom := var op value
var := LOCATION | CALLER | TIME | TEMPERATURE
op := = | < | > | <= | => | <>;
value := CONTEXT;
action := method userprofile;
method := RANDOM | RSS | COST | QUALITY | LIFETIME | AUHO;
userprofile := mode;
mode := ORDINARY userpreference_ordinary | ADVANCED
    user_preference_advanced;
user_preference_ordinary := RSS? COST? QUALITY? LIFETIME?
user_preference_advanced := (pref weight)+;
pref := RSS | COST | QUALITY | LIFETIME;
weight := 0.digits | 1.0 ;
digits := digit+;
digit : = 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9;
```

Listing IV.2: XML Example of the Handover Decision Policy

```
<rulebase>
 <rule>
  <name>voicecall_rule</name>
  <event>Voice Call</event>
  <condition>
   <atom><var>LOCATION</var><op>=</op>
    <value>HOME</value></atom>
  </condition>
  <action>
   <method>AUHO</method>
   <user_profile>
    <ordinary>
     <user_preference>
      <Cost />
      <Quality />
     </user_preference>
    </ordinary>
   </user_profile>
```

```
  </action>
 </rule>
 <rule>
....
  <action>
   <method>AUHO</method>
   <user_profile>
    <advanced>
     <user_preference>
      <pref>Cost</pref>
      <weight>0.7</weight>
      <pref>Quality</pref>
      <weight>0.3</weight>
     </user_preference>
    </advanced>
   </user_profile>
  </action>
 </rule>
...
</rulebase>
```

a policy rule is defined as an *Event-Condition-Action* tuple. In the context of AUHO calculations, each Event is related to applications of a mobile device, and is used to trigger the evaluation of the condition(s) of the policy rule; Conditions are defined using context information; Actions are then executed based on whether a set of conditions for that policy rule are evaluated as TRUE (or FALSE).

The notation of UP is a set of weights of user preferences, such as:

$$UP = (W_R, W_C, W_Q, W_L) \tag{IV.1}$$

, where $W_R + W_C + W_Q + W_L = 1.0$.

Examples of policies for handover decisions are:

```
IF location=home AND service=VoIP THEN UP=(0.1,0.4,0.4,0.1)
```

(IV.2)

```
IF location=office AND service=VoIP THEN UP=(0.7,0.1,0.1,0.1)
```

(IV.3)

Although we use the same service, the user preferences associated with that service can take on different values due to changes in the current context, such as location. Metrics for evaluating each user preference for an application are as follows:

- **RSS**: measured RSSI from network link layer
- **Cost**: different cost models
- **Quality**: a weighted combination of bandwidth, delay, jitter, BER, throughput, burst error, and PLR for evaluating quality of service
- **Lifetime**: a combination of transmit, receive, and idle power consumption values of the network interface card

Table IV.1: Pre-defined weights of user profiles for ordinary users

User Preference	RSS	Cost	Quality	Lifetime	RSS & Cost	Cost & Quality	...	Cost & Quality & Lifetime	RSS & Cost & Quality & Lifetime
W_R	0.7	0.1	0.1	0.1	0.4	0.1		0.1	0.25
W_C	0.1	0.7	0.1	0.1	0.4	0.4		0.3	0.25
W_Q	0.1	0.1	0.7	0.1	0.1	0.4		0.3	0.25
W_L	0.1	0.1	0.1	0.7	0.1	0.1		0.3	0.25

In our previous work [78], we assumed that all end users could assign weights for each user preference. However, most ordinary users do not have much knowledge about access network technologies and parameters for evaluating each access network. It is difficult for them to assign their own weights for preferences. Therefore, we divide the complete set of user profile settings into two groups: a) ordinary and b) advanced mode. The former addresses the needs of ordinary users, and consists of a set of pre-defined weights as shown in Table IV.1; the latter is provided by a user's personalized settings. In this thesis, we do not consider assigning each weight for optimizing performance; this is part of our future work. We will discuss optimization methods in Section 7.4. However, this is considered a special case of using pre-defined settings, which we tested extensively.

4.3 Decision Making Algorithm

In this section, we present our decision making algorithm for AUHO. First, we provide an overview of our algorithm and introduce two-value calculations, APAV and APSV. Then, we explain how the APAV and APSV metrics are calculated.

4.3.1 Overview

Figure IV.1 is a flowchart of our proposed algorithm. First, a user starts an application on a mobile device, and then selects a network. After that, the mobile device gets a list of candidate APs from the network interface manager and loads the policy for the current application and the current context. If there is an appropriate policy in the policy repository, it is used. Otherwise, the default policy is loaded. We assume that all policy rules are conflict free, because policy conflict checking is beyond the scope of this thesis. After that, the SLAF and SF are applied to remove APs that do not support the SLA and speed requirements of the user. We then calculate the APAVs and APSVs for all remaining candidate APs, and determine the AP that best satisfies the current application and context requirements. If the new candidate AP is the same as the old AP, no handover is performed. In addition, the APSV of the new AP is higher than that of the current AP, we must consider handover overheads such as latency. We control handover overhead using the threshold δ, which we set by analyzing handover overheads among APs. Otherwise, handover to the new AP is performed. This process is continuously repeated within a pre-defined timeout that is defined by profiling. This is a our algorithm's feedback control loop to achieve autonomic management.

After connecting the best satisfying AP, we repeat a maintenance loop by evaluating the current connected AP. If a connected AP exists, the network selection task is stopped. We then calculate the APAVs of the current AP and calculate the APSV based on them. If the APSV of the current AP is lower than the pre-defined threshold (β in Figure IV.1), the network selection task is started again and all candidate APs are evaluated for selecting the best satisfying AP.

Our algorithm supports handover decisions by monitoring context information periodically. However, a periodic method cannot determine the best AP between the timeout. For overcoming this problem, we use a reactive method which a system notifies the degradation of APSV of the current AP for new handover decisions.

Algorithm 1 represents the pseudo code of the autonomic handover decision making procedure, whose inputs are a network interface list and a current application, and whose outputs are the best network interface and the best AP for the current application and user preference. In the feedback control loop, this procedure is repeated to maintain the best handover decision. In line 23, we add a threshold, δ for considering handover overhead. Although the APSV of the new AP is higher

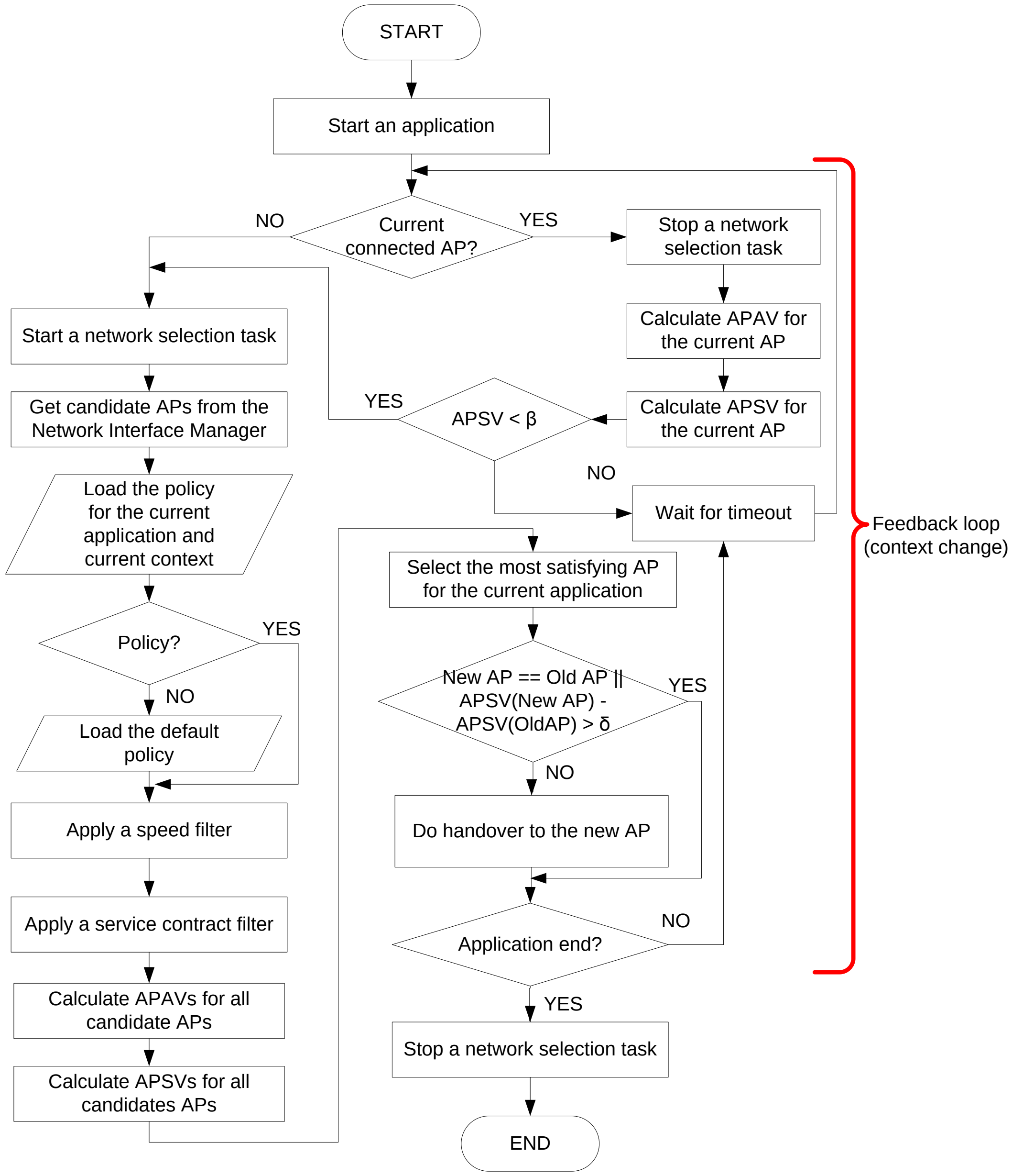


Figure IV.1: Flowchart of autonomic handover decision with a feedback control loop

than that of the current AP, we must consider handover overheads such as latency. We control handover overhead using the threshold δ, which we set by analyzing handover overheads among APs.

Algorithm 1: AUHO decision making process

```
input : An Network Interface list NI of size n and a current application App
output: The best satisfying NI,bestNI, and the Best satisfying AP,bestAP
up ← LoadPolicy(App) ;
bestNI ← null;
bestAP ← null;
for i ← 1 to n do
    if isSpeedSupported(NI[i]) and isSLASupported(NI[i]) then
        if bestNI is equal to null then
            bestNI ← NI[i] ;
        AP ← GetCandidateAPList(NI[i]) ;
        m ← the number of AP ;
        maxAP ← AP[1] ;
        for j ← 2 to m do
            if maxAP is equal to null then
                maxAP ← AP[j] ;
            else if GetAPSV(maxAP,up) < GetAPSV(AP[j],up) then
                maxAP ← AP[j] ;
        if bestAP is equal to null then
            bestAP ← maxAP ;
        else if GetAPSV(bestAP,up) < GetAPSV(maxAP,up) then
            bestAP ← maxAP ;
            bestNI ← NI[i] ;
currentAP ← GetCurrentAP() ;
currentNI ← GetCurrentNI() ;
if GetAPSV(bestAP,up) − GetAPSV(currentAP,up) ≥ δ then
// threshold for considering handover overheads
    bestAP ← currentAP ;
    bestNI ← currentNI ;
```

We describe how to calculate APAVs and APSVs in detail in the following subsections.

4.3.2 AP Acceptance Value Calculation

In this section, we briefly describe fuzzy logic, then we define membership functions and fuzzy rules used for calculating APAVs.

Fuzzy Logic

Fuzzy logic provides the ability to use data values that can have a specific range of values that are resolved at runtime [82, 83, 84]; as such, it allows a flexible engineering design but is simple to implement. Furthermore, the strength of fuzzy logic is that it can represent a vague term, such as “low” or “high”, which obviates the need to choose a specific value. It is simple, but it still has flexibility, adaptivity, and extensibility. Also, fuzzy parameters can be optimized using machine learning or bio-inspired techniques. Due to these benefits, fuzzy logic is widely used for various applications including air conditioning, digital image processing, elevator control, and pattern recognition.

This is also true in our scenarios, For example, the parameters that are used in our proposed method can be ambiguous in many cases (e.g., the constraint “delay is high” does not specify a concrete delay level), but nevertheless convey important concepts to validate against, especially for non-functional parameters. We can represent these ambiguous parameters easily, and make a decision based on fuzzy rules by using fuzzy logic.

There are several types of Fuzzy Information Systems (FIS) including Mamdani FIS [85] and Sugeno FIS [86]. We used Mamdani FIS in our proposed method because it has a greater expressive power and interpretability than Sugeno FIS [87].

We also define input metrics, membership functions, and fuzzy rules for calculating APAVs for the given APs. Mamdani FIS has four steps; Fuzzification, Rule evaluation, Aggregation, and Defuzzification, as illustrated in Figure IV.2.

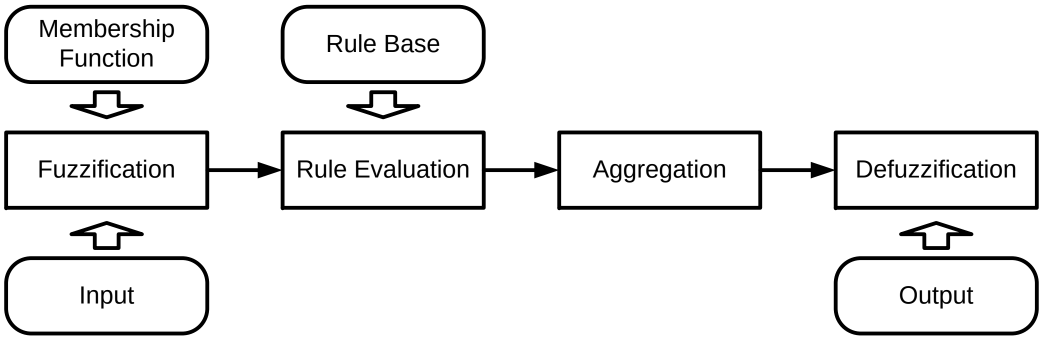


Figure IV.2: Mamdani fuzzy inference system

In the Fuzzification step, FIS gets real values as inputs from outside of the process, and then evaluates these values using membership functions. We defined input metrics and membership functions for calculating the APAV of all candidate APs. The membership function represents the degree to which a variable can be contained in a fuzzy set. The degree is a value between 0 and 1; the closer the degree is to 1, the more likely it is that the variable is contained in a fuzzy set. The following is a simple example for determining the quality of service in this paper. If a delay of voice call traffic, which is 25 ms, is entered as an input, then the membership function can evaluate whether this delay is low or high. The evaluated results are passed to the Rule evaluation step. In the Rule evaluation step, membership values that were passed from the Fuzzification step are evaluated using fuzzy rules, which are stored in the Rule base. For example, let us assume that we have a rule as follows:

```
IF delay IS low AND jitter IS low
THEN quality of voice call IS high
```
(IV.4)

FIS takes the delay and the jitter measurement, translates these values into fuzzy sets using the membership functions in the Fuzzification step, and then decides the quality of voice call based on the rules in the Rule evaluation step. Every result that was evaluated by fuzzy rules in the Rule evaluation step is aggregated into one fuzzy set for each output variable in the Aggregation step. The output fuzzy sets are converted into appropriate output values in the Defuzzification step. Finally, the output values are used by the system that is outside of the FIS. In our scheme, we used the FIS output value to generate APAVs.

APAV Calculation using Fuzzy Logic

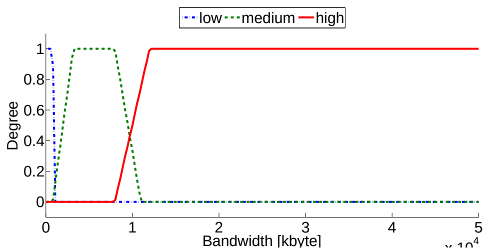
We calculate an APAV using fuzzy logic. In this thesis, we use four user preferences to make a handover decision: RSS, Cost, Quality, and Lifetime. We define four APAVs, one for each of the following user preferences: RSS ($APAV_R$), cost ($APAV_C$), quality ($APAV_Q$), and lifetime ($APAV_L$).

An $APAV_R$ is calculated using *Received Signal Strength Indicator (RSSI)* which is a measurement of the power present in a received radio signal [88]. RSSI measurements are unitless and in the range 0 to 255, expressible as a one-byte unsigned integer. The maximum value, $RSSI_{Max}$, is vendor dependent. This is because the IEEE 802.11 standard does not define any relationship between RSSI value and power level in mW or dBm. Vendors provide their own accuracy, granularity, and range for the actual power and their range of RSSI values. For example, Cisco

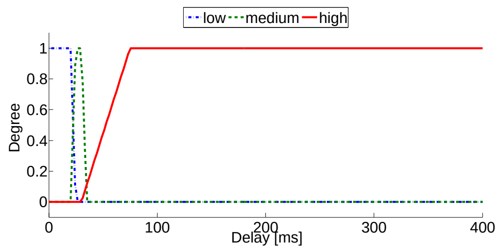
Systems cards have a $RSSI_{Max}$ of 100 and will report 101 different power levels, corresponding to RSSI values from 0 to 100. Another popular Wi-Fi chipset is made by Atheros. An Atheros card will return an RSSI value of 0 to 127 with 128 indicating an invalid value. There is no specified relationship of any particular physical parameter to the RSSI reading. Furthermore, RSSI specifications of CDMA, Mobile WiMax, or other access networks are different. Therefore, we need to normalize this RSSI value from 0 to 1, because the values of $APAV_R$ and RSSI are proportional. That is, if the RSSI of an AP is higher, its $APAV_R$ is higher and the possibility of accepting it is also higher.

The cost of each access network is defined by each access network provider, and can be represented as $\$/min$, $\$/bytes$ or a flat-rate charge in $\$/session$. We normalize it from 0 to 1 for representing $APAV_C$. An AP and its associated cost are inversely proportional. That is, as the cost rate becomes higher, a larger quantity of end users will not accept it as the best access point.

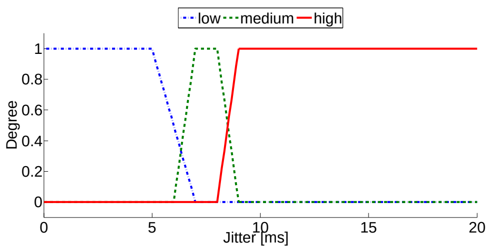
For calculating $APAV_Q$, we use fuzzy rules to satisfy the service requirement. We defined seven input membership functions to convert seven input metrics into fuzzy sets for the Fuzzification step as shown in Figure IV.3. We also defined different fuzzy rule sets for each application type for the Rule evaluation step. One output membership function is defined for generating the APAV, as shown in Figure IV.4. There are five output values: *SA (Strong Accept)*, *WA (Weak Accept)*, *NU (Neutral)*, *WR (Weak Reject)*, and *SR (Strong Reject)*. From the various available Defuzzification methods, we used the Center of Gravity (CoG) method [89] due to a common and useful defuzzificuation technique. This method finds the point where a vertical line would slice the aggregate set into two equal sections.



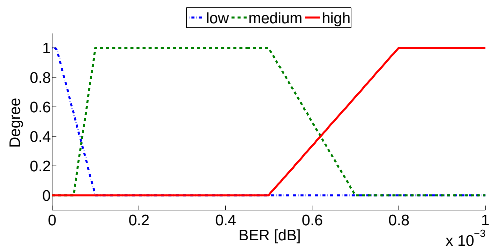
(a) Membership function for bandwidth



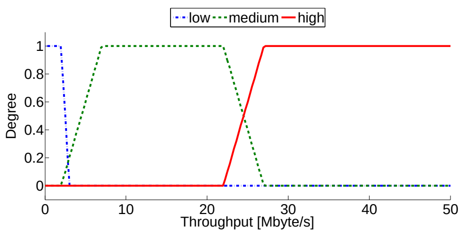
(b) Membership function for delay



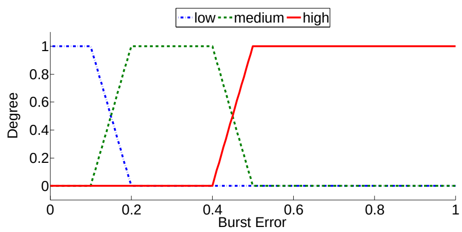
(c) Membership function for jitter



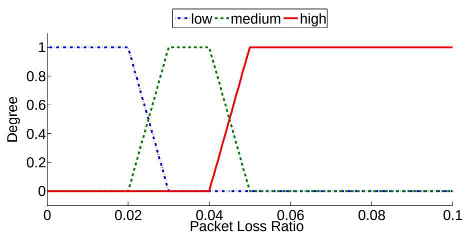
(d) Membership function for bit error rate



(e) Membership function for throughput



(f) Membership function for burst error



(g) Membership function for packet loss ratio

Figure IV.3: Input fuzzy membership functions for calculating $APAV_Q$

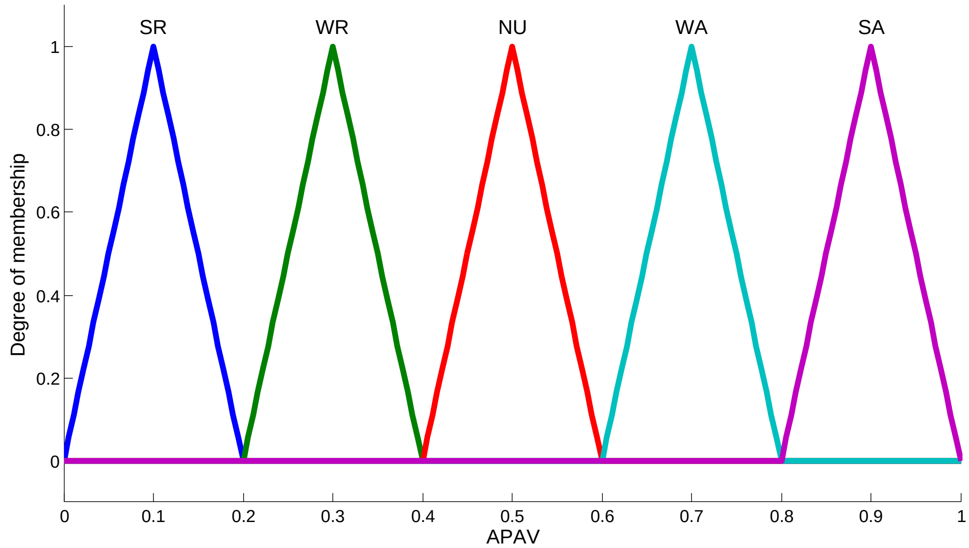


Figure IV.4: Output fuzzy membership function for calculating APAV

In this thesis, we used three different types of applications: voice call, streaming multimedia, and FTP. We defined different fuzzy rules for them. When we measure the quality of a voice call application, the delay and jitter are important factors. We defined nine fuzzy rules for a voice call using these two factors (Listing IV.3).

Listing IV.3: Fuzzy rule definition for calculating $APAV_Q$ of a voice call application

```
RULE 1: IF delay IS low AND jitter IS low THEN APAV IS SA;
RULE 2: IF delay IS low AND jitter IS medium THEN APAV IS WA;
RULE 3: IF delay IS low AND jitter IS high THEN APAV IS NU;
RULE 4: IF delay IS medium AND jitter IS low THEN APAV IS WA;
RULE 5: IF delay IS medium AND jitter IS medium THEN APAV IS NU;
RULE 6: IF delay IS medium AND jitter IS high THEN APAV IS WR;
RULE 7: IF delay IS high AND jitter IS low THEN APAV IS NU;
RULE 8: IF delay IS high AND jitter IS medium THEN APAV IS WR;
RULE 9: IF delay IS high AND jitter IS high THEN APAV IS SR;
```

In the case of a streaming application, bandwidth, jitter, and throughput are important factors, while delay is a less important factor. We defined eighty one fuzzy rules for a streaming application using them (Listing IV.4).

Listing IV.4: Fuzzy rule definition for calculating $APAV_Q$ of a streaming application

```
RULE 1: IF bandwidth IS low AND jitter IS low  AND throughput IS low AND delay
    IS low  THEN APAV IS WR;
RULE 2: IF bandwidth IS low AND jitter IS low  AND throughput IS low AND delay
    IS medium THEN APAV IS WR;
RULE 3: IF bandwidth IS low AND jitter IS low  AND throughput IS low AND delay
    IS high  THEN APAV IS SR;
RULE 4: IF bandwidth IS low AND jitter IS low  AND throughput IS medium AND
    delay IS low  THEN APAV IS NU;

RULE 70 :  IF bandwidth IS high AND jitter IS medium AND throughput IS high
    AND delay IS low  THEN APAV IS SA;
RULE 71 :  IF bandwidth IS high AND jitter IS medium AND throughput IS high
    AND delay IS medium  THEN APAV IS SA;
RULE 72 :  IF bandwidth IS high AND jitter IS medium AND throughput IS high
    AND delay IS high  THEN APAV IS WA;
```

For an FTP application, BER, burst error, and PLR are important factors. We defined twenty seven fuzzy rules for an FTP application (Listing IV.5). Using these fuzzy rules, we then calculate the APAV for each application with their service requirements. The complete set of fuzzy rules are listed in Appendix A.

Listing IV.5: Fuzzy rule definition for calculating $APAV_Q$ of an FTP application

```
RULE 1: IF ber IS low  AND bursterror IS low AND packetlossratio IS low  THEN
    APAV IS SA;
```

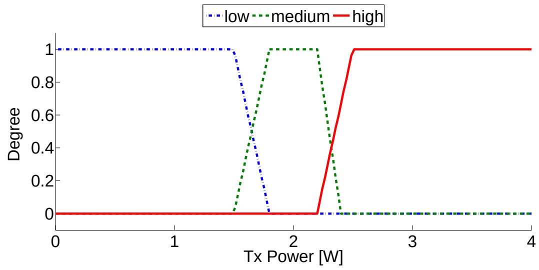
```
RULE 2: IF ber IS low  AND bursterror IS low AND packetlossratio IS medium THEN
     APAV IS SA;
RULE 3: IF ber IS low  AND bursterror IS low AND packetlossratio IS high  THEN
    APAV IS WA;
RULE 4 : IF ber IS low  AND bursterror IS medium AND packetlossratio IS low
    THEN APAV IS SA;
RULE 5 : IF ber IS low  AND bursterror IS medium AND packetlossratio IS medium
    THEN APAV IS WA;
RULE 6 : IF ber IS low  AND bursterror IS medium AND packetlossratio IS high
    THEN APAV IS NU;

RULE 25: IF ber IS high  AND bursterror IS high AND packetlossratio IS low
    THEN APAV IS WR;
RULE 26: IF ber IS high  AND bursterror IS high AND packetlossratio IS medium
    THEN APAV IS SR;
RULE 27: IF ber IS high  AND bursterror IS high AND packetlossratio IS high
    THEN APAV IS SR;
```

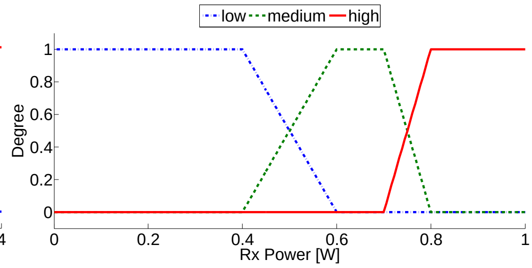
For calculating $APAV_L$, fuzzy rules should also be defined to satisfy the service requirement. We calculate the power consumption as follows:

$$\begin{aligned} PowerConsumption(Application) &= W_{Tx} * Power(Tx) + W_{Rx} * Power(Rx) \\ &\quad + W_{Idle} * Power(Idle) \end{aligned} \tag{IV.5}$$

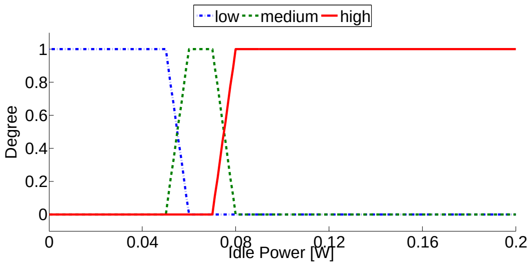
We defined three input metrics (*Transmitter (Tx)*, *Receiver (Rx)*, and Idle power consumption rates) and three input membership functions for the Fuzzification step (Figure IV.5). We then defined different fuzzy rule sets for each application type for the Rule evaluation step. We use the same output membership function as we used for $APAV_Q$, which was shown in Figure IV.4. The power consumption of



(a) Membership function for Tx power



(b) Membership function for Rx power



(c) Membership function for Idle power

Figure IV.5: Input fuzzy membership functions for calculating $APAV_L$

each application is different because their consumption patterns are different. For example, when we use a voice call application, the power consumption is highly dependent on the Tx and Rx power consumption rates. We defined twenty seven fuzzy rules for voice calls using these two factors (Listing IV.6).

Listing IV.6: Fuzzy rule definition for calculating $APAV_L$ of a voice call application

```
RULE 1: IF tx IS low AND rx IS low AND idle IS low THEN APAV IS SA;
RULE 2: IF tx IS low AND rx IS low AND idle IS medium THEN APAV IS SA;
RULE 3: IF tx IS low AND rx IS low AND idle IS high THEN APAV IS WA;

RULE 25: IF tx IS high AND rx IS high AND idle IS low THEN APAV IS SR;
RULE 26: IF tx IS high AND rx IS high AND idle IS medium THEN APAV IS SR;
RULE 27: IF tx IS high AND rx IS high AND idle IS high THEN APAV IS SR;
```

In the case of streaming applications, the power consumption is dependent on the Rx power consumption. We also defined twenty seven fuzzy rules for a streaming application using them (Listing IV.7).

Listing IV.7: Fuzzy rule definition for calculating $APAV_L$ of a streaming application

```
RULE 1: IF tx IS low AND rx IS low AND idle IS low THEN APAV IS SA;
RULE 2: IF tx IS low AND rx IS low AND idle IS medium THEN APAV IS SA;
RULE 3: IF tx IS low AND rx IS low AND idle IS high THEN APAV IS SA;

RULE 25: IF tx IS high AND rx IS high AND idle IS low THEN APAV IS SR;
RULE 26: IF tx IS high AND rx IS high AND idle IS medium THEN APAV IS SR;
RULE 27: IF tx IS high AND rx IS high AND idle IS high THEN APAV IS SR;
```

For an FTP application, the power consumption is dependent on the Idle power consumption rate. We defined twenty seven fuzzy rules for an FTP application (Listing IV.8). Using these fuzzy rules, we calculated the APAV for each application with their service requirements.

Listing IV.8: Fuzzy rule definition for calculating $APAV_L$ of an FTP application

```
RULE 1: IF tx IS low AND rx IS low AND idle IS low THEN APAV IS SA;
RULE 2: IF tx IS low AND rx IS low AND idle IS medium THEN APAV IS SA;
RULE 3: IF tx IS low AND rx IS low AND idle IS high THEN APAV IS SA;

RULE 25: IF tx IS high AND rx IS high AND idle IS low THEN APAV IS SR;
RULE 26: IF tx IS high AND rx IS high AND idle IS medium THEN APAV IS SR;
RULE 27: IF tx IS high AND rx IS high AND idle IS high THEN APAV IS SR;
```

We implemented the fuzzy membership functions and inference rules using jFuzzy-Logic [90], which is an open source fuzzy logic written in the Java language. The implementation details of fuzzy membership functions and inference rules are described in Appendix A.

4.3.3 AP Satisfaction Value Calculation

We use utility theory for measuring end user satisfaction. First we briefly review utility theory and then present our APSV calculation based on it.

Utility Theory

In economics, utility is a measure of relative satisfaction. That is, it represents the ability of a good or service to satisfy a human need. Given this measure, one may speak meaningfully of increasing or decreasing utility, and thereby explain economic behavior in terms of attempts to increase one's utility [91]. The basic utility theory was proposed by John von Neumann and Oskar Morgenstern who used the assumption of expected utility maximization in their formulation of game theory [91, 92]. Since then, many people have developed and expanded the theory.

An associated term is utility function which relates to the utility derived by a consumer from a good or service [62, 93, 94]. Different consumers with different preferences (tastes) will have different utility values for the same product. Thus, individual preferences should be taken into account in the utility evaluation. The concept of utility applies to both single-criterion (attribute, characteristic) and multi-criteria consequences. A utility function is defined mathematically as a function $U(\mathbf{w}, \mathbf{x})$ from a set of observed product criteria $\mathbf{x}$ (by the user) and user preferences $\mathbf{w}$ into a real number. As the user preferences associated with a set of considered criteria do not change while considering alternatives, hereafter we simply denote $U(\mathbf{x})$

as the utility function associated with criteria vector $\mathbf{x}$ of the product of interest. The details of the mathematical properties of such a function are described in the following.

This thesis uses ordinal utility as a means to quantify preferences among alternatives in the process of making a decision. Such preference relations can be represented by a continuous utility function. The fundamental assumption in the utility theory is that the decision maker always chooses the alternative with the highest utility value (i.e., the decision maker is assumed to be rational). Note that, if all that is known is that a user prefers p to q, this fact gives us no indication of how much more that user prefers p to q. Put another way, if $U(\mathbf{x}_p) = 3U(\mathbf{x}_q)$, p is preferred to q but p is not necessarily three times better than q. For example, a person can say that a WiFi access network is preferable to a CDMA access network for voice call applications, but not that it is twenty times preferable to the CDMA access network. The reason is that the utility of twenty CDMA access networks is not twenty times the utility of one CDMA access network, due to diminishing marginal utility. An alternative was suggested by Neumann and Morgenstern, and was based on considering probabilities [92]. If a person can choose between various randomized events (lotteries), then it is possible to *additively* compare a WiFi access network and a CDMA access network. It is possible to compare *a CDMA access network with probability 1, to a WiFi access network with probability* p *or nothing with probability* $1-p$. By adjusting p, the point at which the CDMA access network becomes preferable defines the ratio of the utilities of the two options. A notion for a *lottery* is as follows: If options A and B have probability p and $1-p$ in the lottery, it can be written as a linear combination:

$$L = pA + (1 - p)B \tag{IV.6}$$

More generally, for a lottery with many possible options:

$$L = \sum p_i A_i \tag{IV.7}$$

with the sum of the p_i equalling 1.

By making some reasonable assumptions about the way choices behave, von Neumann and Morgenstern showed that if an agent can choose between the lotteries, then this agent has a utility function which can be added and multiplied by real numbers, which means the utility of an arbitrary lottery can be calculated as a linear combination of the utility of its parts. This is called the *expected utility theorem.*

In handover decisions, when evaluating the utility of an access network or an AP, we use pre-calculated APAVs as an *upward* criterion. Upward criteria are criteria where the higher preference relation is in favor of the higher value criteria. Obviously, users prefer the higher values of upward criteria. Consider a utility function $u(x_i)$ of an upward quality-related parameter x_i, $0 \leq x_i < \infty$. Without loss of generality, we can regards x_i as the amount of resources that an access network can allocate to the user. As an upper and/or lower bound will always exist for every parameter due to technological constraints and/or user's requirements (i.e., $x_\alpha \leq x_i \leq x_\beta$, the utility also has an upper bound value. Consequently, we can normalize the utility to scale the interval $[0, 1]$, i.e., $u(x_i) \in [0, 1]$.

Our Approach

The handover decisions in heterogeneous wireless networks are based on multiple criteria. The following is a common approach to compute the aggregate multi-criteria utility of an access network:

$$U(\mathbf{x}) = \sum_{i=1}^{n} w_i u_i(X_i) \quad where \sum_{i=1}^{n} w_i = 1 \tag{IV.8}$$

where $\mathbf{x}$ is the vector of n criteria considered and w_i are the user preferences. This approach is usually referred to as an additive utility. The multi-criteria based network selection schemes were introduced in [54, 57]. We also use this additive utility function for calculating APSVs because additive utility offers an easy and comprehensible approach to aggregate different elementary utilities and allows users to introduce their preferences for different criteria.

In the previous section, we calculated APAVs for all candidate APs. We represent the APAV vector of each AP as follows:

$$\overrightarrow{APAV(AP_{i,j})} = \begin{pmatrix} APAV_R(AP_{i,j}) & APAV_C(AP_{i,j}) & APAV_Q(AP_{i,j}) & APAV_L(AP_{i,j}) \end{pmatrix} \tag{IV.9}$$

, where AP_{ij} is the jth access point of the ith access network.

By using this vector, we can select the best AP (i.e., the one that has the maximum value of UPrefs that are selected by the user). However, we assert that the AP selected by the maximum APAV is not always the AP that best satisfies the needs of the user for a specific context. For example, if the user wants to use an application with a high quality of service and does not care about the price of the network, the AP that has the maximum $APAV_Q$ is the best one. However, if the user wants to use an application that has a high quality of serice but a low price, the AP that has the maximum $APAV_Q$ may not be the best one, since its $APAV_C$ may be unacceptably low (i.e., the network is too expensive). This also applies to the AP that has the maximum $APAV_C$ (i.e., the AP that has the least cost) because it may have an $APAV_Q$ that is unacceptably low. Thus, APAVs by themselves are not enough to decide the best AP to use if the user has multiple user preferences. Therefore, we define an APSV for solving these problems. An APSV represents how well a particular AP satisfies the needs of the end user based on his or her user profile (which is selected by the end user's preferences) for a specific context.

In determining an AP that best satisfies the needs of the end user, APAVs based on fuzzy goals and fuzzy constraints have unequal importance to decision making, and the proper fuzzy decision making operator should be considered. The weighted additive model (which is widely used in vector objective optimization problems) can handle this problem; the basic concept is to use a single utility function to express the overall preference of decision making to draw out the relative importance of each criterion [95]. In this case, a linear weighted utility function is obtained by multiplying each membership function of fuzzy goals by their corresponding weights and then adding the results together.

In this thesis, we define a utility function to calculate the set of APSVs of all candidate APs by applying a weighted UP. As we mentioned before, we use an additive aggregate utility function [96] which aggregate multiple criteria in a composite criterion, using the information given by a subjective ranking. We used user profiles as subjective ranking. The following Equation IV.10 calculate an APSV of each AP.

$$\begin{aligned} APSV(AP_{i,j}) &= \overrightarrow{UP} \bullet \overrightarrow{APAV(AP_{i,j})}^T \\ &= \begin{pmatrix} W_R & W_C & W_Q & W_L \end{pmatrix} \bullet \begin{pmatrix} APAV_R(AP_{i,j}) \\ APAV_C(AP_{i,j}) \\ APAV_Q(AP_{i,j}) \\ APAV_L(AP_{i,j}) \end{pmatrix} \\ &= W_R \bullet APAV_R(AP_{i,j}) + W_C \bullet APAV_C(AP_{i,j}) \\ &\quad + W_Q \bullet APAV_Q(AP_{i,j}) + W_L \bullet APAV_L(AP_{i,j}) \end{aligned} \tag{IV.10}$$

, where AP_{ij} is the jth access point of the ith access network. We select the best AP, which has the maximum APSV, after calculating all APSVs.

4.4 System Architecture

In this section, we present the architecture of the autonomic handover decision maker for supporting our decision making algorithm.

The block diagram of a *Terminal Management System (TMS)* is shown in Figure IV.6 [78]. Traditionally, a TMS selects the network interface for vertical handover by only using the RSS. However, a TMS for next-generation networks require an innovative architecture that is capable of dynamically selecting the appropriate access network through which services can be obtained efficiently in terms of cost and quality of service in a transparent manner. Our proposed architecture, which

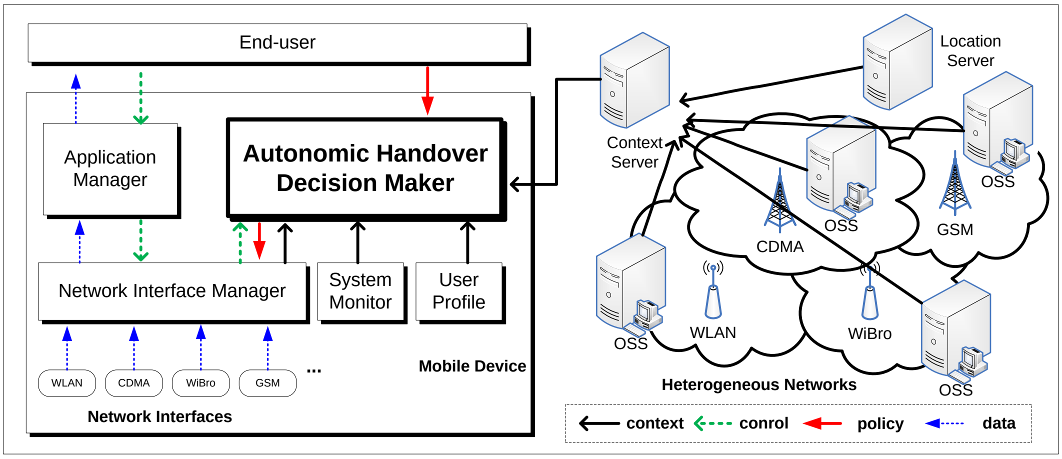


Figure IV.6: Block diagram of a terminal management system in heterogeneous wireless network environment

has an *Autonomic Handover Decision Maker (AHDM)*, is able to use the context information from the mobile device and the context server to make a more informed handover decision. The context server collects the network context information from the respective *Operations and Support Systems (OSS)* that are used to manage the network. Currently, this is not realistic because it is difficult to share diverse context information from disparate data sources among different service providers; this is primarily due to the different languages that are used to express context information from each data source, along with the inherent unwillingness of a service provider to divulge information about how their network operates. We assume that this will be possible in a future network and service environment. Indeed, this is one of the primary reasons why the FOCALE autonomic architecture was developed [17]. FOCALE has a "*model-based normalization*" function that can be used to map different data to a single normalized form, so that the different data can be integrated into a single coherent whole. In the scope of this thesis, we focus not on developing context servers in heterogeneous wireless networks, but rather on using a well-developed context server for handover decisions. In the current literature, there are many good research approaches for context servers [97, 98].

There are two major parts in this architecture – the network side and the terminal side. An optimal handover decision must consider their joint contributions. On the network side, the OSS of each network performs network monitoring and reports to the context server. The various repositories distributed in the networks store the context information, such as location information and user profiles. The context server located in the network collects the relevant context information from the context repositories. On the terminal side, the TMS interacts with the context server mentioned above for the purpose of making the optimal selection of the appropriate radio segment to which the terminal will eventually be assigned. The terminal's estimation of RSS and QoS levels in the system are beneficially combined for making an informed selection of the appropriate radio technologies through which services can be obtained as efficiently as possible. Thus, both the network and the terminal contribute useful information that should be combined in order to make an optimal decision.

The AHDM interacts with the context server, system monitor, and user profile repository. After processing the context evaluation, it decides on an appropriate policy and sends it to the service manager. The application manager starts an application and requires session initialization from the session manager, which creates a session for each application using the policy from the AHDM. The session manager maintains the created session and sends the decision on the appropriate network interface for the application to the network interface manager. The network interface manager serves two purposes. One is the retrieval of measurements at the link layer in the network interface, and the other is the connection of the appropriate interface during a handover. Our management solution is located in the management layer and is independent of the OSI layers. Thus, it controls and monitors all layers in terms of a cross-layer approach. The system monitor collects all required system information, such as the remaining battery power level and other user settings in the user profile.

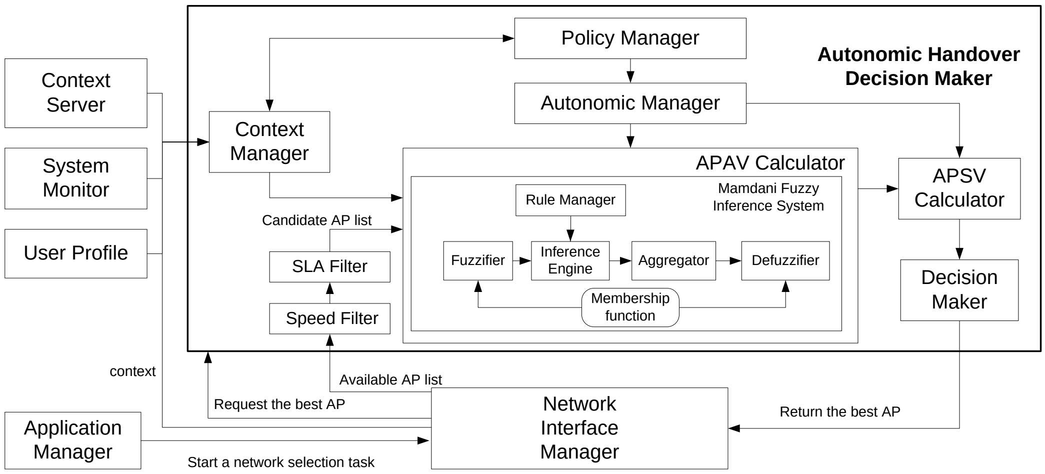


Figure IV.7: Block diagram of an autonomic handover decision maker

Figure IV.7 illustrates a block diagram of our proposed AHDM, which is based on the FOCALE autonomic architecture and the Mamdani FIS, and

Figure IV.8 shows a sequence diagram of each component for autonomic handover decision. The network interface manager requests the best AP for the current application. First, an SF removes APs that do not support speed for the current speed of the mobile device. Then, an SLAF removes APs that do not support service contracts for the current application. The context manager gathers context informa-

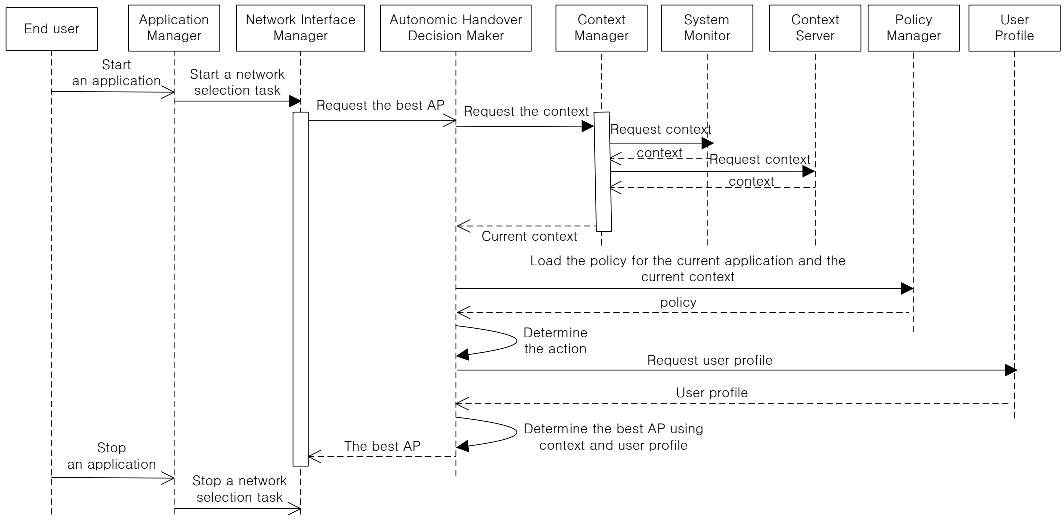


Figure IV.8: Sequence diagram for deciding handover by exchanging context information

tion from the context server, the system monitor, and the network interface manager, which detects changes in the network, mobile devices, and user needs; these context changes in turn trigger a new set of policies to take control of the autonomic system. These "*context-aware policy rules*" are a unique feature of FOCALE. The autonomic manager uses these policies to govern each of the architectural components of the control loop, enabling the different control loop components to change user profiles used as a function of context. For example, it controls the APAV calculator and the APSV calculator for evaluating the given candidate APs.

4.5 Chapter Summary

In this chapter, we explained the decision making algorithm and the system architecture of an AHDM, which is the self-governing entity managing handover decisions in AUHO. We also presented how to determine the best AP for the current service using APAVs and APSVs. In the next chapter, we will present implementation details of our simulation tool for validating our proposed method.

Chapter V

HMNToolSuite

In this chapter, we present the development of our simulation tool for testing handover decision algorithms. We call it the *HMNToolSuite*, which stands for Heterogeneous Mobile Network Tool Suite. We first present why we developed this simulation tool. Then, we present the requirements, design, and implementation of our tool. Finally, we present some case studies that use our tool.

5.1 Introduction

Next generation networks are comprised of heterogeneous access networks, and are intended to support highly mobile user terminals. A foreseen feature of these networks is the support of flexible and personalized handover decisions by dedicated devices that can choose the most appropriate access networks to satisfy the demands of the end user. Existing network simulators have focused on low-level network protocol implementation, but do not address handover decisions in a heterogeneous network environment. While the performance of such Layer 2 mobility protocols, such as mobile IP or *Media Independent Handover (MIH)*, is important, we focus on higher-level aspects of the handover decision as Layer 7 mobility, such as how to use context information and policies for handover decisions. Therefore, we decided to develop a more flexible and user-friendly simulation tool, called HMNToolSuite, which models these aspects and also enables the integration of these aspects with data from existing network simulators for modeling the low-level aspects of handover decisions.

Our HMNToolSuite is a tool for emulating and simulating heterogeneous mobile networks with mobile nodes, network devices, and servers, and it is currently available as an *open source project* [99] to encourage and enable other researchers to use our tool. This tool supports the creation of heterogeneous access networks, different types of mobile nodes, and servers. It also supports the creation and simulation of various scenarios using a custom network map. Currently, time-series packet traffic data is manually configured for simulation. We will support this tool to import packet trace files generated from traditional network simulator tools, such as NS-2. It is important to note that this tool is not an independent simulator designed to replace traditional simulators, such as NS-2. Rather, this tool has been designed as a component to support handover decision modeling. Thus, it can either be used to simulate the high-level aspects of handover decisions or, if a complete scenario is desired, it can be used in conjunction with other simulators, with it modeling the high-level aspects and other components modeling the low-level aspects. Each simulation was performed using this tool. In addition, anyone can use this tool for testing and comparing other handover decision algorithms without implementing low-level protocols. We have implemented six handover decision algorithms (including our own), and hope that this can be used to contribute to future research for handover decisions. We will present these algorithms in Chapter VI.

5.2 Requirements

The requirements for our HMNToolSuite are summarized as follows:

- **Heterogeneous Networks Modeling:** The tool should be able to create, modify, and delete heterogeneous wireless access networks, mobile nodes, and servers. It should also be able to specify their characteristics. Mobile services should be implemented via access networks.

- **Handover Decisions:** The tool should be able to implement handover decision algorithms in mobile nodes and provide how to use context information.

- **Scalability:** The tool should be able to run simulations with a large number of nodes in a reasonable amount of time.

- **Flexibility:** The user should be able to specify all relevant simulation parameters, policies, network status, and services in a human readable configuration file or a GUI-based configuration manager.

- **Reuse of Simulation Code:** The provided implementation of handover decisions should be reusable for real network applications enabling researchers to validate the simulation results by comparing them to the results from real-world test networks.

- **Statistics:** The tool should be able to collect statistical data such as the number of handovers, connect time of each access network, APAVs, and APSVs. The output should be in a format that is easy to post-process (e.g., for generating gnuplot-based graphs).

- **Interactive Visualizer:** In order to validate and debug new or existing handover decision algorithms, there should be a GUI, which visualizes the network map, access networks, servers, and mobile nodes in a customizable way.

Our HMNToolSuite is made up of three main tools: a) network map creator, b) network emulator, and c) network simulator.

The main features of the network map creator are as follows:

- Create/modify/export network maps (a network map contains the types of networks and network devices for a given scenario, along with their physical placement, and the path of one or more mobile nodes through that environment)

- Add/modify/delete Networks

- Add/modify/delete Mobile Nodes

- Create new mobile nodes based on feature models[1] (see Appendix B, Section 2.1)

- Network maps with zoom-in/zoom-out capability

- Edit the moving path of mobile nodes

[1]A feature model is a compact representation of all the products of an software product line in terms of features [100, 101, 102]

- Create/modify/open/save simulation scenarios

The main features of the network emulator are as follows:

- Open a network map (created by the network map creator tool)
- Emulate how networks and mobile nodes function in the environment represented by a network map
- Visualize the path taken by mobile nodes
- Support the simulation of key operational characteristics of networks defined in the network map
- Support the simulation of detecting available networks in a network map using mobile devices
- Support the simulation of the selection, by the mobile device, of one network for each application based on a given policy or set of policies
- Monitor horizontal and vertical handovers
- Monitor key network characteristics, connected and unconnected mobile nodes, the current velocity and direction of a mobile node, the number and type of handovers for each mobile node, the available network(s) and their associated metrics, such as RSS, connected network(s) based on those metrics, and Application Status

The main features of the network simulator are as follows:

- Open a network map (created by the network map creator tool)

- Simulate networks and mobile nodes based on a given time period
- Show the network status and mobile node status
- Show the handover status
- Show the simulation performance using graphs
- Show the number of handovers, velocity, and connected time of each mobile node in the network map
- Generate random network maps
- Support a *Command Line Interface (CLI)*

5.3 Design of the HMNToolSuite

In this section, we present the design details of our HMNToolSuite. First, we describe the overall structure of our tool. Then, we present the design of mobile devices and handover decision algorithms.

5.3.1 Overall Design

Figure V.1 is the main class diagram of our tool. We used the *Model-View-Controller (MVC)* pattern for this design, which is a well-known software pattern for separating the modeling of the domain from the presentation and the actions taken in the domain based on user input [42].

The HMNEmulator class is the main class responsible for executing the emulation tasks. It is built with no concern for how it will "look and feel" when presented to

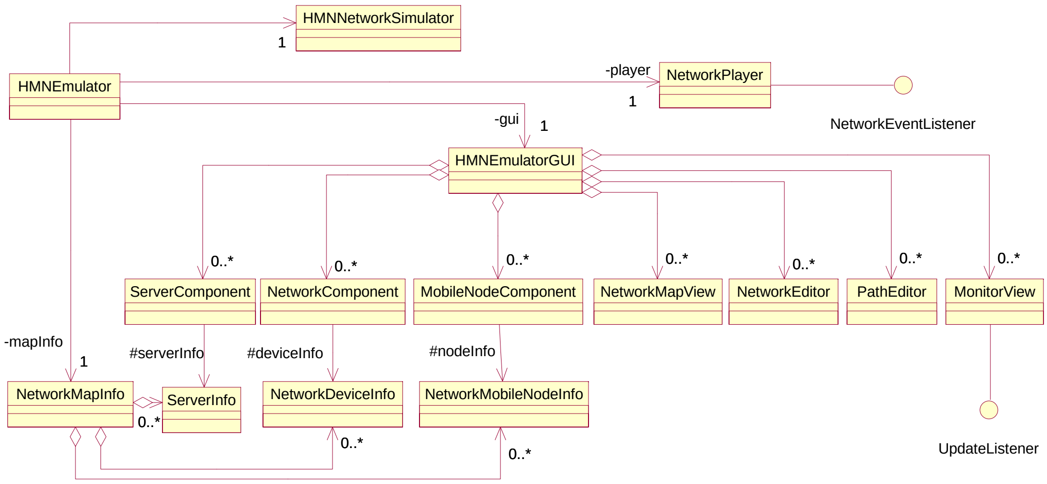


Figure V.1: Class diagram of the main components of the HMNToolSuite

the user. It has a purely functional interface, meaning that it has a set of public functions that can be used to execute all of its functionality. It provides interfaces to access the NetworkMapInfo data classes. The NetworkMapInfo has three types of data: a) NetworkDeviceInfo, b) NetworkMobileNodeInfo, and c) ServerInfo. The NetworkDeviceInfo class provides information related to network devices, such as type of BS or AP, and their characteristics. It also provides network information, such as CDMA, WLAN, or Mobile WiMax. The NetworkMobileNodeInfo class provides information related to how the node moves mobile nodes, such as by walking, or using a car or a bus. It also provides mobile device information, such as the set of applications and network interfaces that it supports.

The HMNEmulator supports several different views of the network map, including HMNEmulatorGUI, HMNNetworkSimulator, MonitorView, and CLI view. The HMNEmulatorGUI shows the current emulating environment. We also create emulating scenarios using this GUI. It has ServerComponents, NetworkComponents, MobileNodeComponents, a NetworkMapView, a NetworkEditor, a PathEditor, and a MonitorView. The ServerComponent, NetworkComponent, and MobileNodeComponent have their specific icons and information defined using the ServerInfo, NetworkDeviceInfo, and NetworkMobileNodeInfo information classes, respectively. The NetworkMapView shows the current network map and all components. The PathEditor enables us to create and modify paths for each mobile node. The MonitorView provides a current snapshot of all components by monitoring them periodically and displaying them on demand. Finally, the NetworkPlayer generates network events for transferring packets between network devices, mobile devices, and servers in the network map.

5.3.2 Mobile Device Design

This section describes the design details of mobile devices in the HMNToolSuite. This tool suite supports designing mobile devices for testing handover decisions based on context information. Mobile devices have many functions, but we focus on only their network interfaces and the needs of applications that are run on the mobile device. We used *Feature Oriented Software Development (FOSD)* [103] for creating mobile devices in our tool. We describe FOSD in Appendix B and how to apply FOSD to create mobile device software in Appendix 2.3.

Figure V.2 shows a class diagram of a mobile device in our tool. The MobileDevice class has its own mobile device operating system; this class (MobileDeviceOS, not shown) has a GUIManagementComponent (not shown) that provides GUI interface capabilities. The MobileDevice class also has relationships with the following classes: PolicyManager, NetworkInterfaceManager, StateManager, and Applica-

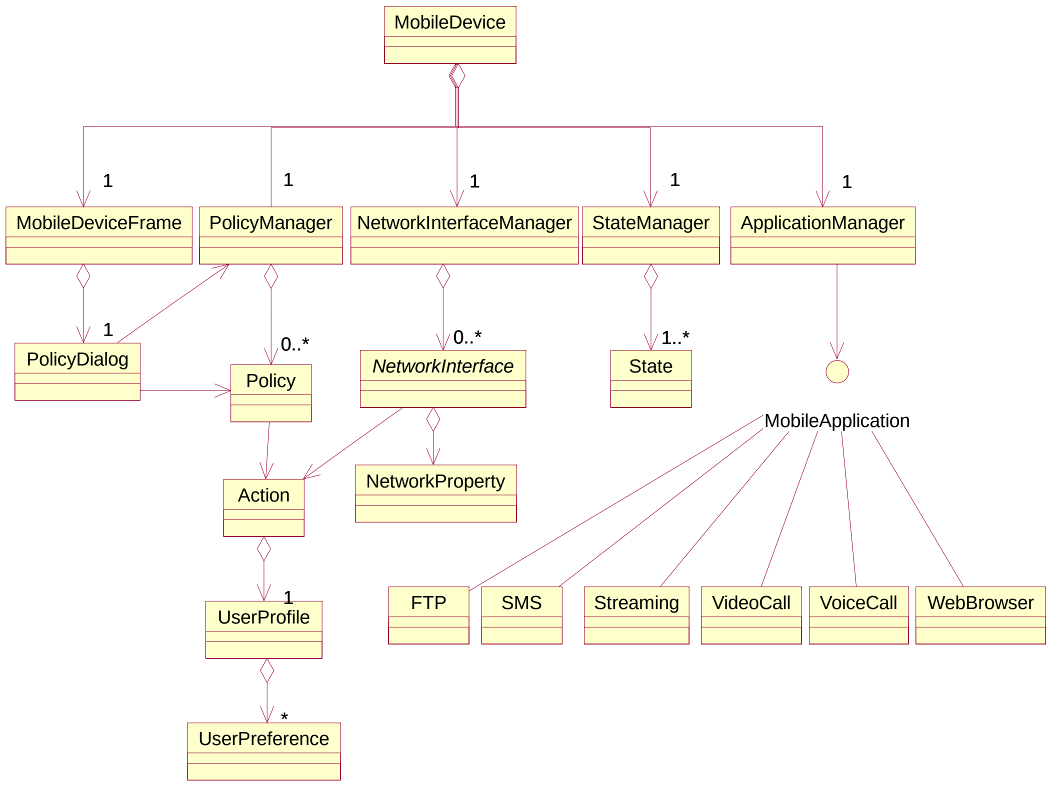


Figure V.2: Class diagram for a mobile device of HMNToolSuite

tionManager. The GUIManagementComponent provides a GUI for interacting with users and displaying current information of mobile devices. The PolicyManager manages all policies for handover decisions for the mobile device. As we mentioned in 4.2, we defined policies with event-condition-action tuples; hence, our policy rules, along with the events, conditions, and actions that they use, reuse the rich DEN-ng policy model that has already been tested and used by many different organizations [39, 40]. Actions are defined as a tuple, which has the semantics $SET < variable > TO < value >$. This can be used to change the state of one or more objects in the system. In our case, it can be used to change all or part of a

UserProfile, which is composed of a set of user preferences, UserPreference (among other items, but those are beyond the scope of this thesis). The StateManager is used to manage the state of mobile devices. The ApplicationManager is used to manage various aspects of the life cycle of applications. Currently, our tool supports six types of applications: FTP, SMS, Streaming, VideoCall, VoiceCall, and WebBrowser.

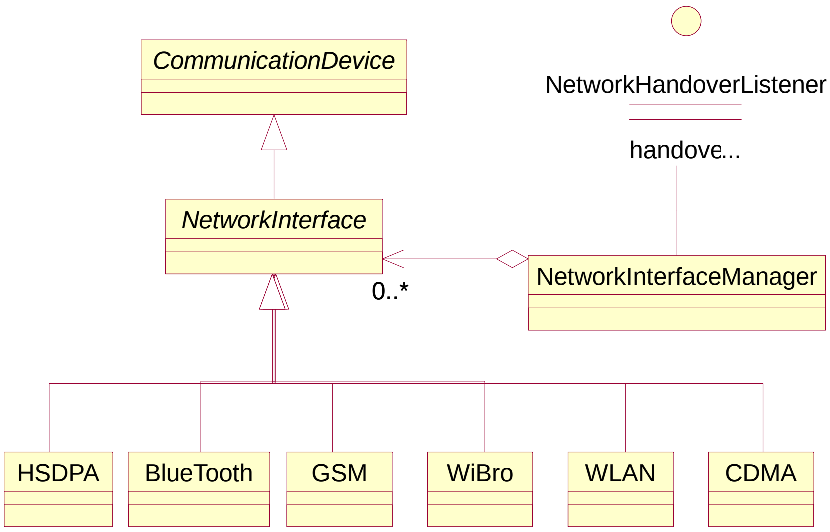


Figure V.3: Class diagram for a network interface of HMNToolSuite

The NetworkInterfaceManager manages network interfaces to connect access networks. Figure V.3 shows a class diagram of network interfaces in a mobile device. The MediaInterface class, defined in DEN-ng, is an abstract class that serves as the superclass for all interfaces whose functionality is dependent on a particular transmission medium. We subclass the MediaInterface class to add new wireless interface classes. Currently, our tool support six types of network interfaces: HSDPA, Bluetooth, GSM, Mobile WiMax, WLAN, and CDMA. However, we can easily add new network interfaces.

5.3.3 Handover Decision Manager Design

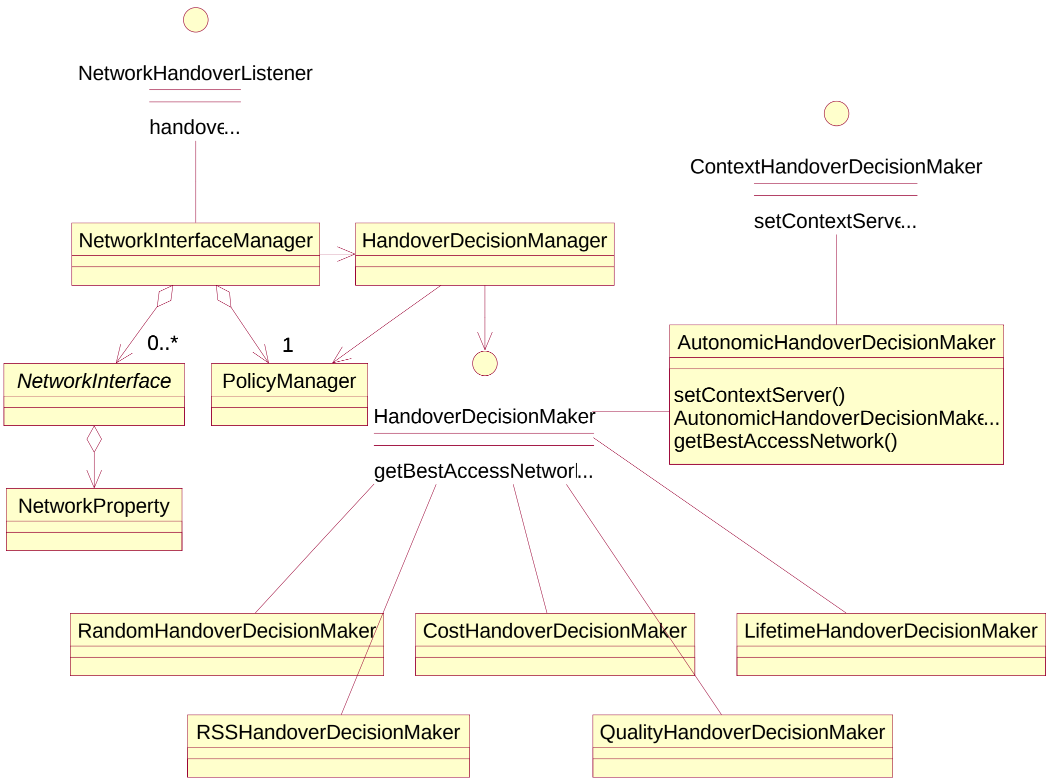


Figure V.4: Class diagram of a handover decision supported by the HMNToolSuite

A handover decision manager is one of the core components of the NetworkInterfaceManager. The NetworkInterfaceManager decides which of the available network interfaces should be used for a given application or task. The HandoverDecisionManager selects an appropriate handover decision algorithm based on the current policy provided by the PolicyManager. In our tool, we already implemented six handover decision algorithms: 1) Random, 2) RSS-based, 3) Cost-based, 4) Quality-based, 5) Lifetime-based, and 6) our proposed AUHO. If anyone wants to add a new handover decision algorithm, he or she can easily implement his or her algorithm by extending the HandoverDecisionMaker interface. This is shown in Figure V.4.

5.4 Implementation of HMNToolSuite

In this section, we present implementation details of our HMNToolSuite. We implemented our HMNToolSuite using the Java programming language (Java platform standard edition, JDK 6) [104]. We used an XML parser in the javax.xml.parsers package for creating and editing configuration files. We used jFuzzyLogic [90] for implementing fuzzy membership functions and rules. We also used jFreeChart [105] for displaying performance result graphs. Finally, we used Java Swing for constructing a GUI [106].

We describe our tool using some screenshots. We also present some additional screenshots and configuration files in Appendix C.

Figure V.5 shows a screenshot of our HMNToolSuite based on all requirements and design decisionss mentioned before. First, we create a network map with a given map image and size. Then, we create new access networks by selecting the “Add New Network” command button from the menu palette or the menu bar. This creates a dialog box that prompts the developer to assign some important characteristics for the access network. Then, the developer clicks on the network map where it is to be positioned. Each access network has a different sort of predefined characteristics, but our tool enables the developer to configure each parameter for each supported network type. Listing C.1 of Appendix C shows a sample configuration file for an access network. Thus, we can modify the existing access network configuration, or create a new one. In Figure V.5, circles with the different colors represent the different access networks. For example, the red circle represents a CDMA access network.

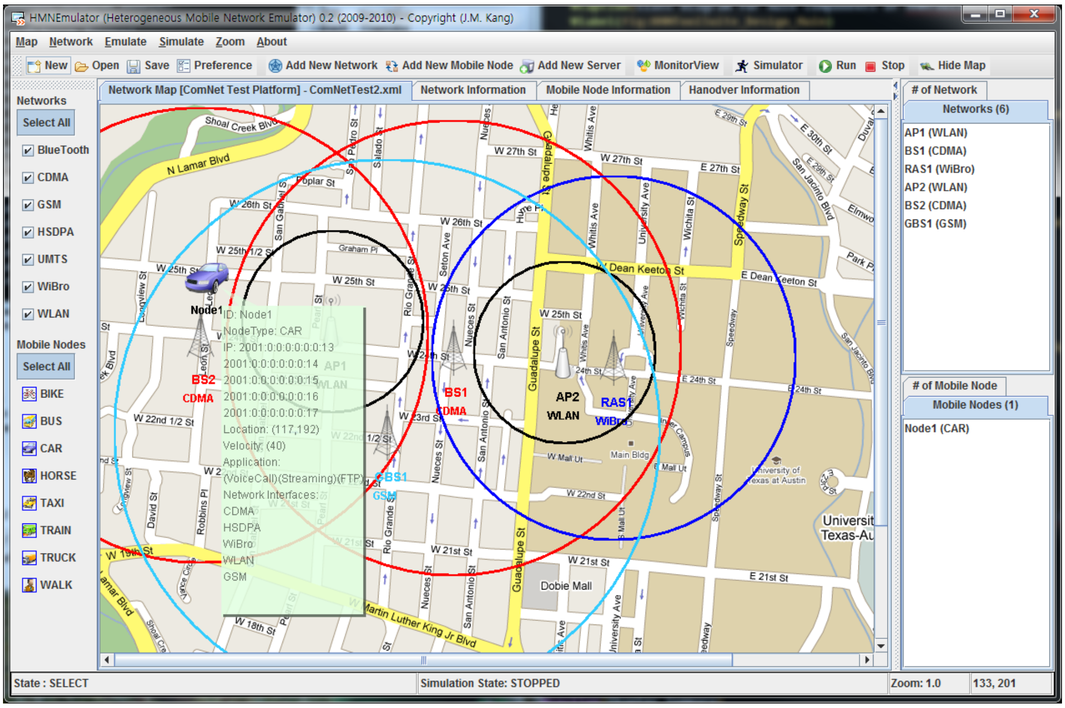


Figure V.5: A screenshot of the HMNToolSuite

Then, we create a mobile node by selecting the "Add New Mobile Node" command button from the menu palette. This creates a dialog box that prompts the developer to assign some important characteristics for the mobile node, as shown in Figure V.6. Then, the developer clicks on the network map where it is to be positioned.

As we mentioned earlier, we developed the mobile node creator using FOSD. We can create various mobile nodes, which have different types of applications and network interfaces. When we create a mobile node, we determine possible network

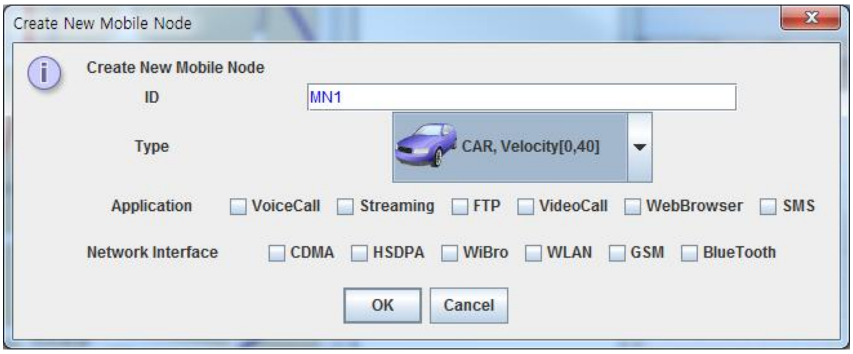


Figure V.6: A screenshot of a mobile node creator of the HMNToolSuite

interfaces to connect for mobile services. For example, if we select CDMA, HSDPA, and Mobile WiMax access networks for a mobile device, the mobile device can only access those three types of access networks. Listing C.2 of Appendix C shows a sample configuration file for a mobile node. We can modify the configuration or create a new one to meet the needs of the scenario being simulated.

After creating all access networks and mobile nodes that are required for a given scenario, we define handover decision policies as shown in Figure V.7. We create a new policy with a name, an event, a set of conditions to be specified, and a set of actions to be taken, as we mentioned in Section 4.2. In this case, an event or set of events, signal the occurrence that something significant has happened (e.g., request to start an application, or the loss of communication). More importantly, events are used to trigger the evaluation of a condition. Conditions (one or a boolean combination of conditions) are used to determine which action or set of actions should be executed in response to the event (or set of events). Contextual information such as environmental data, is one important type of condition. We implemented three types of context: location, time, and contact. An action can be used to invoke one of the handover decision methods. Currently, six handover decision methods are available. When we select AUHO as a handover decision method, we read user preferences that directly assign weighted values for each preference item. The policies can be changed dynamically at runtime.

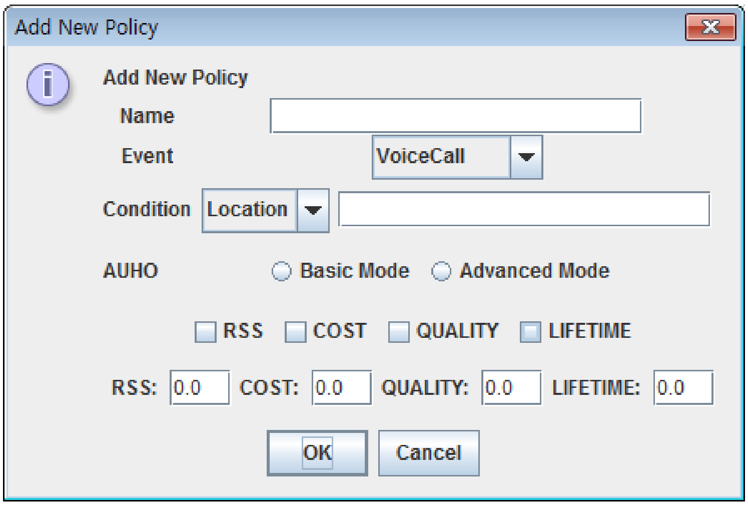


Figure V.7: A screenshot of a policy setting dialog of the HMNToolSuite

After setting policies, we assign moving paths for each mobile node using a path editor as shown in Figure V.8. We create a moving path by adding points that define the path to be taken. We can also change the velocity and the time that the node stays at each point as shown in Figure C.1 of Appendix C. We use the moving path for simulating mobile nodes.

Figure V.9 shows a screenshot of a simulator view using the created network map. The mobile node, `Node1`, is moving based on its defined moving path. The connection of a mobile node and an AP is represented by a colored line. In Figure V.9, `Node1` is connected to `BS2`. This network connection is performed by a handover decision policy.

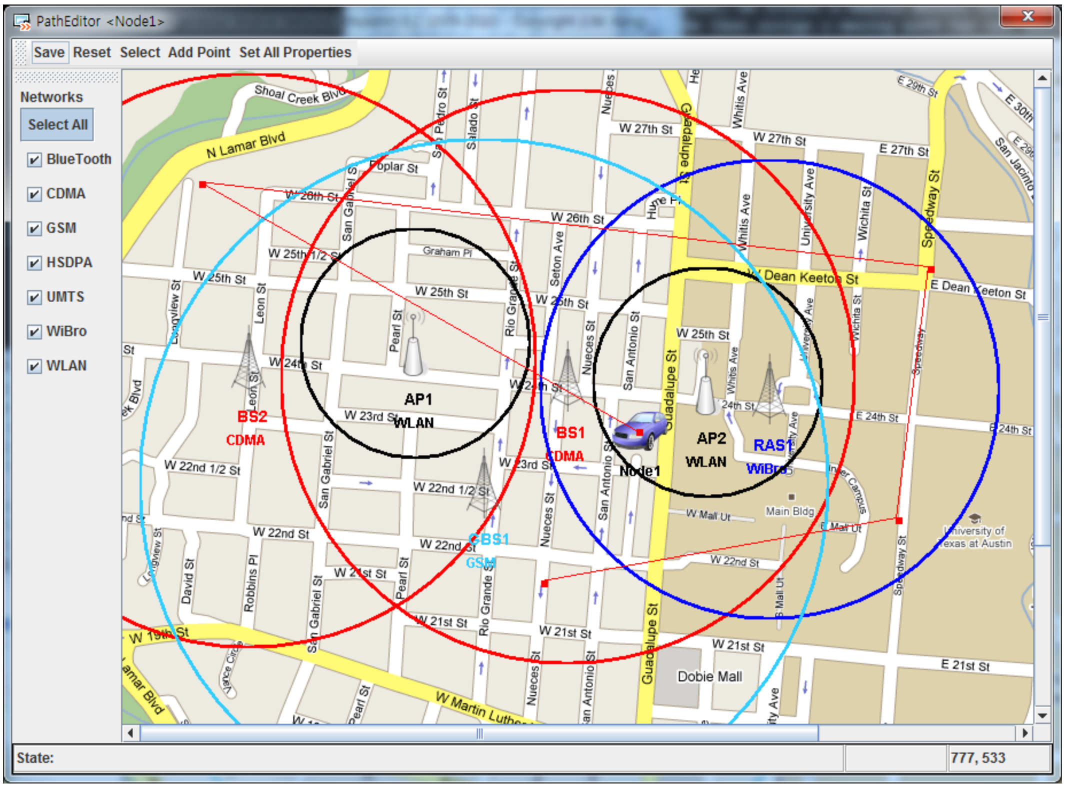


Figure V.8: A screenshot of a path editor of the HMNToolSuite

Figure V.10 shows a monitoring view. In the network screen, all characteristics and connected nodes are displayed; hence, the mobile node screen displays available access networks and APs, their RSSs, and a connected access network.

By simulating a network map, we can get result reports to analyze. These reports include important metrics such as the number of handovers, connected time, APAVs, and APSVs as shown in Figure C.2 of Appendix C.

To aid simulation, our tool supports a CLI-based simulation, as shown in Figure C.3 of Appendix C. We control all simulating parameters and can get all results from the CLI.

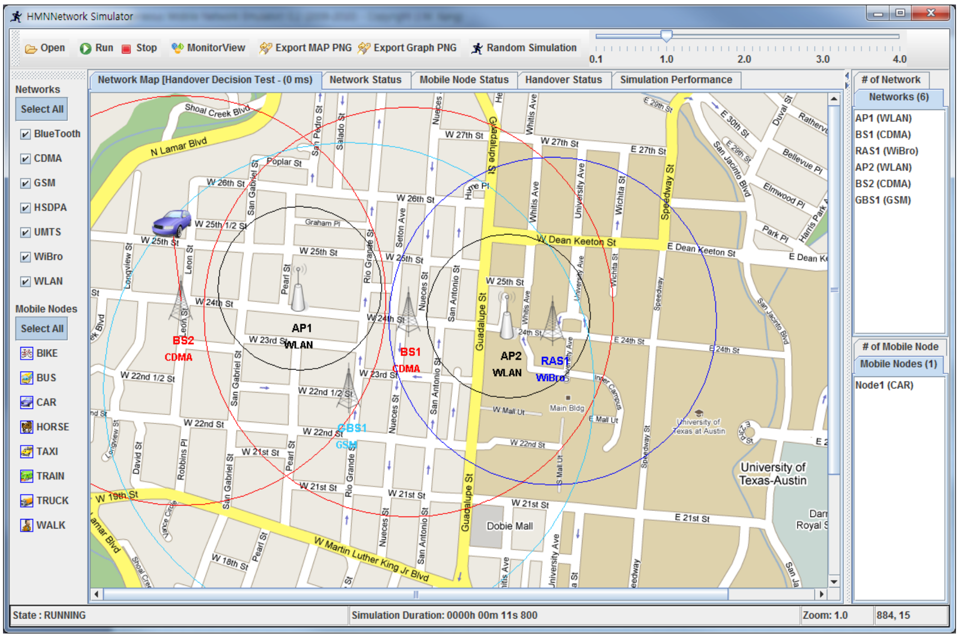


Figure V.9: A screenshot of the simulator view of the HMNToolSuite

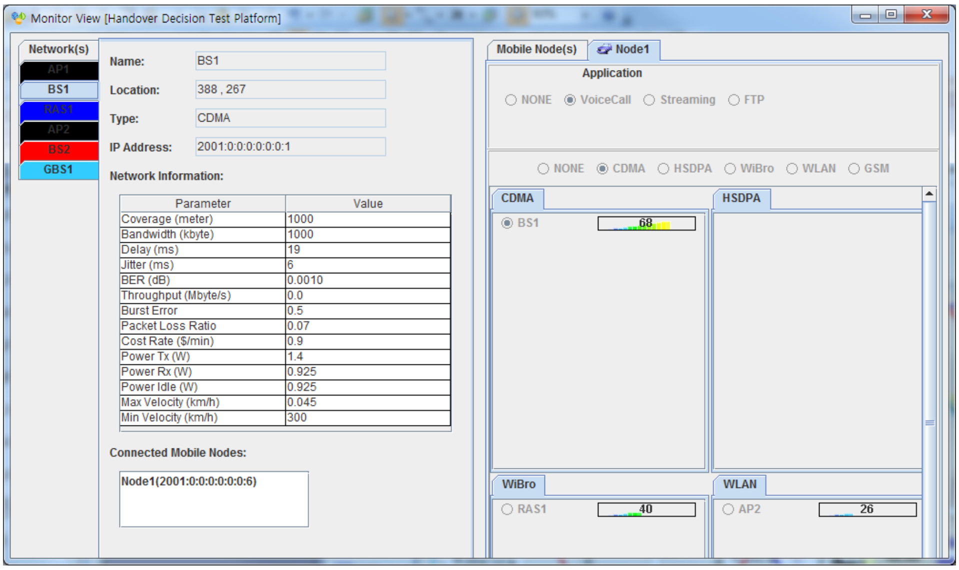


Figure V.10: A screenshot of the monitoring view of the HMNToolSuite

5.5 Validation

Our simulator focuses on Layer 7 mobility and uses other Layer 2 handover protocols from existing network simulators such as ns-2. Those protocols have been widely used and well validated on wireless communications. We used the *Free Space Path Loss (FSPL)* [107] for wireless transmission media because it is the most common model where the received signal strength is computed assuming a perfect obstacle free environment, where transmission losses due to multipath fading, shadowing, etc. are ignored. Although the current version of our simulator has some limitations for applying real wireless communication environments, it can be easily applied by extending with different signal modeling. This signal modeling is beyond this thesis. After developing our simulator, we tested previous decision algorithms and validated it for testing our proposed algorithm by getting the same results . Moreover, we can generate any possible scenario with heterogeneous access networks, applications, mobile devices, and servers easily.

5.6 Chapter Summary

In this chapter, we introduced our simulator tool, HMNToolSuite, for testing and validating handover decision algorithms in heterogeneous wireless networks. We presented the requirements, designs, and implementation details of the tool. In the next chapter, we will present performance evaluation and results of our handover decision algorithm compared to other algorithms using the tool.

Chapter VI

EVALUATION AND RESULTS

In this chapter, we present several simulation scenarios and their results for validating our proposed AUHO algorithm. First, we will describe our experimental setup and simulation environment for testing handover decision making algorithms in heterogeneous wireless networks. Then, we will explain how our testing tool works in the context of two case studies: a) the same application using different user profiles, and b) different applications using the same user profile. The former tests different weighting factors for each user preference, while the latter tests different application requirements for the same user profile. Finally, we will show experimental results for validating our AUHO to select the best access network and AP in those two case studies in terms of end user satisfaction.

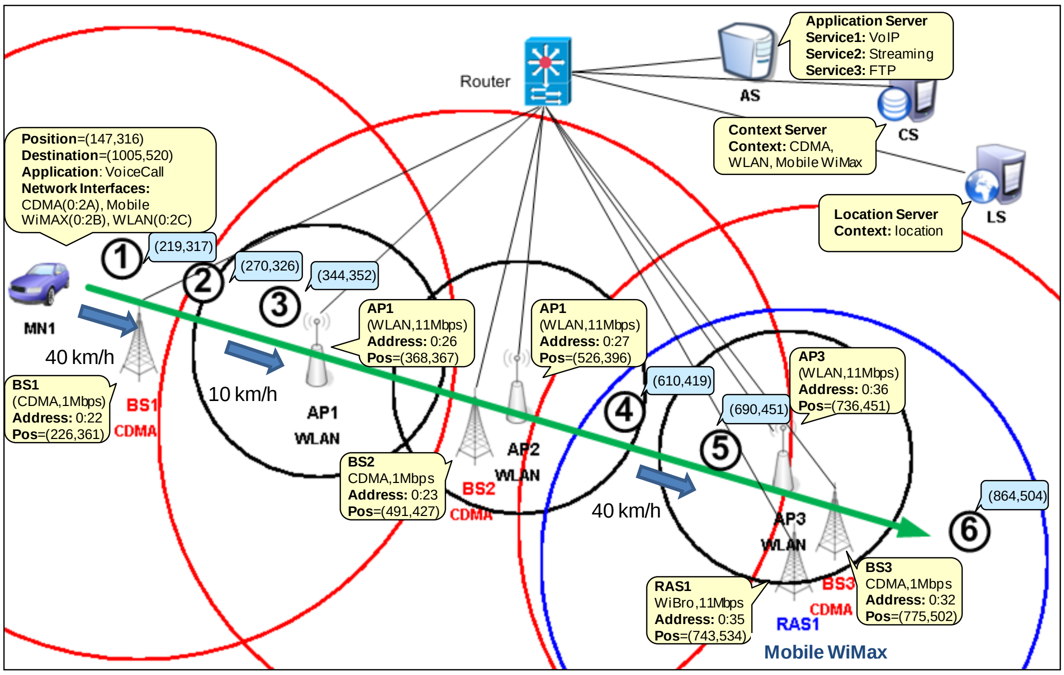


Figure VI.1: Simulation environment for handover decisions in CDMA, WLAN, and Mobile WiMax access networks

6.1 Experimental Setup

In our experiment, the subject is a mobile device that includes our AUHO algorithm and the base is a mobile device that includes the following handover decision algorithms: Random, RSS-based, Cost-based, Quality-based, and Lifetime-based. We compare each of these algorithms to our proposed AUHO algorithm. The measurement metric is end user satisfaction, which we measure by using an APSV for the selected AP. First, we construct a heterogeneous wireless network environment, as illustrated in Figure VI.1. Then, we create a mobile device that supports multiple network interfaces and applications. We then assign a moving path for the mobile device; this is shown in Figure VI.1 as the large horizontal arrow. We then apply three different types of application traffic, which we generated from an NS-2 network simulator. Finally, we measure the APSVs of each handover decision algorithm and compare them.

6.2 Simulation Environment

In this section, we present our simulation environment for testing scenarios. We created a simulation environment that is made up of multiple heterogeneous wireless networks using the HMNToolSuite that we described in Chapter V.

In this experiment, we used CDMA, IEEE 802.16 Mobile WiMax (Mobile WiMax), and IEEE 802.11 based WLAN access networks, as illustrated in Figure VI.1. The area of the simulation network was 1,000 m by 1,000 m. Three CDMA BSs, one Mobile WiMax *Radio Access Station (RAS)*, and three WLAN APs were covering the area. In this experiment, we considered BSs, RASs, and APs to each function as an AP. These access nodes were connected to the Router via 100 Mbps trunks with different traffic parameters. The coverage of each access point was represented by an associated ellipse. We chose the MIPv6 protocol as the IP mobility management protocol for the mobile nodes. One mobile node, MN1, was managed in our simulation environment. This mobile node moved from a starting coordinate $(147, 316)$ to an ending coordinate $(864, 504)$, with a speed of 40 km/h. The MN1 had three different types of network interfaces: CDMA, Mobile WiMax, and WLAN, which enabled it to communicate with each access network for the specific application. The context server gathered the context information from each access network. We controlled all network parameters of each network device. The application server provided three different types of application traffic: VoIP, Streaming Multimedia, and FTP. We created traffic for each application using an NS-2 network simulator.

Table VI.1: Network device parameter settings at each location

Access Network (Access Point)	**CDMA (BS1)**	**CDMA (BS2)**	**CDMA (BS3)**	**WLAN (AP1)**	**WLAN (AP2)**	**WLAN (AP3)**	**Mobile WiMax (RAS1)**
Coverage (meter)	1000	1000	1000	400	400	400	800
Bandwidth (kbyte)	1000	1000	1000	11000	11000	11000	2000
Delay (ms)	25	19	22	8	25	45	25
Jitter (ms)	7	6	7	4	8	10	8
Bit Error Ratio (dB)	0.001	0.001	0.001	0.00001	0.00001	0.00001	0.0001
Throughput (Mbyte/s)	1.3	1.7	1.7	25	25	25	15
Burst Error	0.6	0.5	0.5	0.2	0.2	0.2	0.1
Packet Loss Ratio	0.08	0.07	0.07	0.04	0.04	0.04	0.02
Cost Rate ($/min)	0.9	0.9	0.9	0.2	0.2	0.2	0.5
Power Tx (W)	1.4	1.4	1.4	2.8	2.8	2.8	2
Power Rx (W)	0.925	0.925	0.925	0.495	0.495	0.495	0.7
Power Idle (W)	0.045	0.045	0.045	0.082	0.082	0.082	0.06
Minimum Speed (km/h)	0	0	0	0	0	0	0
Maximum Speed (km/h)	300	300	300	12	12	12	80

In the experiment, we configured network parameters for our case studies as shown in Table VI.1. Each of the six locations represents different control points to calculate handover decisions. The characteristics of each location, and the different semantics that they provide, are as follows:

- Location 1: Starting point (only one access network, CDMA (BS1), is available. All decision algorithms will select it.
- Location 2: The delay and jitter of BS1 are higher than those of BS2, and the speed of the MN1 is changed to 10 km/h.

- Location 3: The power consumption rate of CDMA is lower than that of WLAN.
- Location 4: The quality of WLAN is lower than that of CDMA. However, the price of WLAN is lower than that of CDMA.
- Location 5: The speed of MN1 is changed to 40 km/h. WLAN is filtered by the speed filter. The quality of BS2 is higher than that of BS3.
- Location 6: The price of Mobile WiMax is lower than that of CDMA.

We will show that our proposed algorithm selects the best AP at all locations in terms of end user satisfaction, and hence performs better than the other algorithms.

6.3 Experimental Results

In this section, we present our experimental results. To evaluate our proposed AUHO algorithm, we compared its performance with the following five handover decision methods: 1) *Random decision (RD)*, 2) *RSS-based decision (RSSD)*, 3) *Cost-based decision (CD)*, 4) *Quality-based decision (QD)*, and 5) *Lifetime-based decision (LD)*. First, we compare available access networks, and then reduce the candidate access networks by speed filtering, and then further reduce the number of candidate access networks by SLA filtering. We then compute all APAVs and APSVs for all candidate APs, and present the AP selected by all handover decision algorithms at all locations in Figure VI.1. Finally, we compare the APSVs of the AP selected by all handover decision algorithms to prove our hypothesis.

6.3.1 Case Study 1: Same Application with Different User Profiles

In the first case study, we use a voice call application with three different ordinary (i.e., pre-defined) user profiles: *Cost & Quality (CQ)*, *Quality & Lifetime (QL)*, and *Cost & Quality & Lifetime (CQL)*. A voice call application uses a VoIP traffic in Figure VI.1. The duration of our simulation is *651 seconds* which the mobile node will take from the starting point to the ending point. Table VI.2 shows the experimental results of a voice call with the user profile, CQ.

At location 1, all decision algorithms select BS1 as the best AP.

At location 2, RD, RSSD, CD, and LD select the CDMA (BS1) as the best AP, whereas QD and AUHO select the CDMA (BS2) as the best AP. Although the RSS of BS1 is stronger than the RSS of BS2, the quality of voice call traffic of BS2 is better than that of BS1 (because the delay and jitter of BS1 are higher than that of BS2). That is, the $APAV_Q$ and $APSV$ of BS2 are higher than the $APAV_Q$ and $APSV$ of BS1. In this experiment, BS2 is the best AP because the UP is CQ. Our AUHO provides a better solution than RD, RSSD, CD, and LD at location 2.

At location 3, RD, RSSD, CD, QD, and AUHO select WLAN (AP1) as the best AP, whereas LD selects the CDMA (BS1) because the power consumption rate of CDMA is lower than that of WLAN. In this location, AP1 is the best AP because the UP is CQ. Our AUHO method provides a better solution than LD at location 3.

At location 4, RD, CD, and AUHO select WLAN (AP2) as the best AP, whereas RSSD, QD, and LD select CDMA (BS2) as the best AP. The quality of a voice call application of BS2 is higher than that of AP2, but the cost of BS2 is higher than

Table VI.2: Experimental results at each location (Application=Voice Call, UP=Cost & Quality)

Location	**1**	**2**	**3**	**4**	**5**	**6**
Simulation Time (sec)	25	44	157	553	585	651
Available Access Networks (AP)	CDMA(BS1)	CDMA(BS1,BS2)	CDMA(BS1,BS2), WLAN(AP1)	CDMA(BS2,BS3), WLAN(AP2), Mobile WiMax(RAS1)	CDMA(BS2,BS3), WLAN(AP3), Mobile WiMax(RAS1)	CDMA(BS3), Mobile WiMax(RAS1)
Speed Filtering (AP)	CDMA(BS1)	CDMA(BS1,BS2)	CDMA(BS1,BS2), WLAN(AP1)	CDMA(BS2,BS3), WLAN(AP2), Mobile WiMax(RAS1)	CDMA(BS2,BS3), Mobile WiMax(RAS1)	CDMA(BS3), Mobile WiMax(RAS1)
SLA Filtering (AP)	CDMA(BS1)	CDMA(BS1,BS2)	CDMA(BS1,BS2), WLAN(AP1)	CDMA(BS2,BS3), WLAN(AP2), Mobile WiMax(RAS1)	CDMA(BS2,BS3), Mobile WiMax(RAS1)	CDMA(BS3), Mobile WiMax(RAS1)
AP ($APAV_R$)	BS1(0.816)	BS1(0.779), BS2(0.019)	BS1(0.530), BS2(0.335), AP1(0.703)	BS3(0.256), BS2(0.527), RAS1(0.114), AP2(0.141)	BS3(0.598), BS2(0.203), RAS1(0.501)	BS3(0.652), RAS1(0.385)
AP ($APAV_C$)	BS1(0.100)	BS1(0.100), BS2(0.100)	BS1(0.100), BS2(0.100), AP1(0.800)	BS3(0.100), BS2(0.100), RAS1(0.500), AP2(0.800)	BS3(0.100), BS2(0.100), RAS1(0.500)	BS3(0.100), RAS1(0.500)
AP ($APAV_Q$)	BS1(0.500)	BS1(0.500), BS2(0.900)	BS1(0.500), BS2(0.900), AP1(0.900)	BS3(0.614), BS2(0.900), RAS1(0.500), AP2(0.500)	BS3(0.614), BS2(0.900), RAS1(0.500)	BS3(0.614), RAS1(0.500)
AP ($APAV_L$)	BS1(0.500)	BS1(0.500), BS2(0.500)	BS1(0.500), BS2(0.500), AP1(0.500)	BS3(0.500), BS2(0.500), RAS1(0.203), AP2(0.500)	BS3(0.500), BS2(0.500), RAS1(0.203)	BS3(0.500), RAS1(0.203)
AP ($APSV$)	BS1(0.372)	BS1(0.368), BS2(0.452)	BS1(0.343), BS2(0.483), AP1(0.800)	BS3(0.361), BS2(0.503), RAS1(0.432), AP2(0.584)	BS3(0.395), BS2(0.500), RAS1(0.500)	BS3(0.401), RAS1(0.459)
Random (best AP)	CDMA(BS1)	CDMA(BS2)	WLAN(AP1)	WLAN(AP2)	CDMA(BS3)	CDMA(BS3)
RSS (best AP)	CDMA(BS1)	CDMA(BS1)	WLAN(AP1)	CDMA(BS2)	CDMA(BS3)	CDMA(BS3)
Cost (best AP)	CDMA(BS1)	CDMA(BS1)	WLAN(AP1)	WLAN(AP2)	Mobile WiMax(RAS1)	Mobile WiMax(RAS1)
Quality (best AP)	CDMA(BS1)	CDMA(BS2)	WLAN(AP1)	CDMA(BS2)	CDMA(BS2)	CDMA(BS3)
Lifetime (best AP)	CDMA(BS1)	CDMA(BS1)	CDMA(BS1)	CDMA(BS2)	CDMA(BS3)	CDMA(BS3)
AUHO (best AP)	**CDMA(BS1)**	**CDMA(BS2)**	**WLAN(AP1)**	**WLAN(AP2)**	**CDMA(BS2)**	**Mobile WiMax(RAS1)**

that of AP2. In terms of Quality, BS2 is the best AP. However, AP2 is the best AP in terms of Cost. The strength of our proposed AUHO method is shown here particularly well. In a complex situation such as this, we measure the satisfaction value, $APSV$, of each AP, based on the user profile. In the $APAV$ calculation phase, the $APAV_Q$ of BS2 is 0.9, whereas the $APAV_C$ is 0.1. The $APAV_Q$ of AP2 is 0.5, whereas the $APAV_C$ is 0.8. If we consider only one metric, Quality or Cost, we would simply select BS2 or AP2. In this experiment, if we consider two metrics, Cost and Quality, as the user profile, we cannot select the best satisfying AP with only $APAVs$. We need to calculate $APSVs$ of all APs to solve this problem. With the consideration of end user satisfaction, the $APSV$ of BS2 is 0.503, whereas that of AP2 is 0.584, which is higher than that of BS2. At location 4, our AUHO method provides a better solution than QD.

At location 5, the speed of MN1 is changed to 40 km/h. The WLAN (AP2) is removed from the candidate access network list by the speed filter because the supporting maximum speed of WLAN is 12 km/h. RD, RSSD, and LD select CDMA (BS3), CD selects Mobile WiMax (RAS1), and QD and AUHO select CDMA (BS2). CD selects RAS1 because the cost rate of Mobile WiMax is lower than that of CDMA. In terms of Cost, RAS1 is the best. However, the quality of RAS1 is lower than that of CDMA. In this case, $APSVs$ of BS2 and RAS1 are equal. When they are equal, our proposed algorithm selects the AP that has the stronger RSS (since the UP is CQ).

Finally, at location 6, RD, RSSD, QD, and LD select CDMA (BS3), whereas CD and AUHO select Mobile WiMax (RAS1). The quality of BS3 is higher than that of RAS1, whereas the cost of CDMA is higher than that of Mobile WiMax. The

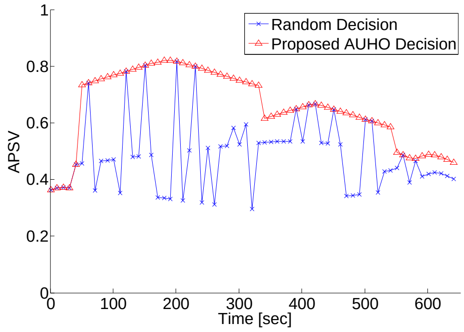
$APSV$ of BS3 is 0.401, whereas that of RAS1 is 0.459. Our proposed AUHO selects RAS1 as the best AP.

Figure VI.2 shows the comparison of our proposed AUHO algorithm with the other decision algorithms over the total duration. We compared the $APSVs$ of the selected AP. Significantly, our proposed AUHO algorithm always provided ABS mobility compared to the other decision algorithms. In addition, we performed the experiments with two other UPs, *Quality and Lifetime (QL)* and *Cost, Quality, and Lifetime (CQL)*, and the results, which are displayed in Figure VI.3 and Figure VI.4, showed that our AUHO algorithm outperformed the other decision algorithms.

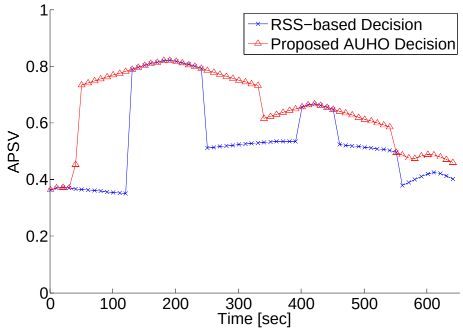
We summarized the mean and standard deviation of the $APSVs$ of the AP selected by all handover decision algorithms with different user profiles in the Table VI.3 and Figure VI.5. In this table and figure, we show that our proposed AUHO algorithm provided a better $APSV$ than other decision algorithms. That is, it provided ABS mobility in this use case.

Table VI.3: Mean and standard deviation of $APSVs$ of the AP selected by each handover decision algorithm ($0 \leq APSV \leq 1$)

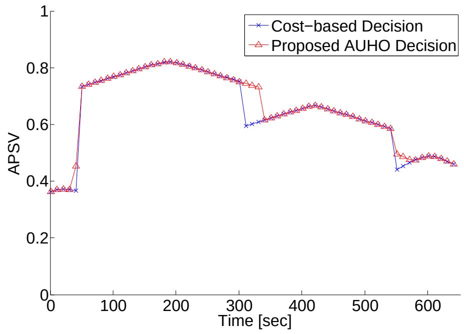
Application	**User Profile**	**Random Decision**		**RSS-based Decision**		**Cost-based Decision**		**Quality-based Decision**		**Lifetime-based Decision**		**Proposed AUHO Decision**	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	**Mean**	**SD**
Voice	Cost & Quality	0.5	0.14	0.54	0.15	0.64	0.14	0.61	0.15	0.54	0.15	**0.65**	**0.13**
Call	Quality & Lifetime	0.55	0.1	0.6	0.08	0.57	0.12	0.64	0.07	0.6	0.08	**0.64**	**0.06**
	Cost & Quality & Lifetime	0.5	0.12	0.53	0.12	0.6	0.12	0.59	0.12	0.53	0.12	**0.61**	**0.11**



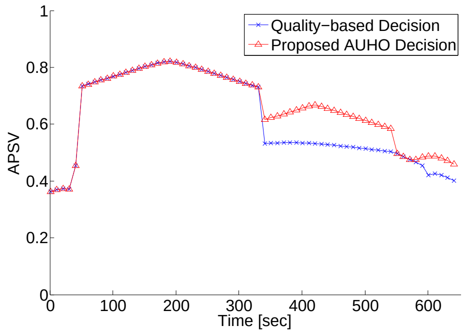
(a) Random-based vs. AUHO



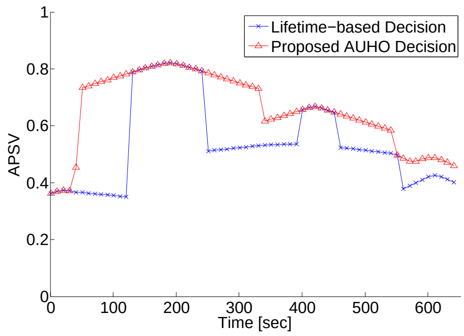
(b) RSS-based vs. AUHO



(c) Cost-based vs. AUHO

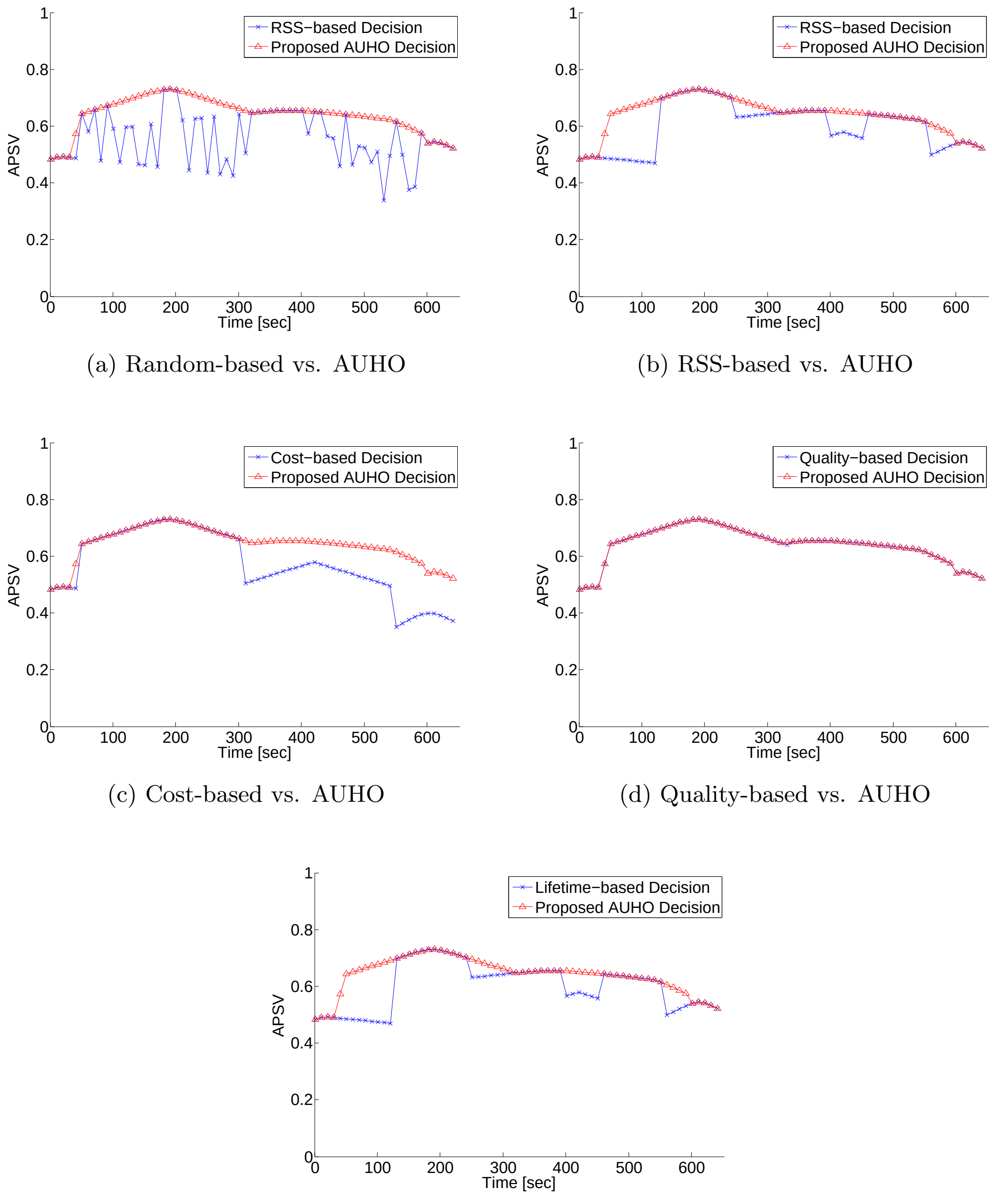


(d) Quality-based vs. AUHO



(e) Lifetime-based vs. AUHO

Figure VI.2: Comparing AUHO with other decision algorithms over time (Application=Voice Call, User Profile = Cost & Quality)



(a) Random-based vs. AUHO

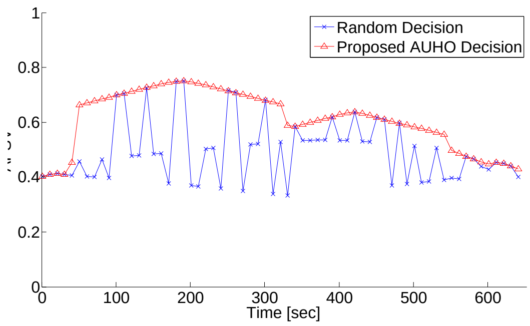
(b) RSS-based vs. AUHO

(c) Cost-based vs. AUHO

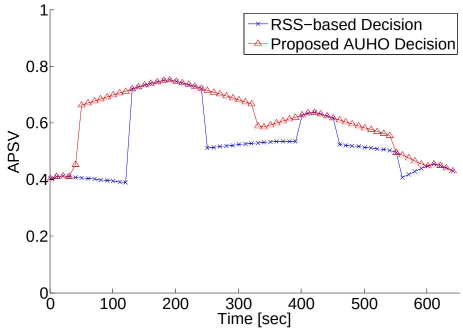
(d) Quality-based vs. AUHO

(e) Lifetime-based vs. AUHO

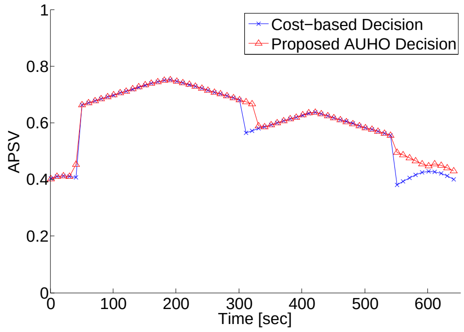
Figure VI.3: Comparing AUHO with other decision algorithms over time (Application=Voice Call, User Profile = Quality & Lifetime)



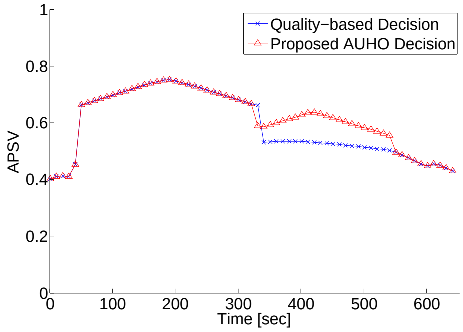
(a) Random-based vs. AUHO



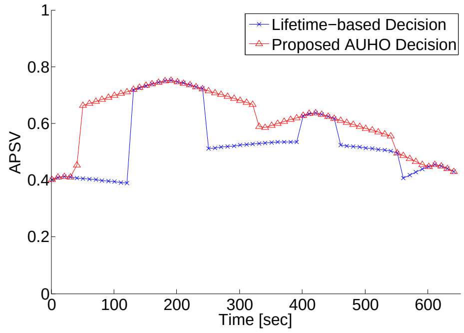
(b) RSS-based vs. AUHO



(c) Cost-based vs. AUHO



(d) Quality-based vs. AUHO



(e) Lifetime-based vs. AUHO

Figure VI.4: Comparing AUHO with other decision algorithms over time (Application=Voice Call, User Profile = Cost & Quality & Lifetime)

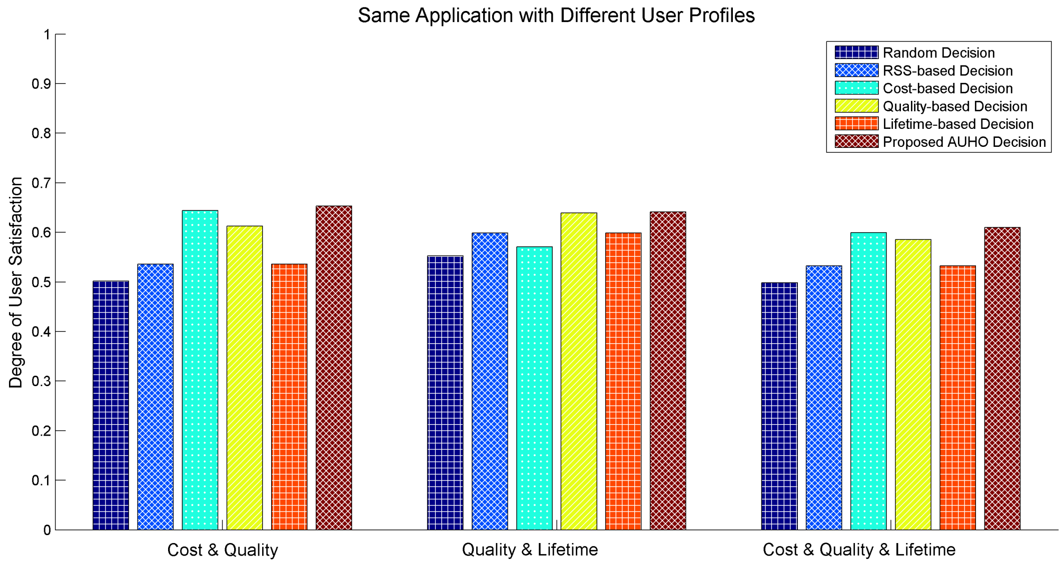


Figure VI.5: Comparison of the mean of all $APSVs$ in the first experiment

6.3.2 Case Study 2: Different Applications with Same User Profile

In the second case study, we use a voice call application, a streaming multimedia application, and an FTP application that each have the same user profile as the first mode (*Cost & Quality (CQ)*). The duration of our simulation is *651 seconds*, as the same of the first experiment.

Table VI.4 shows the experimental results of a streaming application with the user profile CQ. We already presented a voice call application with the CQ user profile, in the previous section. The bandwidth, jitter, and throughput are major factors determining the quality of a streaming application.

At location 1, all decision algorithms select BS1 as the best AP.

At location 2, RD, RSSD, CD, and LD select CDMA (BS1) as the best AP, whereas QD and AUHO select CDMA (BS2) as the best AP. Although the RSS of

Table VI.4: Experimental results at each location (Application=Streaming, UP=Cost & Quality)

Location	**1**	**2**	**3**	**4**	**5**	**6**
Simulation Time (sec)	25	44	157	553	585	651
Available Access Networks (AP)	CDMA(BS1)	CDMA(BS1,BS2)	CDMA(BS1,BS2), WLAN(AP1)	CDMA(BS2,BS3), WLAN(AP2), Mobile WiMax(RAS1)	CDMA(BS2,BS3), WLAN(AP3), Mobile WiMax(RAS1)	CDMA(BS3), Mobile WiMax(RAS1)
Speed Filtering (AP)	CDMA(BS1)	CDMA(BS1,BS2)	CDMA(BS1,BS2), WLAN(AP1)	CDMA(BS2,BS3), WLAN(AP2), Mobile WiMax(RAS1)	CDMA(BS2,BS3), Mobile WiMax(RAS1)	CDMA(BS3), Mobile WiMax(RAS1)
SLA Filtering (AP)	CDMA(BS1)	CDMA(BS1,BS2)	CDMA(BS1,BS2), WLAN(AP1)	CDMA(BS2,BS3), WLAN(AP2), Mobile WiMax(RAS1)	CDMA(BS2,BS3), Mobile WiMax(RAS1)	CDMA(BS3), Mobile WiMax(RAS1)
AP ($APAV_R$)	BS1(0.816)	BS1(0.779), BS2(0.019)	BS1(0.530), BS2(0.335), AP1(0.703)	BS3(0.256), BS2(0.527), RAS1(0.114), AP2(0.141)	BS3(0.598), BS2(0.203), RAS1(0.501)	BS3(0.652), RAS1(0.385)
AP ($APAV_C$)	BS1(0.100)	BS1(0.100), BS2(0.100)	BS1(0.100), BS2(0.100), AP1(0.800)	BS3(0.100), BS2(0.100), RAS1(0.500), AP2(0.800)	BS3(0.100), BS2(0.100), RAS1(0.500)	BS3(0.100), RAS1(0.500)
AP ($APAV_Q$)	BS1(0.100)	BS1(0.300), BS2(0.100)	BS1(0.300), BS2(0.100), AP1(0.300)	BS3(0.234), BS2(0.300), RAS1(0.900), AP2(0.100)	BS3(0.234), BS2(0.300), RAS1(0.900)	BS3(0.234), RAS1(0.900)
AP ($APAV_L$)	BS1(0.100)	BS1(0.100), BS2(0.100)	BS1(0.100), BS2(0.100), AP1(0.500)	BS3(0.100), BS2(0.100), RAS1(0.300), AP2(0.500)	BS3(0.100), BS2(0.100), RAS1(0.300)	BS3(0.100), RAS1(0.300)
AP ($APSV$)	BS1(0.172)	BS1(0.172), BS2(0.168)	BS1(0.203), BS2(0.143), AP1(0.560)	BS3(0.169), BS2(0.223), RAS1(0.601), AP2(0.424)	BS3(0.203), BS2(0.190), RAS1(0.640)	BS3(0.209), RAS1(0.629)
Random (best AP)	CDMA(BS1)	CDMA(BS1)	WLAN(AP1)	CDMA(BS3)	Mobile WiMax(RAS1)	Mobile WiMax(RAS1)
RSS (best AP)	CDMA(BS1)	CDMA(BS1)	WLAN(AP1)	CDMA(BS2)	CDMA(BS3)	CDMA(BS3)
Cost (best AP)	CDMA(BS1)	CDMA(BS1)	WLAN(AP1)	WLAN(AP2)	Mobile WiMax(RAS1)	Mobile WiMax(RAS1)
Quality (best AP)	CDMA(BS1)	CDMA(BS2)	WLAN(AP1)	Mobile WiMax(RAS1)	Mobile WiMax(RAS1)	Mobile WiMax(RAS1)
Lifetime (best AP)	CDMA(BS1)	CDMA(BS1)	WLAN(AP1)	WLAN(AP2)	Mobile WiMax(RAS1)	Mobile WiMax(RAS1)
AUHO (best AP)	**CDMA(BS2)**	**CDMA(BS2)**	**WLAN(AP1)**	**Mobile WiMax(RAS1)**	**Mobile WiMax(RAS1)**	**Mobile WiMax(RAS1)**

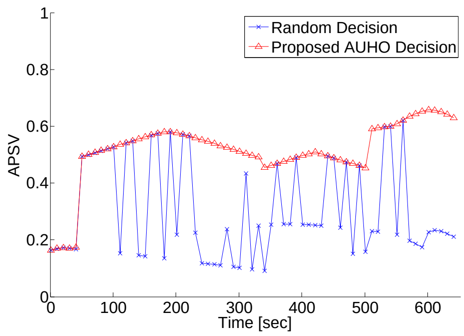
BS1 is stronger than that of BS2, the quality of streaming traffic of BS2 is better than that of BS1 because the throughput of BS2 is higher than that of BS1. That is, the $APAV_Q$ and $APSV$ of BS2 are higher than the corresponding values of BS1. In this experiment, BS2 is the best AP because the UP is CQ. Our AUHO algorithm provides a better solution than RD, RSSD, CD, and LD at location 2.

At location 3, all decision algorithms select WLAN (AP1) as the best AP.

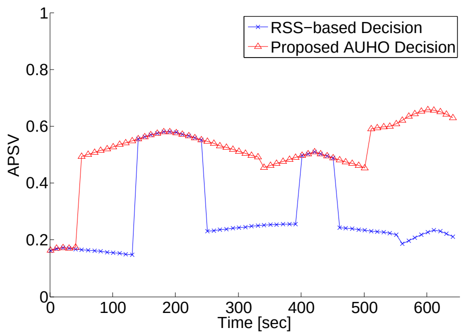
At location 4, RD selects CDMA (BS3) as the best AP. RSSD selects CDMA (BS2) because it has the strongest RSS. CD and LD select WLAN (AP2) because the Rx power consumption rate of WLAN is lower than that of CDMA. QD and AUHO select the Mobile WiMax (RAS1) because the quality of RAS1 is higher than that of other APs, and the APSV of RAS1 is also higher than that of the other APs. Our AUHO algorithm provides a better solution than RD, RSSD, CD, and LD at location 4.

At locations 5 and 6, only RSSD selects CDMA (BS3) as the best AP, whereas the other decision algorithms select Mobile WiMax (RAS1). Although the RSS of BS3 is the strongest, the cost and quality of BS3 are lower than those of RAS1. Thus, RAS1 is the best AP.

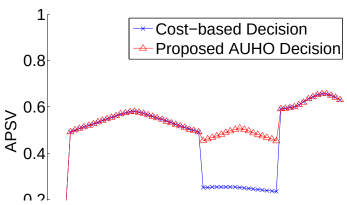
Figure VI.6 contrasts our proposed AUHO algorithm with the other five different decision algorithms by comparing the APSVs of the selected AP. Our proposed AUHO algorithm provides ABS mobility, which the other decision algorithms do not do, over the entire length of the experiment. In addition, we performed the experiment with an FTP application, and the results showed that our AUHO algorithm provided a better solution than the other decision algorithms. The results of these two additional experiments are shown in Figure VI.7 and Figure VI.8.



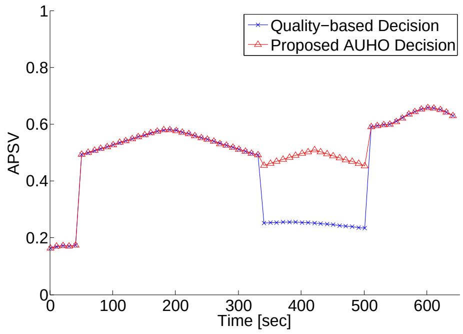
(a) Random-based vs. AUHO



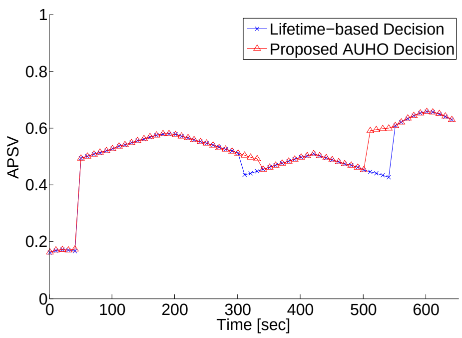
(b) RSS-based vs. AUHO



(c) Cost-based vs. AUHO

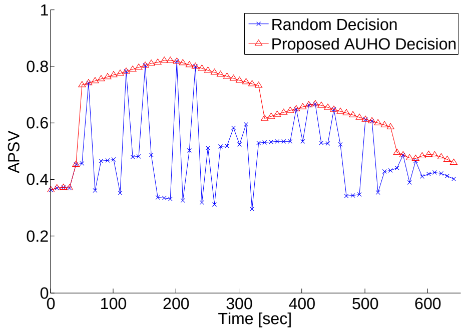


(d) Quality-based vs. AUHO

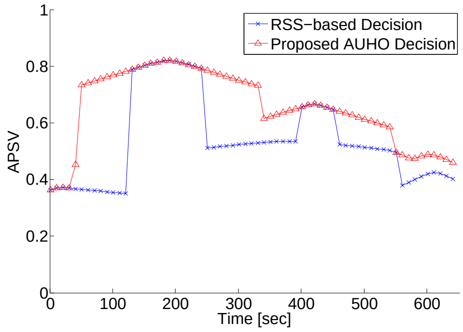


(e) Lifetime-based vs. AUHO

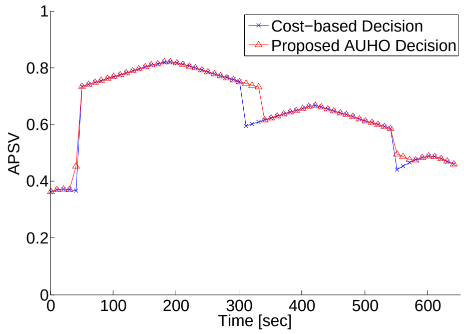
Figure VI.6: Comparing AUHO with other decision algorithms over time (Application=Streaming, User Profile = Cost & Quality)



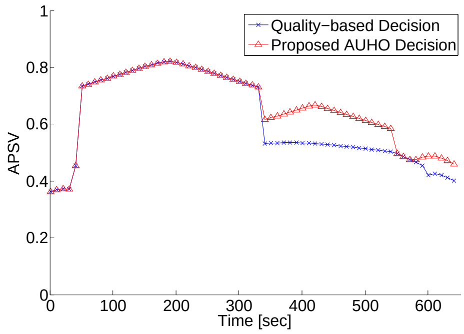
(a) Random-based vs. AUHO



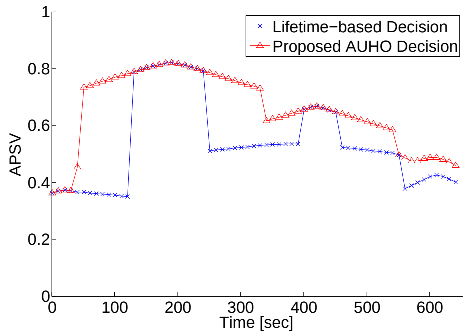
(b) RSS-based vs. AUHO



(c) Cost-based vs. AUHO

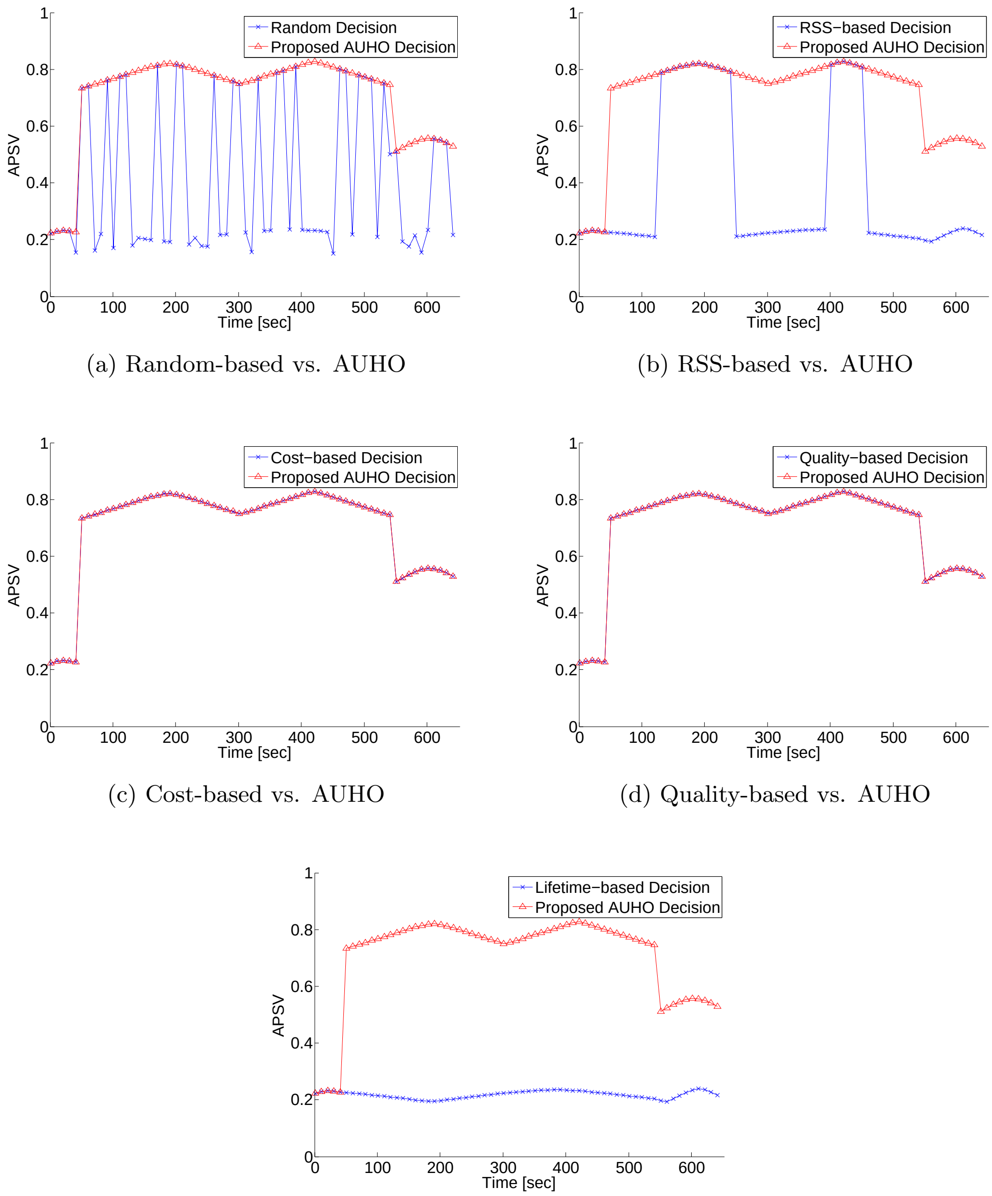


(d) Quality-based vs. AUHO



(e) Lifetime-based vs. AUHO

Figure VI.7: Comparing AUHO with other decision algorithms over time (Application=Voice Call, User Profile = Cost & Quality)



(a) Random-based vs. AUHO

(b) RSS-based vs. AUHO

(c) Cost-based vs. AUHO

(d) Quality-based vs. AUHO

(e) Lifetime-based vs. AUHO

Figure VI.8: Comparing AUHO with other decision algorithms over time (Application=FTP, User Profile = Cost & Quality)

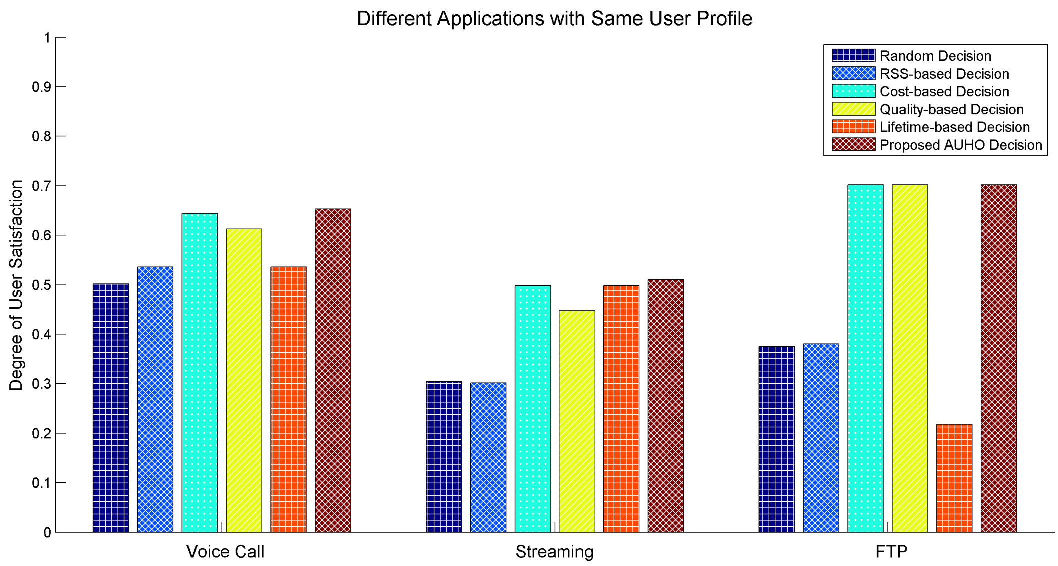


Figure VI.9: Comparison of the mean of all $APSVs$ in the second experiment

We summarized the mean and standard deviation of the APSVs of the AP selected by each handover decision algorithm with different applications in Table VI.5 and Figure VI.9. In this table and figure, we show that our proposed AUHO algorithm provides a better APSV than the other decision algorithms on average. That is, it provides ABS mobility in this use case.

Table VI.5: Mean and standard deviation of $APSVs$ of the AP selected by each handover decision algorithm ($0 \leq APSV \leq 1$)

Application	**User Profile**	**Random Decision**		**RSS-based Decision**		**Cost-based Decision**		**Quality-based Decision**		**Lifetime-based Decision**		**Proposed AUHO Decision**	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	**Mean**	**SD**
VoiceCall	Cost &	0.5	0.14	0.54	0.15	0.64	0.14	0.61	0.15	0.54	0.15	**0.65**	**0.13**
Streaming	Quality	0.3	0.17	0.3	0.15	0.5	0.12	0.45	0.17	0.5	0.12	**0.51**	**0.12**
FTP		0.38	0.25	0.38	0.26	0.7	0.17	0.7	0.17	0.22	0.01	**0.7**	**0.17**

6.4 Discussions

We compared our AUHO algorithm with five established handover decision algorithms in our experiments. Each algorithm focused on only one metric for increasing acceptance in terms of RSS, cost, quality, and lifetime. However, our proposed method focuses on end user satisfaction, which represents how much the current service for a given context satisfies a particular user with a defined set of preferences. Our proposed method calculates $APAVs$ of all candidate APs and then calculates the $APSV$ for selecting the AP that can best meet the current service requirements for a particular context and a given user profile. In the experiments, we showed that our proposed method provides better ABS mobility than the other handover decision algorithms.

In terms of functional requirements, our proposed algorithm did not provide a good solution for handover decisions compared to other decision algorithms. However, we focused on end user satisfaction based on both functional and non-functional requirements. We also considered a threshold for handover overhead to overcome degradation of performance. As future work, we will show that the degradation of performance is reasonable in terms of end user satisfaction.

6.5 Chapter Summary

In this chapter, we presented our experimental results for validating our proposed AUHO. We introduced simulation environments and scenarios. We presented two case studies by the combination of applications and user profiles for validating our method. The experiment results showed that our AUHO outperforms other handover decision algorithms in terms of end user satisfaction all the time. In the next chapter, we will conclude our thesis with a summary, contributions, and possible future work.

Chapter VII

CONCLUSIONS AND FUTURE WORK

This chapter summarizes the overall contents of the thesis, validates our research hypothesis, and lists a set of contributions. Suggested areas for future work are also discussed.

7.1 Summary

In this thesis, we addressed issues related to handover decisions in heterogeneous wireless networks. Seamless mobility and roaming in next-generation networks is an important issue. In particular, vertical and horizontal handover should support not only *Always-Best-Connect (ABC)*, but also *Always-Best-Satisfying (ABS)* for providing personalized mobile services. In this thesis, we proposed a novel handover decision method for supporting ABS based on the end user's preferences and context information. Our method provides a personalized handover decision method for determining the access network and the AP that can best satisfy the requirements of the end user for a particular context.

For supporting autonomic handover decisions, we used a novel feedback control loop of the FOCALE autonomic architecture because it is the only autonomic architecture that uses context-aware policy rules as part of its governance framework. We first defined extensions to the DEN-ng information model (which is used by FOCALE) for defining technology-neutral information for calculating handover decisions. We then presented our decision algorithm by introducing two measurement metrics: APAVs and APSVs. The former represent the suitability of a particular AP for an end user based on a set of UPrefs (e.g., RSS, Quality, Cost, and Lifetime) for that user, and we used fuzzy logic for calculating it. In contrast, the latter represent how well a particular AP satisfies the needs of the end user based on his or her user profile, as used in this context; we used a utility function for calculating this metric. In our approach, APSV represents end user satisfaction. By selecting the AP that has the maximum APSV, our decision algorithm supports ABS. By evaluation with two case studies, we showed that our method supports better ABS in the given simulation environment than other decision algorithms.

We found the following things from this thesis.

- The problems of current handover decision management were defined, and solutions to the problems were also described.
- Methods to solve the problems using context information and user profiles for personalization were described.

- A detailed AUHO algorithm, system architecture, consisting of an autonomic handover decision maker, terminal management system, and context server, were described.

- From our experience in implementing an autonomic handover management system, guidelines for developing an autonomic management system based on the FOCALE autonomic architecture were presented.

- Through validation of personalized handover decisions, the efficiency and the programmability of the personalized handover decision management system were validated.

7.2 Hypothesis Validation

In Section 3.1, we presented our research hypothesis as follows: "Our proposed AUHO algorithm always *maximizes end user satisfaction* by computing the optimal handover decision for different types of mobile services in heterogeneous wireless networks based on user preferences". For validating our hypothesis, we presented our handover decision algorithm in Chapter IV and the evaluation results in Chapter VI. Our decision algorithms determined the *always-best-satisfying* AP for any mobile service using current context information, application requirements, and user preferences in heterogeneous wireless networks. Our simulation results showed that our method outperforms other handover decision algorithms in terms of end user satisfaction. We conclude that our hypothesis is valid.

7.3 Contributions

The following are the key contributions of the thesis.

- Introduce extensions to the DEN-ng information model to support autonomic management of personalized handover decisions
- Enable users to easily select an optimal access network and access point for each service based on a set of preferences in the given context and environment condition
- Measure and optimize end user satisfaction based on user preferences
- Implement a novel and hybrid decision making algorithm for personalized handover
- Prove that personalized services for end users can be delivered even if context changes; this is one of the key tenets of seamless mobility
- Implement an extensible simulator for validating the work of this thesis; this simulator can be reconfigured for testing other handover decision algorithms as well
- Describe real-world use cases, and how autonomic management mechanisms can be used to provide a good solution for handover decisions

7.4 Future Work

For future work, we will optimize our AUHO decision algorithm by using a genetic algorithm [108] or ant-colony optimization [109].

We used fuzzy logic for calculating APAVs. However, the membership functions and fuzzy rules were obtained by manual analysis of the performance comparison results. These parameters can be optimized by using more sophisticated methods, such as machine learning algorithms or bio-inspired techniques. In order to adjust the fuzzy parameters that yields an optimal solution, we will apply an ant colony optimization algorithm [109].

We assumed that weight values of user preferences for building user profiles were either assigned by end users or chosen from a pre-defined table. In order to find optimal values for the weights, we will apply a genetic algorithm to help the users or network operators [69] revise these initial definitions. The genetic algorithm can accommodate a large number of variables and a complex search space (including handover decision criteria weights) with a high probability of finding an optimal solution, or barring that, a near optimal or good solution. The genetic algorithm also handles the different constraints and objectives of the handover decision criteria weights. It also works with numerically generated data, experimental data, or analytical functions. This flexibility can give different options when designing the handover decision algorithm.

We used an additive utility function for calculating APSVs. Despite its widespread use and its advantages, the additive utility function can exhibit some serious limitations [93]. A fundamental issue is whether the multi-criteria utility function can be separated into independent parts where u_i, the utility of criterion i, does not depend on the value of the other criteria. If it can indeed be separated, the elementary utilities $u_i(x_i)$ can simply be added to produce the aggregate utility. Unfortunately, the independence among the handover decision criteria does not always hold. We will apply a multiplicative utility function presented in [93] for overcoming these limitations.

In Section 4.4, we assume that a centralized context server can collect all available context information from heterogeneous wireless networks for supporting our handover decisions. This centralized context server seems impractical due to the cost overhead and limitations of unified OSSs. We will continue to provide a good context server based on the existing approaches [97, 98, 110, 111, 112, 113, 114, 115].

Our approach monitors context information for handover decisions periodically. So, the timeout value is very important. We will find the optimized timeout value by performing more tests. We will optimize our decision algorithm by considering handover overhead and network performance at the level of layer 2 or layer 3. We will also apply real network traffic (instead of relying on simulated traffic) for each application to our HMNToolSuite to better evaluate our AUHO decision algorithm. We will show that the degradation of performance is reasonable in terms of end user satisfaction.

In our approach, handover decisions are performed at mobile devices based on a user's preferences. We presented a solution for network load balancing at mobile devices. Generally, network operators have their own policy framework for network load balancing [116, 117, 118]. We will provide a good network load balancing by integrating policies from both end users and network operators.

We will improve our decision algorithm using mobility prediction. If we can predict a path of mobile devices, this information can be used for handover decisions [119, 120, 121].

We will also apply ontology and semantic reasoning to infer new data and facts that can be used to fine-tune our decision algorithm; this will provide a more complete autonomic decision architecture [122, 40, 123]. Furthermore, we will implement an autonomic handover management system for real mobile devices based on our proposed autonomic architecture.

We will include policy conflict analysis processes for our policy definition. We will harness knowledge embodied in information models and ontologies [124, 125, 126].

Finally, we will contribute our proposed handover decision algorithm to provide real cognition methods to *Cognitive Radio (CR)* technology [127]. The current CR technology focuses on the flexible use of spectrum. We believe that our algorithm can be used to develop new intelligent spectrum selection methods to improve CR technology.

7.5 Chapter Summary

In this chapter, we concluded our thesis with a summary, hypothesis validation, and major contributions. We also suggested future work to extend our AUHO algorithm.

Appendix A

Implementation Details of Fuzzy Logic

We implemented our fuzzy membership functions and fuzzy rules using jFuzzyLogic [90]. Our implementation details, which are represented using a fuzzy control language (fcl), are summarized in this appendix.

Listing A.1: Fuzzy rule definition for calculating the $APAV_Q$ of a voice call application

```
// Quality_VoiceCall.fcl
// Block definition (there may be more than one block per file)
// This is for calculating the APAV to determine the Quality of a Voice Call
FUNCTION_BLOCK handover

// Define input variables
VAR_INPUT
  bandwidth : REAL;
  delay : REAL;
  jitter : REAL;
  ber : REAL;
  throughput : REAL;
  bursterror : REAL;
  packetlossratio: REAL;
END_VAR

// Define output variable
VAR_OUTPUT
  APAV : REAL;
END_VAR

// Fuzzify input variable 'RSS'
FUZZIFY bandwidth
  TERM low := trape 0 0 800 1100;
  TERM medium := trape 800 3200 8000 11000;
  TERM high := trape 8000 12000 50000 50000;
END_FUZZIFY

FUZZIFY delay
  TERM low := trape 0 0 20 25;
  TERM medium := trape 20 25 30 35;
  TERM high := trape 30 75 400 400;
END_FUZZIFY
```

```
FUZZIFY jitter
   TERM low := trape 0 0 5 7;
   TERM medium := trape 6 7 8 9;
   TERM high := trape 8 9 20 20;
END_FUZZIFY

FUZZIFY ber
   TERM low := trape 0 0 0.00001 0.0001;
   TERM medium := trape 0.00005 0.0001 0.0005 0.0007;
   TERM high := trape 0.0005 0.0008 0.001 0.001;
END_FUZZIFY

FUZZIFY throughput
   TERM low := trape 0 0 2 3;
   TERM medium := trape 2 7 22 27;
   TERM high := trape 22 27 50 50;
END_FUZZIFY

FUZZIFY bursterror
   TERM low := trape 0 0 0.1 0.2;
   TERM medium := trape 0.1 0.2 0.4 0.5;
   TERM high := trape 0.4 0.5 1 1;
END_FUZZIFY

FUZZIFY packetlossratio
   TERM low := trape 0 0 0.02 0.03;
   TERM medium := trape 0.02 0.03 0.04 0.05;
   TERM high := trape 0.04 0.05 0.1 0.1;
END_FUZZIFY

// Defzzzify output variable 'APAV' (Access Point Acceptance Value)
DEFUZZIFY APAV
   TERM SR := trian 0 0.1 0.2;
   TERM WR := trian 0.2 0.3 0.4;
   TERM NU := trian 0.4 0.5 0.6;
   TERM WA := trian 0.6 0.7 0.8;
   TERM SA := trian 0.8 0.9 1;
   // Use 'Center Of Gravity' defuzzification method
   METHOD : COG;
   // Default value is 0 (if no rule activates defuzzifier)
   DEFAULT := 0;
END_DEFUZZIFY

RULEBLOCK No1
   // Use 'min' for 'and' (also implicit use 'max'
   // for 'or' to fulfill DeMorgan's Law)
   AND : MIN;
   // Use 'min' activation method
   ACT : MIN;
   // Use 'max' accumulation method
   ACCU : MAX;

 // for Voice call service
 // (bandwidth, delay, jitter, ber, throughput, bursterror, packetlossratio)
 // (0.0435, 0.3913, 0.3913, 0.0.0435, 0.0435, 0.0435, 0.0435)
 // delay, jitter (IMPORTANT)
   RULE 1 : IF delay IS low AND jitter IS low  THEN APAV IS SA;
   RULE 2 : IF delay IS low AND jitter IS medium THEN APAV IS WA;
   RULE 3 : IF delay IS low AND jitter IS high  THEN APAV IS NU;
   RULE 4 : IF delay IS medium AND jitter IS low  THEN APAV IS WA;
   RULE 5 : IF delay IS medium AND jitter IS medium THEN APAV IS NU;
   RULE 6 : IF delay IS medium AND jitter IS high  THEN APAV IS WR;
   RULE 7 : IF delay IS high AND jitter IS low  THEN APAV IS NU;
   RULE 8 : IF delay IS high AND jitter IS medium THEN APAV IS WR;
   RULE 9 : IF delay IS high AND jitter IS high  THEN APAV IS SR;
END_RULEBLOCK

END_FUNCTION_BLOCK
```

Listing A.2: Fuzzy rule definition for calculating the $APAV_Q$ of a streaming application

```
// Quality_Streaming.fcl
// Block definition (there may be more than one block per file)
// This is for calculating the APAV to determine the Quality of a Streaming application
FUNCTION_BLOCK handover

// Define input variables
VAR_INPUT
  bandwidth : REAL;
  delay : REAL;
  jitter : REAL;
  ber : REAL;
  throughput : REAL;
  bursterror : REAL;
  packetlossratio: REAL;
END_VAR

// Define output variable
VAR_OUTPUT
  APAV : REAL;
END_VAR

// Fuzzify input variable 'bandwidth'
FUZZIFY bandwidth
  TERM low := trape 0 0 800 1100;
  TERM medium := trape 800 3200 8000 11000;
  TERM high := trape 8000 12000 50000 50000;
END_FUZZIFY

FUZZIFY delay
  TERM low := trape 0 0 20 25;
  TERM medium := trape 20 25 30 35;
  TERM high := trape 30 75 400 400;
END_FUZZIFY

FUZZIFY jitter
  TERM low := trape 0 0 5 7;
  TERM medium := trape 6 7 8 9;
  TERM high := trape 8 9 20 20;
END_FUZZIFY

FUZZIFY ber
  TERM low := trape 0 0 0.00001 0.0001;
  TERM medium := trape 0.00005 0.0001 0.0005 0.0007;
  TERM high := trape 0.0005 0.0008 0.001 0.001;
END_FUZZIFY

FUZZIFY throughput
  TERM low := trape 0 0 2 3;
  TERM medium := trape 2 7 22 27;
  TERM high := trape 22 27 50 50;
END_FUZZIFY

FUZZIFY bursterror
  TERM low := trape 0 0 0.1 0.2;
  TERM medium := trape 0.1 0.2 0.4 0.5;
  TERM high := trape 0.4 0.5 1 1;
END_FUZZIFY

FUZZIFY packetlossratio
  TERM low := trape 0 0 0.02 0.03;
  TERM medium := trape 0.02 0.03 0.04 0.05;
  TERM high := trape 0.04 0.05 0.1 0.1;
END_FUZZIFY

// Defzzzify output variable 'APAV' (Access Point Acceptance Value)
DEFUZZIFY APAV
  TERM SR := trian 0 0.1 0.2;
  TERM WR := trian 0.2 0.3 0.4;
  TERM NU := trian 0.4 0.5 0.6;
  TERM WA := trian 0.6 0.7 0.8;
  TERM SA := trian 0.8 0.9 1;
  // Use 'Center Of Gravity' defuzzification method
```

```
  METHOD : COG;
  // Default value is 0 (if no rule activates defuzzifier)
  DEFAULT := 0;
END_DEFUZZIFY

RULEBLOCK No1
  // Use 'min' for 'and' (also implicit use 'max'
  // for 'or' to fulfill DeMorgan's Law)
  AND : MIN;
  // Use 'min' activation method
  ACT : MIN;
  // Use 'max' accumulation method
  ACCU : MAX;

 // for Streaming service
 // (bandwidth, delay, jitter, ber, throughput, bursterror, packetlossratio)
 // (0.2771, 0.1428, 0.2571, 0.0286, 0.2571, 0.0286, 0.0286)
 // bandwidth, jitter, throughput (IMPORTANT)
 // delay (CONSIDERABLE)
  RULE 1 : IF bandwidth IS low  AND jitter IS low  AND throughput IS low  AND delay IS low  THEN APAV IS WR;
  RULE 2 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS low  AND delay IS medium  THEN APAV IS WR;
  RULE 3 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS low  AND delay IS high  THEN APAV IS SR;
  RULE 4 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS medium AND delay IS low  THEN APAV IS NU;
  RULE 5 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS medium AND delay IS medium  THEN APAV IS NU;
  RULE 6 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS medium AND delay IS high  THEN APAV IS WR;
  RULE 7 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS high  AND delay IS low  THEN APAV IS WA;
  RULE 8 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS high  AND delay IS medium  THEN APAV IS WA;
  RULE 9 :  IF bandwidth IS low  AND jitter IS low  AND throughput IS high  AND delay IS high  THEN APAV IS NU;
  RULE 10 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS low  AND delay IS low  THEN APAV IS SR;
  RULE 11 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS low  AND delay IS medium  THEN APAV IS SR;
  RULE 12 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS low  AND delay IS high  THEN APAV IS SR;
  RULE 13 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS medium AND delay IS low  THEN APAV IS WR;
  RULE 14 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS medium AND delay IS medium  THEN APAV IS WR;
  RULE 15 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS medium AND delay IS high  THEN APAV IS SR;
  RULE 16 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS high  AND delay IS low  THEN APAV IS NU;
  RULE 17 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS high  AND delay IS medium  THEN APAV IS NU;
  RULE 18 :  IF bandwidth IS low  AND jitter IS medium AND throughput IS high  AND delay IS high  THEN APAV IS WR;
  RULE 19 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS low  AND delay IS low  THEN APAV IS SR;
  RULE 20 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS low  AND delay IS medium  THEN APAV IS SR;
  RULE 21 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS low  AND delay IS high  THEN APAV IS SR;
  RULE 22 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS medium AND delay IS low  THEN APAV IS SR;
  RULE 23 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS medium AND delay IS medium  THEN APAV IS SR;
  RULE 24 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS medium AND delay IS high  THEN APAV IS SR;
  RULE 25 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS high  AND delay IS low  THEN APAV IS WR;
  RULE 26 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS high  AND delay IS medium  THEN APAV IS WR;
  RULE 27 :  IF bandwidth IS low  AND jitter IS high  AND throughput IS high  AND delay IS high  THEN APAV IS SR;
```

```
RULE 28 : IF bandwidth IS medium AND jitter IS low AND throughput IS low AND delay IS low THEN APAV IS WR;
RULE 29 : IF bandwidth IS medium AND jitter IS low AND throughput IS low AND delay IS medium THEN APAV IS WR;
RULE 30 : IF bandwidth IS medium AND jitter IS low AND throughput IS low AND delay IS high THEN APAV IS SR;
RULE 31 : IF bandwidth IS medium AND jitter IS low AND throughput IS medium AND delay IS low THEN APAV IS WA;
RULE 32 : IF bandwidth IS medium AND jitter IS low AND throughput IS medium AND delay IS medium THEN APAV IS WA;
RULE 33 : IF bandwidth IS medium AND jitter IS low AND throughput IS medium AND delay IS high THEN APAV IS NU;
RULE 34 : IF bandwidth IS medium AND jitter IS low AND throughput IS high AND delay IS low THEN APAV IS SA;
RULE 35 : IF bandwidth IS medium AND jitter IS low AND throughput IS high AND delay IS medium THEN APAV IS SA;
RULE 36 : IF bandwidth IS medium AND jitter IS low AND throughput IS high AND delay IS high THEN APAV IS WA;
RULE 37 : IF bandwidth IS medium AND jitter IS medium AND throughput IS low AND delay IS low THEN APAV IS WA;
RULE 38 : IF bandwidth IS medium AND jitter IS medium AND throughput IS low AND delay IS medium THEN APAV IS SR;
RULE 39 : IF bandwidth IS medium AND jitter IS medium AND throughput IS low AND delay IS high THEN APAV IS WA;
RULE 40 : IF bandwidth IS medium AND jitter IS medium AND throughput IS medium AND delay IS low THEN APAV IS NU;
RULE 41 : IF bandwidth IS medium AND jitter IS medium AND throughput IS medium AND delay IS medium THEN APAV IS NU;
RULE 42 : IF bandwidth IS medium AND jitter IS medium AND throughput IS medium AND delay IS high THEN APAV IS WR;
RULE 43 : IF bandwidth IS medium AND jitter IS medium AND throughput IS high AND delay IS low THEN APAV IS WA;
RULE 44 : IF bandwidth IS medium AND jitter IS medium AND throughput IS high AND delay IS medium THEN APAV IS WA;
RULE 45 : IF bandwidth IS medium AND jitter IS medium AND throughput IS high AND delay IS high THEN APAV IS NU;
RULE 46 : IF bandwidth IS medium AND jitter IS high AND throughput IS low AND delay IS low THEN APAV IS SR;
RULE 47 : IF bandwidth IS medium AND jitter IS high AND throughput IS low AND delay IS medium THEN APAV IS SR;
RULE 48 : IF bandwidth IS medium AND jitter IS high AND throughput IS low AND delay IS high THEN APAV IS SR;
RULE 49 : IF bandwidth IS medium AND jitter IS high AND throughput IS medium AND delay IS low THEN APAV IS WR;
RULE 50 : IF bandwidth IS medium AND jitter IS high AND throughput IS medium AND delay IS medium THEN APAV IS WR;
RULE 51 : IF bandwidth IS medium AND jitter IS high AND throughput IS medium AND delay IS high THEN APAV IS SR;
RULE 52 : IF bandwidth IS medium AND jitter IS high AND throughput IS high AND delay IS low THEN APAV IS NU;
RULE 53 : IF bandwidth IS medium AND jitter IS high AND throughput IS high AND delay IS medium THEN APAV IS NU;
RULE 54 : IF bandwidth IS medium AND jitter IS high AND throughput IS high AND delay IS high THEN APAV IS WR;
RULE 55 : IF bandwidth IS high AND jitter IS low AND throughput IS low AND delay IS low THEN APAV IS WA;
RULE 56 : IF bandwidth IS high AND jitter IS low AND throughput IS low AND delay IS medium THEN APAV IS WA;
RULE 57 : IF bandwidth IS high AND jitter IS low AND throughput IS low AND delay IS high THEN APAV IS NU;
RULE 58: IF bandwidth IS high AND jitter IS low AND throughput IS medium AND delay IS low THEN APAV IS SA;
RULE 59 : IF bandwidth IS high AND jitter IS low AND throughput IS medium AND delay IS medium THEN APAV IS SA;
RULE 60 : IF bandwidth IS high AND jitter IS low AND throughput IS medium AND delay IS high THEN APAV IS WA;
RULE 61 : IF bandwidth IS high AND jitter IS low AND throughput IS high AND delay IS low THEN APAV IS SA;
RULE 62 : IF bandwidth IS high AND jitter IS low AND throughput IS high AND delay IS medium THEN APAV IS SA;
RULE 63 : IF bandwidth IS high AND jitter IS low AND throughput IS high AND delay IS high THEN APAV IS WA;
RULE 64 : IF bandwidth IS high AND jitter IS medium AND throughput IS low AND delay IS low THEN APAV IS NU;
RULE 65 : IF bandwidth IS high AND jitter IS medium AND throughput IS low AND delay IS medium THEN APAV IS NU;
```

```
   RULE 66 :  IF bandwidth IS high AND jitter IS medium AND throughput IS low  AND delay IS high  THEN
        APAV IS WR;
   RULE 67 :  IF bandwidth IS high AND jitter IS medium AND throughput IS medium AND delay IS low  THEN
        APAV IS WA;
   RULE 68 :  IF bandwidth IS high AND jitter IS medium AND throughput IS medium AND delay IS medium  THEN
         APAV IS WA;
   RULE 69 :  IF bandwidth IS high AND jitter IS medium AND throughput IS medium AND delay IS high  THEN
        APAV IS NU;
   RULE 70 :  IF bandwidth IS high AND jitter IS medium AND throughput IS high  AND delay IS low  THEN
        APAV IS SA;
   RULE 71 :  IF bandwidth IS high AND jitter IS medium AND throughput IS high  AND delay IS medium  THEN
        APAV IS SA;
   RULE 72 :  IF bandwidth IS high AND jitter IS medium AND throughput IS high  AND delay IS high  THEN
        APAV IS WA;
   RULE 73 :  IF bandwidth IS high AND jitter IS high  AND throughput IS low  AND delay IS low  THEN APAV
        IS WR;
   RULE 74 :  IF bandwidth IS high AND jitter IS high  AND throughput IS low  AND delay IS medium  THEN
        APAV IS WR;
   RULE 75 :  IF bandwidth IS high AND jitter IS high  AND throughput IS low  AND delay IS high  THEN APAV
         IS SR;
   RULE 76 :  IF bandwidth IS high AND jitter IS high  AND throughput IS medium AND delay IS low  THEN
        APAV IS NU;
   RULE 77 :  IF bandwidth IS high AND jitter IS high  AND throughput IS medium AND delay IS medium  THEN
        APAV IS NU;
   RULE 78 :  IF bandwidth IS high AND jitter IS high  AND throughput IS medium AND delay IS high  THEN
        APAV IS WR;
   RULE 79 :  IF bandwidth IS high AND jitter IS high  AND throughput IS high  AND delay IS low  THEN APAV
         IS WA;
   RULE 80 :  IF bandwidth IS high AND jitter IS high  AND throughput IS high  AND delay IS medium  THEN
        APAV IS WA;
   RULE 81 :  IF bandwidth IS high AND jitter IS high  AND throughput IS high  AND delay IS high  THEN
        APAV IS NU;
END_RULEBLOCK

END_FUNCTION_BLOCK
```

Listing A.3: Fuzzy rule definition for calculating the $APAV_Q$ of an FTP application

```
// Quality_FTP.fcl
// Block definition (there may be more than one block per file)
// This is for calculating the APAV to determine the Quality of an FTP application
FUNCTION_BLOCK handover

// Define input variables
VAR_INPUT
   bandwidth : REAL;
   delay : REAL;
   jitter : REAL;
   ber : REAL;
   throughput : REAL;
   bursterror : REAL;
   packetlossratio: REAL;
END_VAR

// Define output variable
VAR_OUTPUT
   APAV : REAL;
END_VAR

// Fuzzify input variable 'RSS'
FUZZIFY bandwidth
   TERM low := trape 0 0 800 1100;
   TERM medium := trape 800 3200 8000 11000;
   TERM high := trape 8000 12000 50000 50000;
END_FUZZIFY

FUZZIFY delay
   TERM low := trape 0 0 20 25;
   TERM medium := trape 20 25 30 35;
   TERM high := trape 30 75 400 400;
END_FUZZIFY

FUZZIFY jitter
```

```
    TERM low := trape 0 0 5 7;
    TERM medium := trape 5 7 8 9;
    TERM high := trape 8 9 20 20;
END_FUZZIFY

FUZZIFY ber
    TERM low := trape 0 0 0.00001 0.0001;
    TERM medium := trape 0.00005 0.0001 0.0005 0.0007;
    TERM high := trape 0.0005 0.0008 0.001 0.001;
END_FUZZIFY

FUZZIFY throughput
    TERM low := trape 0 0 2 3;
    TERM medium := trape 2 7 22 27;
    TERM high := trape 22 27 50 50;
END_FUZZIFY

FUZZIFY bursterror
    TERM low := trape 0 0 0.1 0.2;
    TERM medium := trape 0.1 0.2 0.4 0.5;
    TERM high := trape 0.4 0.5 1 1;
END_FUZZIFY

FUZZIFY packetlossratio
    TERM low := trape 0 0 0.02 0.03;
    TERM medium := trape 0.02 0.03 0.04 0.05;
    TERM high := trape 0.04 0.05 0.1 0.1;
END_FUZZIFY

// Defzzzify output variable 'APAV' (Access Point Acceptance Value)
DEFUZZIFY APAV
    TERM SR := trian 0 0.1 0.2;
    TERM WR := trian 0.2 0.3 0.4;
    TERM NU := trian 0.4 0.5 0.6;
    TERM WA := trian 0.6 0.7 0.8;
    TERM SA := trian 0.8 0.9 1;
    // Use 'Center Of Gravity' defuzzification method
    METHOD : COG;
    // Default value is 0 (if no rule activates defuzzifier)
    DEFAULT := 0;
END_DEFUZZIFY

RULEBLOCK No1
    // Use 'min' for 'and' (also implicit use 'max'
    // for 'or' to fulfill DeMorgan's Law)
    AND : MIN;
    // Use 'min' activation method
    ACT : MIN;
    // Use 'max' accumulation method
    ACCU : MAX;

 // for FTP service
 // (bandwidth, delay, jitter, ber, throughput, bursterror, packetlossratio)
 // (0.0522, 0.0307, 0.0307, 0.2761, 0.0522, 0.2761, 0.2761)
 // ber, bursterror, packetlossratio (IMPORTANT)
    RULE 1 : IF ber IS low  AND bursterror IS low  AND packetlossratio IS low  THEN APAV IS SA;
    RULE 2 :  IF ber IS low  AND bursterror IS low  AND packetlossratio IS medium THEN APAV IS SA;
    RULE 3 :  IF ber IS low  AND bursterror IS low  AND packetlossratio IS high  THEN APAV IS WA;
    RULE 4 :  IF ber IS low  AND bursterror IS medium AND packetlossratio IS low  THEN APAV IS SA;
    RULE 5 :  IF ber IS low  AND bursterror IS medium AND packetlossratio IS medium THEN APAV IS WA;
    RULE 6 :  IF ber IS low  AND bursterror IS medium AND packetlossratio IS high  THEN APAV IS NU;
    RULE 7 :  IF ber IS low  AND bursterror IS high  AND packetlossratio IS low  THEN APAV IS WA;
    RULE 8 :  IF ber IS low  AND bursterror IS high  AND packetlossratio IS medium THEN APAV IS NU;
    RULE 9 :  IF ber IS low  AND bursterror IS high  AND packetlossratio IS high  THEN APAV IS WR;
    RULE 10 :  IF ber IS medium AND bursterror IS low  AND packetlossratio IS low  THEN APAV IS SA;
    RULE 11 :  IF ber IS medium AND bursterror IS low  AND packetlossratio IS medium THEN APAV IS WA;
    RULE 12 :  IF ber IS medium AND bursterror IS low  AND packetlossratio IS high  THEN APAV IS NU;
    RULE 13 :  IF ber IS medium AND bursterror IS medium AND packetlossratio IS low  THEN APAV IS WA;
    RULE 14 :  IF ber IS medium AND bursterror IS medium AND packetlossratio IS medium THEN APAV IS NU;
    RULE 15 :  IF ber IS medium AND bursterror IS medium AND packetlossratio IS high  THEN APAV IS WR;
    RULE 16 :  IF ber IS medium AND bursterror IS high  AND packetlossratio IS low  THEN APAV IS NU;
    RULE 17 :  IF ber IS medium AND bursterror IS high  AND packetlossratio IS medium THEN APAV IS WR;
    RULE 18 :  IF ber IS medium AND bursterror IS high  AND packetlossratio IS high  THEN APAV IS SR;
    RULE 19 :  IF ber IS high  AND bursterror IS low  AND packetlossratio IS low  THEN APAV IS WA;
```

```
    RULE 20 :  IF ber IS high  AND bursterror IS low  AND packetlossratio IS medium THEN APAV IS NU;
    RULE 21 :  IF ber IS high  AND bursterror IS low  AND packetlossratio IS high  THEN APAV IS WR;
    RULE 22 :  IF ber IS high  AND bursterror IS medium AND packetlossratio IS low  THEN APAV IS NU;
    RULE 23 :  IF ber IS high  AND bursterror IS medium AND packetlossratio IS medium THEN APAV IS WR;
    RULE 24 :  IF ber IS high  AND bursterror IS medium AND packetlossratio IS high  THEN APAV IS SR;
    RULE 25 :  IF ber IS high  AND bursterror IS high  AND packetlossratio IS low  THEN APAV IS WR;
    RULE 26 :  IF ber IS high  AND bursterror IS high  AND packetlossratio IS medium THEN APAV IS SR;
    RULE 27 :  IF ber IS high  AND bursterror IS high  AND packetlossratio IS high  THEN APAV IS SR;
END_RULEBLOCK

END_FUNCTION_BLOCK
```

Listing A.4: Fuzzy rule definition for calculating the $APAV_L$ of a voice call application

```
// Power_VoiceCall.fcl
// Block definition (there may be more than one block per file)
// This is for calculating the APAV to determine power consumption of a voice call
FUNCTION_BLOCK handover

// Define input variables
VAR_INPUT
   tx : REAL;
   rx : REAL;
   idle : REAL;
END_VAR

// Define output variable
VAR_OUTPUT
   APAV : REAL;
END_VAR

// Fuzzify input variable 'tx'
FUZZIFY tx
   TERM low := trape 0 0 1.5 1.8;
   TERM medium := trape 1.5 1.8 2.2 2.4;
   TERM high := trape 2.2 2.5 4 4;
END_FUZZIFY

// Fuzzify input variable 'rx'
FUZZIFY rx
   TERM low := trape 0 0 0.4 0.6;
   TERM medium := trape 0.4 0.6 0.7 0.8;
   TERM high := trape 0.7 0.8 1 1;
END_FUZZIFY

// Fuzzify input variable 'idle'
FUZZIFY idle
   TERM low := trape 0 0 0.05 0.06;
   TERM medium := trape 0.05 0.06 0.07 0.08;
   TERM high := trape 0.07 0.08 0.2 0.2;
END_FUZZIFY

// Defzzzify output variable 'APAV' (Access Point Acceptance Value)
DEFUZZIFY APAV
   TERM SR := trian 0 0.1 0.2;
   TERM WR := trian 0.2 0.3 0.4;
   TERM NU := trian 0.4 0.5 0.6;
   TERM WA := trian 0.6 0.7 0.8;
   TERM SA := trian 0.8 0.9 1;
   // Use 'Center Of Gravity' defuzzification method
   METHOD : COG;
   // Default value is 0 (if no rule activates defuzzifier)
   DEFAULT := 0;
END_DEFUZZIFY

RULEBLOCK No1
   // Use 'min' for 'and' (also implicit use 'max'
   // for 'or' to fulfill DeMorgan's Law)
   AND : MIN;
```

```
  // Use 'min' activation method
  ACT : MIN;
  // Use 'max' accumulation method
  ACCU : MAX;

// for VoiceCall service
// (tx, rx, idle)
// (0.47, 0.47, 0.05)
// ber, bursterror, packetlossratio (IMPORTANT)
  RULE 1 : IF tx IS low AND rx IS low  AND idle IS low  THEN APAV IS SA;
  RULE 2 :  IF tx IS low AND rx IS low  AND idle IS medium THEN APAV IS SA;
  RULE 3 :  IF tx IS low AND rx IS low  AND idle IS high THEN APAV IS WA;
  RULE 4 :  IF tx IS low AND rx IS medium AND idle IS low  THEN APAV IS WA;
  RULE 5 :  IF tx IS low AND rx IS medium AND idle IS medium THEN APAV IS WA;
  RULE 6 :  IF tx IS low AND rx IS medium AND idle IS high THEN APAV IS NU;
  RULE 7 :  IF tx IS low AND rx IS high  AND idle IS low  THEN APAV IS NU;
  RULE 8 :  IF tx IS low AND rx IS high  AND idle IS medium THEN APAV IS NU;
  RULE 9 :  IF tx IS low AND rx IS high  AND idle IS high THEN APAV IS WR;
  RULE 10 :  IF tx IS medium AND rx IS low  AND idle IS low  THEN APAV IS WA;
  RULE 11 :  IF tx IS medium AND rx IS low  AND idle IS medium THEN APAV IS WA;
  RULE 12 :  IF tx IS medium AND rx IS low  AND idle IS high THEN APAV IS NU;
  RULE 13 :  IF tx IS medium AND rx IS medium AND idle IS low  THEN APAV IS NU;
  RULE 14 :  IF tx IS medium AND rx IS medium AND idle IS medium THEN APAV IS NU;
  RULE 15 :  IF tx IS medium AND rx IS medium AND idle IS high THEN APAV IS WR;
  RULE 16 :  IF tx IS medium AND rx IS high  AND idle IS low  THEN APAV IS WR;
  RULE 17 :  IF tx IS medium AND rx IS high  AND idle IS medium THEN APAV IS WR;
  RULE 18 :  IF tx IS medium AND rx IS high  AND idle IS high THEN APAV IS SR;
  RULE 19 :  IF tx IS high AND rx IS low  AND idle IS low  THEN APAV IS NU;
  RULE 20 :  IF tx IS high AND rx IS low  AND idle IS medium THEN APAV IS NU;
  RULE 21 :  IF tx IS high AND rx IS low  AND idle IS high THEN APAV IS WR;
  RULE 22 :  IF tx IS high AND rx IS medium AND idle IS low  THEN APAV IS WR;
  RULE 23 :  IF tx IS high AND rx IS medium AND idle IS medium THEN APAV IS WR;
  RULE 24 :  IF tx IS high AND rx IS medium AND idle IS high THEN APAV IS SR;
  RULE 25 :  IF tx IS high AND rx IS high  AND idle IS low  THEN APAV IS SR;
  RULE 26 :  IF tx IS high AND rx IS high  AND idle IS medium THEN APAV IS SR;
  RULE 27 :  IF tx IS high AND rx IS high  AND idle IS high THEN APAV IS SR;
END_RULEBLOCK

END_FUNCTION_BLOCK
```

Listing A.5: Fuzzy rule definition for calculating the $APAV_L$ of a streaming application

```
// Power_Streaming.fcl
// Block definition (there may be more than one block per file)
// This is for calculating the APAV to determine power consumption of a streaming application
FUNCTION_BLOCK handover

// Define input variables
VAR_INPUT
  tx : REAL;
  rx : REAL;
  idle : REAL;
END_VAR

// Define output variable
VAR_OUTPUT
  APAV : REAL;
END_VAR

// Fuzzify input variable 'tx'
FUZZIFY tx
  TERM low := trape 0 0 1.5 1.8;
  TERM medium := trape 1.5 1.8 2.2 2.4;
  TERM high := trape 2.2 2.5 4 4;
END_FUZZIFY

// Fuzzify input variable 'rx'
FUZZIFY rx
  TERM low := trape 0 0 0.4 0.6;
  TERM medium := trape 0.4 0.6 0.7 0.8;
```

```
   TERM high := trape 0.7 0.8 1 1;
END_FUZZIFY

// Fuzzify input variable 'idle'
FUZZIFY idle
   TERM low := trape 0 0 0.05 0.06;
   TERM medium := trape 0.05 0.06 0.07 0.08;
   TERM high := trape 0.07 0.08 0.2 0.2;
END_FUZZIFY

// Defzzzify output variable 'APAV' (Access Point Acceptance Value)
DEFUZZIFY APAV
   TERM SR := trian 0 0.1 0.2;
   TERM WR := trian 0.2 0.3 0.4;
   TERM NU := trian 0.4 0.5 0.6;
   TERM WA := trian 0.6 0.7 0.8;
   TERM SA := trian 0.8 0.9 1;
   // Use 'Center Of Gravity' defuzzification method
   METHOD : COG;
   // Default value is 0 (if no rule activates defuzzifier)
   DEFAULT := 0;
END_DEFUZZIFY

RULEBLOCK No1
   // Use 'min' for 'and' (also implicit use 'max'
   // for 'or' to fulfill DeMorgan's Law)
   AND : MIN;
   // Use 'min' activation method
   ACT : MIN;
   // Use 'max' accumulation method
   ACCU : MAX;

 // for Streaming service
 // (tx, rx, idle)
 // (0.1, 0.9, 0.0)
 // ber, bursterror, packetlossratio (IMPORTANT)
   RULE 1 : IF tx IS low AND rx IS low  AND idle IS low  THEN APAV IS SA;
   RULE 2 :  IF tx IS low AND rx IS low  AND idle IS medium THEN APAV IS SA;
   RULE 3 :  IF tx IS low AND rx IS low  AND idle IS high THEN APAV IS SA;
   RULE 4 :  IF tx IS low AND rx IS medium AND idle IS low  THEN APAV IS NU;
   RULE 5 :  IF tx IS low AND rx IS medium AND idle IS medium THEN APAV IS NU;
   RULE 6 :  IF tx IS low AND rx IS medium AND idle IS high THEN APAV IS NU;
   RULE 7 :  IF tx IS low AND rx IS high  AND idle IS low  THEN APAV IS SR;
   RULE 8 :  IF tx IS low AND rx IS high  AND idle IS medium THEN APAV IS SR;
   RULE 9 :  IF tx IS low AND rx IS high  AND idle IS high THEN APAV IS SR;
   RULE 10 :  IF tx IS medium AND rx IS low  AND idle IS low  THEN APAV IS SA;
   RULE 11 :  IF tx IS medium AND rx IS low  AND idle IS medium THEN APAV IS SA;
   RULE 12 :  IF tx IS medium AND rx IS low  AND idle IS high THEN APAV IS SA;
   RULE 13 :  IF tx IS medium AND rx IS medium AND idle IS low  THEN APAV IS NU;
   RULE 14 :  IF tx IS medium AND rx IS medium AND idle IS medium THEN APAV IS NU;
   RULE 15 :  IF tx IS medium AND rx IS medium AND idle IS high THEN APAV IS NU;
   RULE 16 :  IF tx IS medium AND rx IS high  AND idle IS low  THEN APAV IS SR;
   RULE 17 :  IF tx IS medium AND rx IS high  AND idle IS medium THEN APAV IS SR;
   RULE 18 :  IF tx IS medium AND rx IS high  AND idle IS high THEN APAV IS SR;
   RULE 19 :  IF tx IS high AND rx IS low  AND idle IS low  THEN APAV IS WA;
   RULE 20 :  IF tx IS high AND rx IS low  AND idle IS medium THEN APAV IS WA;
   RULE 21 :  IF tx IS high AND rx IS low  AND idle IS high THEN APAV IS NU;
   RULE 22 :  IF tx IS high AND rx IS medium AND idle IS low  THEN APAV IS WR;
   RULE 23 :  IF tx IS high AND rx IS medium AND idle IS medium THEN APAV IS WR;
   RULE 24 :  IF tx IS high AND rx IS medium AND idle IS high THEN APAV IS WR;
   RULE 25 :  IF tx IS high AND rx IS high  AND idle IS low  THEN APAV IS SR;
   RULE 26 :  IF tx IS high AND rx IS high  AND idle IS medium THEN APAV IS SR;
   RULE 27 :  IF tx IS high AND rx IS high  AND idle IS high THEN APAV IS SR;
END_RULEBLOCK

END_FUNCTION_BLOCK
```

Listing A.6: Fuzzy rule definition for calculating the $APAV_L$ of an FTP application

```
// Power_FTP.fcl
// Block definition (there may be more than one block per file)
```

```
// This is for calculating the APAV to determine power consumption of an FTP application
FUNCTION_BLOCK handover

// Define input variables
VAR_INPUT
   tx : REAL;
   rx : REAL;
   idle : REAL;
END_VAR

// Define output variable
VAR_OUTPUT
   APAV : REAL;
END_VAR

// Fuzzify input variable 'tx'
FUZZIFY tx
   TERM low := trape 0 0 1.5 1.8;
   TERM medium := trape 1.5 1.8 2.2 2.4;
   TERM high := trape 2.2 2.5 4 4;
END_FUZZIFY

FUZZIFY rx
   TERM low := trape 0 0 0.4 0.6;
   TERM medium := trape 0.4 0.6 0.7 0.8;
   TERM high := trape 0.7 0.8 1 1;
END_FUZZIFY

FUZZIFY idle
   TERM low := trape 0 0 0.05 0.06;
   TERM medium := trape 0.05 0.06 0.07 0.08;
   TERM high := trape 0.07 0.08 0.2 0.2;
END_FUZZIFY

// Defzzzify output variable 'APAV' (Access Point Acceptance Value)
DEFUZZIFY APAV
   TERM SR := trian 0 0.1 0.2;
   TERM WR := trian 0.2 0.3 0.4;
   TERM NU := trian 0.4 0.5 0.6;
   TERM WA := trian 0.6 0.7 0.8;
   TERM SA := trian 0.8 0.9 1;
   // Use 'Center Of Gravity' defuzzification method
   METHOD : COG;
   // Default value is 0 (if no rule activates defuzzifier)
   DEFAULT := 0;
END_DEFUZZIFY

RULEBLOCK No1
   // Use 'min' for 'and' (also implicit use 'max'
   // for 'or' to fulfill DeMorgan's Law)
   AND : MIN;
   // Use 'min' activation method
   ACT : MIN;
   // Use 'max' accumulation method
   ACCU : MAX;

 // for FTP service
 // (tx, rx, idle)
 // (0, 0.1, 0.9)
 // ber, bursterror, packetlossratio (IMPORTANT)
   RULE 1 : IF tx IS low AND rx IS low  AND idle IS low  THEN APAV IS SA;
   RULE 2 :  IF tx IS low AND rx IS low  AND idle IS medium THEN APAV IS NU;
   RULE 3 :  IF tx IS low AND rx IS low  AND idle IS high THEN APAV IS SR;
   RULE 4 :  IF tx IS low AND rx IS medium AND idle IS low  THEN APAV IS SA;
   RULE 5 :  IF tx IS low AND rx IS medium AND idle IS medium THEN APAV IS NU;
   RULE 6 :  IF tx IS low AND rx IS medium AND idle IS high THEN APAV IS SR;
   RULE 7 :  IF tx IS low AND rx IS high  AND idle IS low  THEN APAV IS WA;
   RULE 8 :  IF tx IS low AND rx IS high  AND idle IS medium THEN APAV IS WR;
   RULE 9 :  IF tx IS low AND rx IS high  AND idle IS high THEN APAV IS SR;
   RULE 10 :  IF tx IS medium AND rx IS low  AND idle IS low  THEN APAV IS SA;
   RULE 11 :  IF tx IS medium AND rx IS low  AND idle IS medium THEN APAV IS NU;
   RULE 12 :  IF tx IS medium AND rx IS low  AND idle IS high THEN APAV IS SR;
   RULE 13 :  IF tx IS medium AND rx IS medium AND idle IS low  THEN APAV IS SA;
```

```
    RULE 14 :  IF tx IS medium AND rx IS medium AND idle IS medium THEN APAV IS NU;
    RULE 15 :  IF tx IS medium AND rx IS medium AND idle IS high THEN APAV IS SR;
    RULE 16 :  IF tx IS medium AND rx IS high  AND idle IS low  THEN APAV IS WA;
    RULE 17 :  IF tx IS medium AND rx IS high  AND idle IS medium THEN APAV IS WR;
    RULE 18 :  IF tx IS medium AND rx IS high  AND idle IS high THEN APAV IS SR;
    RULE 19 :  IF tx IS high AND rx IS low  AND idle IS low  THEN APAV IS SA;
    RULE 20 :  IF tx IS high AND rx IS low  AND idle IS medium THEN APAV IS NU;
    RULE 21 :  IF tx IS high AND rx IS low  AND idle IS high THEN APAV IS SR;
    RULE 22 :  IF tx IS high AND rx IS medium AND idle IS low  THEN APAV IS SA;
    RULE 23 :  IF tx IS high AND rx IS medium AND idle IS medium THEN APAV IS NU;
    RULE 24 :  IF tx IS high AND rx IS medium AND idle IS high THEN APAV IS SR;
    RULE 25 :  IF tx IS high AND rx IS high  AND idle IS low  THEN APAV IS WA;
    RULE 26 :  IF tx IS high AND rx IS high  AND idle IS medium THEN APAV IS WR;
    RULE 27 :  IF tx IS high AND rx IS high  AND idle IS high THEN APAV IS SR;
END_RULEBLOCK

END_FUNCTION_BLOCK
```

Appendix B

Feature Oriented Software Development for Mobile Devices

Here, we present our approach for creating mobile devices based on *Product Line Engineering (PLE)* in our HMNToolSuite. We collaborated with Prof. Kyo Kang (SE Lab., POSTECH) [128] who is a pioneer of feature-oriented product line engineering and Prof. Don Batory (Automated Software UT Austin) [129] who is a leading researcher of feature-oriented programming.

Feature Oriented Software Development (FOSD) is a general paradigm for program synthesis in *Software Product Lines (SPL)* [103]. An SPL is a set of software-intensive systems sharing a common, managed set of features that satisfy the specific need of a particular market segment or mission and that are developed from a common set of core assets in a prescribed way [130]. The purpose of FOSD is to define a discrete and enumerable space of configurations for creating SPL using a feature model [102]. Features are increments in functionality, and thus are the building blocks of programs. Each configuration, which is a composition of features, represents a program.

2.1 Feature Modeling

In 1990, Kang *et al.*, [101] proposed feature models. Most of the extensions to this are based on the relationships allowed between parent and child features. Feature models are considered among the unique contributions in software product line engineering. It is more natural and intuitive for both customers and developers to express both commonalities as well as variabilities in a software product line in terms of features, since features are understood by all stakeholders [101].

A feature model represents all possible products of a software product line in a single model. Feature models are used in different scenarios such as requirements engineering [131, 132, 133], architecture definition [134], architecture maintainability measurement [135], code generation [103, 102, 136, 137], or portlet-based applications [138].

2.2 Feature Oriented Programming

Feature Oriented Programming (FOP) is a paradigm for creating software product lines [103, 138]. Features (a.k.a. feature modules) are the building blocks of programs. An FOP model of a product line is an algebra that offers a set of operations, where each operation implements a feature. We write **M = {f, h, i, j}** to mean model **M** has operations or features **f**, **h**, **i**, and **j**. FOP distinguishes features as *constants* or *functions*. Constants represent base programs. For example:

```
f            // a base program with feature f
h            // a base program with feature h
```

Functions represent *program refinements* that extend a program that is received as input. For instance:

```
i • x        // adds feature i to program x
j • x        // adds feature j to program x
```

where •denotes the application of a function.
The design of a program is a named expression, e.g.:

```
prog1 = i • f          // prog1 has features i and f
prog2 = i • j • h      // prog2 has features i, j, i
```

The set of programs that can be created from a FOP model is its product line. Expression optimization corresponds to program design optimization, and expression evaluation corresponds to program synthesis. Batory summarizes relationships between a parent (or compound) feature and its *child* features (or *subfeatures*) as: [102]

- *And* - all sub-features must be selected,
- *Alternatives* - only one sub-feature can be selected,
- *Or* - one or more sub-features can be selected,
- *Mandatory* - features that are required, and
- *Optional* - features that are optional.

The *Or* relationship can have **n:m** cardinalities, which is read as a minimum of **n** features and at most **m** features can be selected [136].

A *feature diagram* is a graphical representation of a feature model. It is a tree where primitive features are leaves and compound features are interior nodes. Common graphical notations are depicted in Figure B.1.

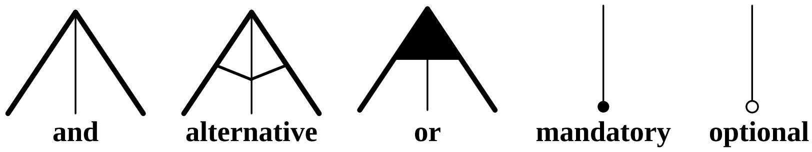


Figure B.1: Feature diagram notations

Figure B.2 is an example of a feature diagram for feature **e**. It defines a product-line, where each application contains two features **r** and **s**. The feature **r** is an alternative feature: only one of **G**, **H**, and **I** can be present in an application. The feature **s** is a compound feature that consists of mandatory features **A** and **C**, and an optional feature **B**. In this feature model, we can generate all configuration by the following grammar (FOP expression):

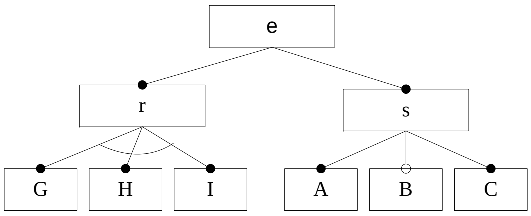


Figure B.2: An example of a feature model

```
e = r • s
r = G | H | I (r = G or r = H or r = I)
s = A [B] C (s = A • C or s = A • B • C)
```

2.3 Feature Modeling for Mobile Devices

In this section, we present a feature model for creating a mobile device product line. The domain of a mobile device is appropriate to applying PLE because mobile devices have many commonalities and variabilities in their functionality. In a mobile device product line, a network interface, an application, a user policy, and a monitor are examples of variation points. These variation points have variants called *features* in a feature model.

Figure B.3 shows the example of a feature model for a mobile device product line. Listing B.1 shows the example of a feature model expressed by the GUIDSL grammar [102]. By using the given model, new mobile devices can be quickly developed by emphasizing their commonalities with and variabilities between existing product features.

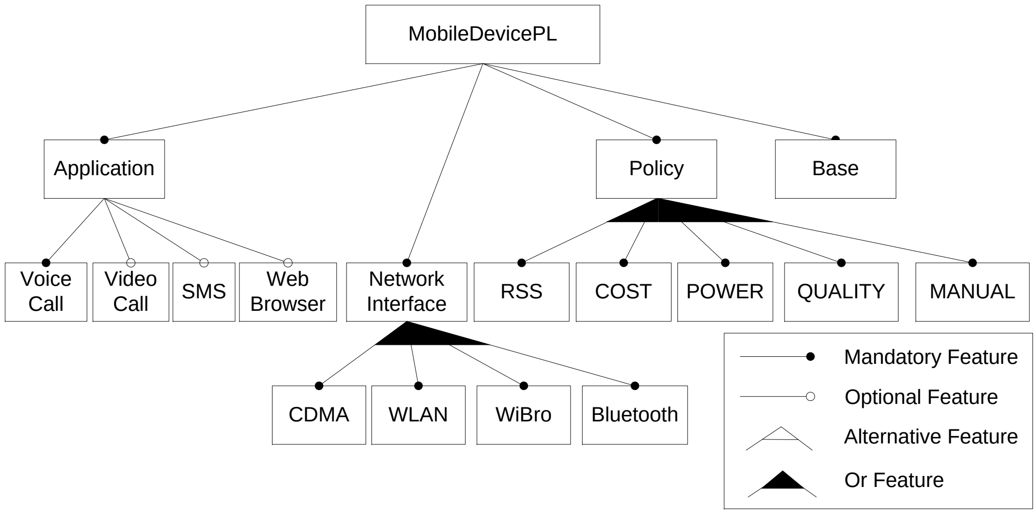


Figure B.3: An example of a feature model for a mobile device PL

Listing B.1: GUIDSL grammar for a feature model for a mobile device product line

```
// grammar of feature model
MobileDevice: Application NetworkInterface+ Policy+ :: MainMD ;
Application: VoiceCall [VideoCall] [SMS] [WebBrowser] :: App ;
NetworkInterface: CDMA | WLAN | Mobile WiMax | BlueTooth ;
Policy: MANUAL | Policy+ :: Autonomic;
Policy: RSS | COST | POWER | QUALITY;
```

They can be represented using the notations described in Section 2.2 as follows:

$$
\begin{aligned}
\mathbf{PL} &= \{p_1, p_2, \ldots, p_m\} \\
p_1 &= Application \bullet NetworkInterface \bullet Policy \\
&= \begin{pmatrix} Application & = VoiceCall \bullet SMS \\ NetworkInteface & = CDMA \bullet WLAN \bullet MobileWiMax \\ Policy & = MANUAL \bullet RSS \bullet COST \end{pmatrix} \\
&= VoiceCall \bullet SMS \bullet CDMA \bullet WLAN \bullet MobileWiMax \bullet RSS \bullet COST \\
p_2 &= VoiceCall \bullet SMS \bullet VideoCall \bullet CDMA \bullet WLAN \bullet POWER \\
&\vdots \\
p_m &= VoiceCall \bullet VideoCall \bullet SMS \bullet WebBrowser \bullet \\
&\quad CDMA \bullet WLAN \bullet MobileWiMax \bullet Bluetoth \bullet \\
&\quad RSS \bullet COST \bullet POWER \bullet QUALITY
\end{aligned} \tag{B.1}
$$

, where PL is a set of mobile device specified by the feature model and p_i is a mobile device configured statically ($1 \geq i \geq m$). For example, the mobile device p_1 has *Application*, $NetworkInterface$, and *Policy* features. As applications, it has $VoiceCall$, and SMS. It has also network interfaces which support $CDMA$, $WLAN$, and $MobileWiMax$ communications and user policies with RSS and $COST$. Our HMNToolSuite supports the creation of mobile devices based on a feature model. Figure B.4 shows screenshots of p_1, p_2, and p_m mobile device as mentioned earlier.

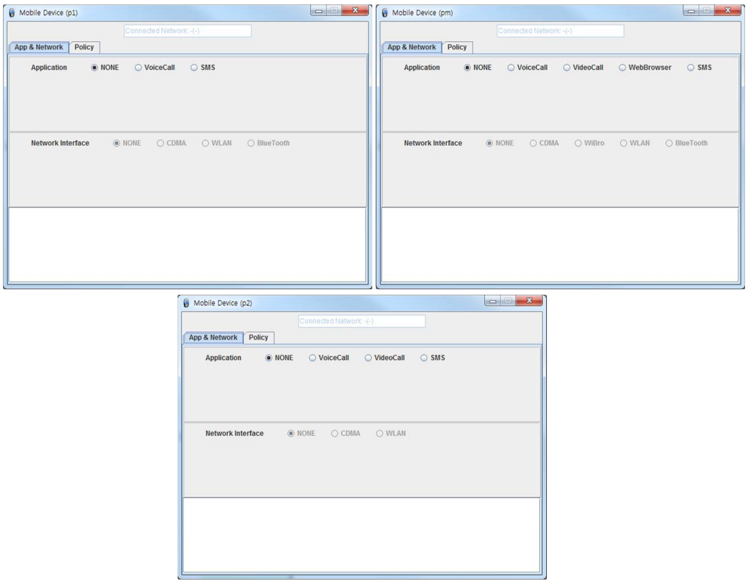


Figure B.4: Screenshot of the mobile device p_1, p_2, and p_m

Appendix C

HMNToolSuite Details

In this chapter, we present additional features of our HMNToolSuite using screenshots. Listing C.1 shows a sample configuration file for a CDMA access network. We define each access network with the following criteria: coverage, bandwidth, delay, jitter, bit error rate, throughput, burst error, packet loss ratio, cost rate, tx power, rx power, idle power, minimum supported velocity, and maximum supported velocity.

Listing C.1: Network configuration file (CDMA Network)

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<emulator>
   <network>
      <name>CDMA</name>
      <device>BaseStation</device>
      <coverage>1000</coverage>
      <bandwidth>1000</bandwidth>
      <delay>19</delay>
      <jitter>6</jitter>
      <bitErrorRate>0.0010</bitErrorRate>
      <throughput>0.0</throughput>
      <burstErr>0.5</burstErr>
      <packetLossRatio>0.07</packetLossRatio>
      <costRate>0.9</costRate>
      <txPower>1.4</txPower>
      <rxPower>0.925</rxPower>
      <idlePower>0.045</idlePower>
      <minVelocity>0</minVelocity>
      <maxVelocity>300</maxVelocity>
      <color>ff0000</color>
   </network>
</emulator>
```

Listing C.2 shows a sample configuration file for a car mobile node. We define each mobile node with the following criteria: mobile node type, icon, color, maximum velocity, and minimum velocity.

Listing C.2: Mobile node configuration file (CAR mobile node)

```xml
<?xml version="1.0" encoding="UTF-8"?>
```

```
<emulator>
  <mobilenode>
    <name>CAR</name>
    <icon>car.png</icon>
    <color>FFC800</color>
    <maxVelocity>40</maxVelocity>
    <minVelocity>0</minVelocity>
  </mobilenode>
</emulator>
```

Figure C.1 is a screen shot of editing velocity and time which the mobile node stays at each point.

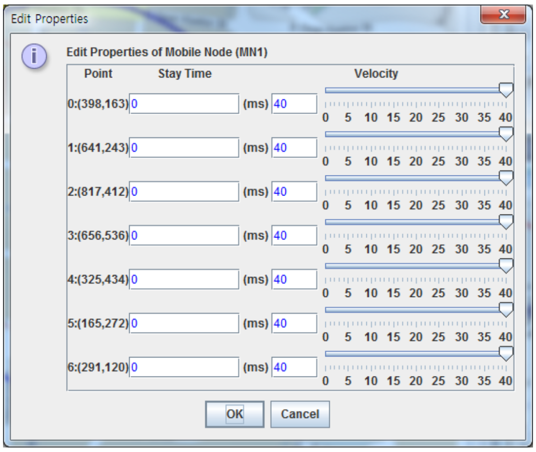
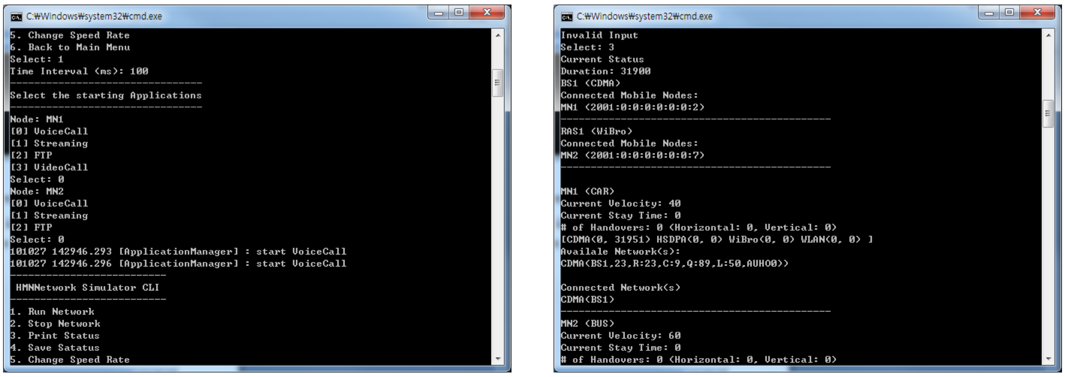


Figure C.1: Editor velocity and staying time in a path editor

Figure C.2 is a screen shot for reporting results (e.g., the number of handovers, connected time, APAVs, and APSVs).

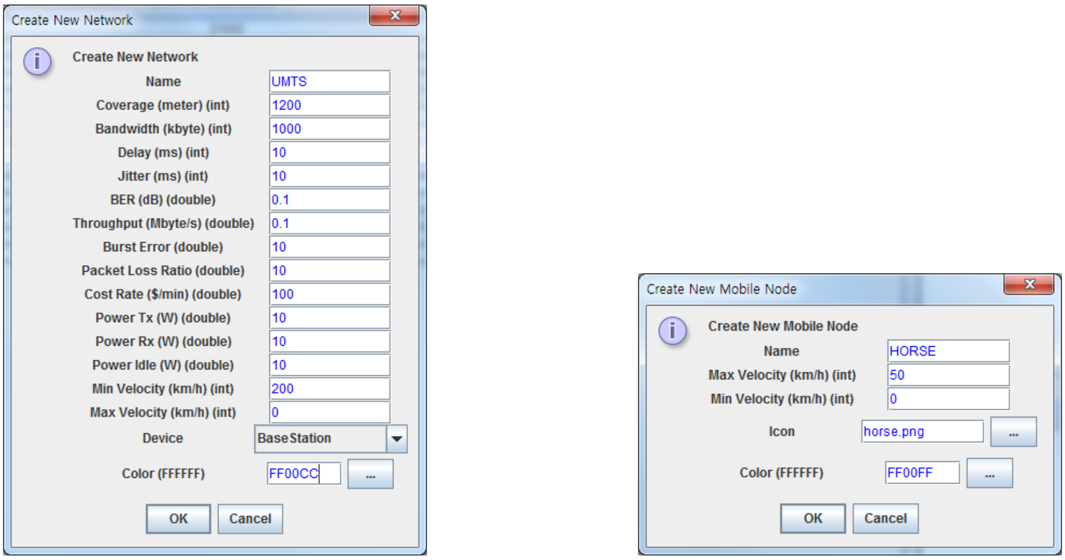
Figure C.2: Performance result graph view

Figure **??** shows a CLI-based simulation. Our tool supports to load a network map and simulate it from the command prompt.



(a) (b)

Figure C.3: CLI simulator view



(a) (b)

Figure C.4: Creating a new access network and a new mobile node

Figure C.4a and Figure C.4b show to create a new access network and a new mobile node in the tool.

Appendix D

Testing Scenario

This appendix contains the entire configuration of our testing scenario for the HMNToolSuite.

Listing D.1: Configuration file for the performance testing scenario

```
<!-- Performance Testing -->
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<emulator>
  <map>
    <name>ComNet Test Platform</name>
    <description>ComNet Test Platform</description>
    <width>1024</width>
    <height>768</height>
    <background>ut_austin.png</background>
    <device>
      <network>
        <name>AP1</name>
        <networktype>WLAN</networktype>
      </network>
      <xpos>255</xpos>
      <ypos>238</ypos>
      <data>
        <coverage>0,400|</coverage>
        <bandwidth>0,2000|20,4000|30,10000|</bandwidth>
        <delay>0,30|</delay>
        <jitter>0,8|</jitter>
        <bitErrorRate>0.0,1.0E-4|</bitErrorRate>
        <throughput>0.0,0.0|</throughput>
        <burstErr>0.0,0.1|</burstErr>
        <packetLossRatio>0.0,0.02|</packetLossRatio>
        <costRate>0.0,0.5|</costRate>
        <txPower>0.0,2.0|</txPower>
        <rxPower>0.0,0.7|</rxPower>
        <idlePower>0.0,0.06|</idlePower>
        <minVelocity>0,60|</minVelocity>
        <maxVelocity>0,0|</maxVelocity>
      </data>
    </device>
    <device>
<network>
<name>BS1</name>
<networktype>CDMA</networktype>
</network>
<xpos>388</xpos>
<ypos>267</ypos>
<data>
<coverage>0,1000|</coverage>
```

```
<bandwidth>0,1000|</bandwidth>
<delay>0,19|</delay>
<jitter>0,6|</jitter>
<bitErrorRate>0.0,0.0010|</bitErrorRate>
<throughput>0.0,0.0|</throughput>
<burstErr>0.0,0.5|</burstErr>
<packetLossRatio>0.0,0.07|</packetLossRatio>
<costRate>0.0,0.9|</costRate>
<txPower>0.0,1.4|</txPower>
<rxPower>0.0,0.925|</rxPower>
<idlePower>0.0,0.045|</idlePower>
<minVelocity>0,300|</minVelocity>
<maxVelocity>0,0|</maxVelocity>
</data>
</device>
<device>
<network>
<name>RAS1</name>
<networktype>WiBro</networktype>
</network>
<xpos>564</xpos>
<ypos>278</ypos>
<data>
<coverage>0,800|</coverage>
<bandwidth>0,11000|</bandwidth>
<delay>0,45|</delay>
<jitter>0,10|</jitter>
<bitErrorRate>0.0,1.0E-5|</bitErrorRate>
<throughput>0.0,0.0|</throughput>
<burstErr>0.0,0.2|</burstErr>
<packetLossRatio>0.0,0.04|</packetLossRatio>
<costRate>0.0,0.2|</costRate>
<txPower>0.0,2.8|</txPower>
<rxPower>0.0,0.495|</rxPower>
<idlePower>0.0,0.082|</idlePower>
<minVelocity>0,4|</minVelocity>
<maxVelocity>0,0|</maxVelocity>
</data>
</device>
<device>
<network>
<name>AP2</name>
<networktype>WLAN</networktype>
</network>
<xpos>510</xpos>
<ypos>272</ypos>
<data>
<coverage>0,400|</coverage>
<bandwidth>0,2000|</bandwidth>
<delay>0,30|</delay>
<jitter>0,8|</jitter>
<bitErrorRate>0.0,1.0E-4|</bitErrorRate>
<throughput>0.0,0.0|</throughput>
<burstErr>0.0,0.1|</burstErr>
<packetLossRatio>0.0,0.02|</packetLossRatio>
<costRate>0.0,0.5|</costRate>
<txPower>0.0,2.0|</txPower>
<rxPower>0.0,0.7|</rxPower>
<idlePower>0.0,0.06|</idlePower>
<minVelocity>0,60|</minVelocity>
<maxVelocity>0,0|</maxVelocity>
</data>
</device>
<device>
<network>
<name>BS2</name>
<networktype>CDMA</networktype>
</network>
<xpos>110</xpos>
<ypos>253</ypos>
<data>
<coverage>0,1000|</coverage>
<bandwidth>0,1000|</bandwidth>
<delay>0,19|</delay>
<jitter>0,6|</jitter>
<bitErrorRate>0.0,0.0010|</bitErrorRate>
<throughput>0.0,0.0|</throughput>
```

```xml
<burstErr>0.0,0.5|</burstErr>
<packetLossRatio>0.0,0.07|</packetLossRatio>
<costRate>0.0,0.9|</costRate>
<txPower>0.0,1.4|</txPower>
<rxPower>0.0,0.925|</rxPower>
<idlePower>0.0,0.045|</idlePower>
<minVelocity>0,300|</minVelocity>
<maxVelocity>0,0|</maxVelocity>
</data>
</device>
<device>
<network>
<name>GBS1</name>
<networktype>GSM</networktype>
</network>
<xpos>315</xpos>
<ypos>360</ypos>
<data>
<coverage>0,1200|</coverage>
<bandwidth>0,100|</bandwidth>
<delay>0,10|</delay>
<jitter>0,10|</jitter>
<bitErrorRate>0.0,0.1|</bitErrorRate>
<throughput>0.0,0.4|</throughput>
<burstErr>0.0,0.44|</burstErr>
<packetLossRatio>0.0,0.11|</packetLossRatio>
<costRate>0.0,0.95|</costRate>
<txPower>0.0,0.11|</txPower>
<rxPower>0.0,0.5|</rxPower>
<idlePower>0.0,0.1|</idlePower>
<minVelocity>0,0|</minVelocity>
<maxVelocity>0,120|</maxVelocity>
</data>
</device>
<mobilenode>
<device>
<id>Node1</id>
<application>VoiceCall</application>
<application>Streaming</application>
<application>FTP</application>
<networkinterface>CDMA</networkinterface>
<networkinterface>HSDPA</networkinterface>
<networkinterface>WiBro</networkinterface>
<networkinterface>WLAN</networkinterface>
<networkinterface>GSM</networkinterface>
</device>
<xpos>380</xpos>
<ypos>355</ypos>
<type>CAR</type>
<path>380,355,40,0|70,100,40,0|705,174,40,0|677,393,40,0|368,448,40,0|</path>
</mobilenode>
<servernode>
<server>
<id>Server</id>
<type>1</type>
</server>
<xpos>972</xpos>
<ypos>48</ypos>
</servernode>
</map>
</emulator>
```

요약문

이종 무선 네트워크에서 개인화된 핸드오버 결정을 위한 오토노믹 관리 방법

최근, 다양한 이종 무선 네트워크간의 통합이 산업계와 학계의 주요 이슈로 떠오르고 있다. 이러한 통합 네트워크 환경에서는 서로 다른 네트워크 기술간의 효율적인 핸드오버 지원이 가장 핵심적인 기술이라고 할 수 있다. 특히, 핸드오버 기술과 관련된 것 중에서 언제 어떤 네트워크로 이동을 해가야 할지 결정하는 핸드오버 시점 결정에 대한 문제가 중요시 되고 있다. 기존에는 해당 네트워크의 신호세기를 측정하여 이를 바탕으로 핸드오버 시점을 결정하는 방법이 주로 활용되어 왔다. 이 신호세기는 수평 핸드오버(Horizontal Handover)에서는 좋은 핸드오버 시점을 위한 기준이 되지만, 다른 네트워크간의 수직 핸드오버(Vertical Handover)에서는 각 네트워크의 특성이 다르기 때문에 신호세기만을 적용하기에는 부족하다. 그리고 이동 단말기를 사용하는 사용자의 다른 요구사항 및 환경적인 조건들도 핸드오버 시점을 결정하는데 중요한 요소가 된다.

본 논문은 이종 무선 네트워크 환경에서 다양한 상황 정보를 활용해서 이동 단말기를 사용하는 사용자에게 개인화된 핸드오버 시점 결정을 제공해주는 방법을 제시한다. 제안하는 방법에서 사용자의 간섭을 최소화하기 위해서 오토노믹 관리(Autonomic Management) 방법을 적용하여 실행중에 정보들을 수집하고 이러한 결과를 다시 핸드오버 시점 결정에 반영하는 피드백 제어 루프를 활용하였다. 본 논문에서는 기존에는 신호세기만을 기준으로 해서 핸드오버 시점을 결정하였지만, 이는 사용자의 요구사항 및 현재의 상황 정보를 활용하지 못한다는 단점을 가지고 있기 때문에 좀 더 유연하게 비기능적인 요소인 사용자의 요구 및 선호도, 응용 프로그램의 특성, 네트워크 환경 정보 및 현재의 상황 정보를 활용한 핸드오버 시점 결

정을 제시한다.

우선, 배경 연구로서 오토노믹 컴퓨팅과 오토노믹 네트워킹에 대해서 설명한다. 그리고 관련 연구로서 기존의 핸드오버 시점 결정 관리에 대한 것을 5가지로 정리한다. 결정 함수 기반의 핸드오버 시점 관리, 사용자 중심의 핸드오버 시점 관리, 다속성 의사결정 기반의 핸드오버 시점 관리, 퍼지 로직 및 신경망 기반의 핸드오버 시점 관리 및 상황 정보 기반의 핸드오버 시점 관리에 대한 방법이 제안되었다. 그러나 기존의 방법은 개인의 프로파일을 이용한 개인화와 피드백 제어를 통한 오토노믹 관리에 대한 것을 제공하지 못했다. 본 논문에서는 기존의 방법들의 장점과 단점을 분석하여 이를 기반으로 새로운 방법을 제시한다.

본 논문에서는 사용자가 이동 단말기에서 다른 형태의 응용 프로그램을 사용할 때, 사용자의 선호도를 바탕으로 해서 항상 가장 만족스러운 네트워크 및 AP를 제공한다는 가설을 제시하고, 제안하는 방법을 통하여 검증한다. 우선, 핸드오버 시점 결정에 사용되는 다양한 상황 정보를 이동 단말기, 네트워크, 사용자 및 서비스로부터 조사하여 제시한다. 이러한 정보들은 다양한 곳으로부터 수집할 수 있고, 다른 형태를 가지고 있기 때문에 이를 통일시키기 위해서 DEN-ng라는 정보 모델 방법을 활용하여 설계한다.

수집한 상황 정보들을 토대로 해서 개인화된 핸드오버 시점을 위한 의사 결정 알고리즘을 제시한다. 본 논문에서는 우선 각 접근 네트워크 및 AP를 평가하기 위해서 APAV (Access Point Acceptance Value)와 APSV (Access Point Satisfaction Value)라는 두가지 값을 정의한다. APAV는 신호세기, 품질, 비용, 사용시간이라는 선호도를 기준으로 AP를 택할지에 대한 값을 제시한다. APSV는 이러한 APAV를 기반으로 해서 사용자가 어떤 선호도를 더 중요시하는가를 설정한 사용자 프로파일을 기준으로 해서 사용자의 만족도를 나타내는 값이다. 사용자의 만족도는 실제 사용자로부터 측정해야 하는 값이지만, 본 논문에서는 사용자가 설정해놓은 프로

파일을 기준으로 해서 이에 가장 적합한 것이 가장 만족도가 높다고 가정을 하였다. 제시하는 알고리즘은 이 APSV가 가장 큰 값을 가지는 AP를 선택하는 것으로 가장 만족도가 높은 AP를 선택할 수 있는 방법을 제시한다. 제안하는 핸드오버 시점 결정 알고리즘은 현재의 서비스에 대한 가장 만족도 높은 접근 네트워크 뿐만 아니라 AP까지 선택하기 때문에 수평 및 수직 핸드오버에 대한 시점 결정을 제시한다.

본 논문에서는 이종 무선 네트워크 환경에서 핸드오버 시점 결정을 구현하고 테스트할 수 있는 HMNToolSuite라는 네트워크 시뮬레이터도 제시한다. 기존의 네트워크 시뮬레이터는 프로토콜 수준의 핸드오버를 실행하는 것에 주로 초점을 맞추어 있기 때문에 다양한 상황 정보를 기반으로 하는 핸드오버 시점 결정 알고리즘에는 적합하지 않다. HMNToolSuite는 GUI 기반에서 누구나 쉽게 다양한 무선 네트워크를 구성할 수 있고, 모바일 노드도 생성할 수 있으며, 핸드오버 시점을 결정하는 알고리즘을 테스트할 수 있는 시뮬레이터이다. 이는 기존 시뮬레이터와 별개의 것이 아니라 기존 것과 같이 병행하여 사용할 수도 있다. HMNToolSuite를 사용하여 사용자 프로파일과 응용 프로그램을 기준으로 두가지 사례연구를 통하여 알고리즘의 성능을 평가하기 위한 실험을 수행하였다. 본 실험에서는 제시하는 알고리즘 뿐만 아니라, 신호세기, 품질, 비용, 사용시간에 대해서 핸드오버 시점을 결정하는 방법과 함께 사용자 만족도를 비교한 결과 제시하는 알고리즘이 항상 사용자의 만족도가 높은 AP를 선택하는 것을 보였다.

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어릴적부터 컴퓨터가 좋아서 1997년 포항공대 전자계산학과에 입학하는 것을 계기로 저의 포항생활이 시작되었습니다. 제 인생에서 잊을 수 없는 추억이 고스란히 담겨진 이 곳 포항에서의 생활을 박사 졸업과 함께 마칠려고 합니다. 처음 입학때부터 박사학위를 마치는 순간까지 너무나 많은 분들께서 도와주셔서 제가 무사히 학위를 마치게 되었습니다. 이 지면을 빌어 그분들께 감사의 말씀을 드립니다.

우선, 세상에서 가장 소중한 제 아내와 아들에게 고맙다고 말하고 싶습니다. 아직 사회에 자리도 못잡은 가난한 대학원생의 아내로 살아간다는 것이 얼마나 힘들었는지, 그리고 1년여 미국 방문 연구 기간 동안 아빠 없이 갓 태어난 민규를 너무나 잘 키워주고, 언제나 내 옆에서 믿음으로 인생을 같이 살아가는 동반자인 나의 반쪽 남희, 사랑해 자기야, 이 학위논문은 자기가 없었으면 이루지 못했을거야. 그리고 대학원생활 동안 태어난 아들 민규, 네가 있기에 아빠는 힘들어도 꾹 참고 열심히 할 수 있었단다. 민규야 사랑한다. 앞으로 건강하고 멋지게 자라다오.

그리고 저와 언제나 함께 하며 저의 성공을 위해 헌신하신 가족들에게 깊은 감사를 드립니다. 어릴 때부터 너무나 많은 혜택속에서 공부를 하게 해주시고, 제가 포항공대에 갈 수 있게 길을 열어주시고, 언제나 제게는 든든한 버팀목이 되어주셨던, 지금은 하늘나라에 계신 아버지께 감사를 드립니다. 꼭 박사학위를 마치고 성공하는 모습을 보여드리고 싶었는데, 그런 모습을 보여드리지 못해서 너무나 죄송합니다. 저의 이 학위를 꼭 아버지께 바치고 싶습니다. 아버지께서 사업하시느라 집에서 너무나 고생만 하신 어머니, 아버지 사업이 부도가 나셔서 어려운 가운데서도 3남매를 키우시느라 너무나 고생만 하셨는데, 이제서야 기나긴 공부를 마치고 조금이나마 어머니께 도움이 되는 큰 아들이 될 것 같습니다. 어머니 그동안 너무나 감사드리고, 앞으로 꼭 성공해서 보답을 드리겠습니다. 그리고 어릴 때부터 많은 것을 같이 하고 언제나 친구처럼 지낸 동생들, 준우와 서진이에게도 감사하다고 말하고 싶습니다. 그리고 아직 사회에 자리도 못 잡은 학생인데도 흔쾌히 결혼 승낙을 해주시고, 제가 대학원 생활을 잘 할 수 있도록 너무나 많은 도움을 주시고 근래에는 민규를 봐주시느라 너무 고생하시는 장인어른과 장모님께도 감사를 드립니다. 두분이 계셔서 제가 아내와 민규 걱정없이 열심히 학업에 전념할 수 있었습니다. 언제나 따뜻한 격려의 말씀을 잊지 않으시는 태엽, 병엽 형님께도 감사를 드립니다.

다음으로, 제가 신념을 가지고 꾸준히 학위과정을 할 수 있게 도와주신 여러분들에게 감사를 드립니다.

우선 저에게 포항공대에서 공부할 수 있는 계기를 만들어주신 박태준 초대설립 이사장님께 감사를 드리고, 열정을 가지고 꿋꿋이 학업에 매진할 수 있는 동기를 주신 고 김호길 총장님께 감사를 드립니다.

지난 6년동안 저에게 연구뿐만 아니라 인생의 지침을 가르쳐 주신 지도교수님이신 홍원기 교수님께 진심으로 감사드립니다. 제가 여러가지 이유로 학업을 그만두고 싶었을 때, 교수님께서 하나하나 주신 큰 가르침이 있었기에 지금의 제가 무사히 학위를 마칠 수 있게 되었습니다. 또한, 제가 넓은 견문을 가질 수 있게 많은 해외 연수 경험을 열어주시고, 유명하신 분들과 교류를 할 수 있게 해주셔서 앞으로 이 모든 것이 너무나 큰 도움이 될 것 같습니다. 앞으로 교수님 이름에 누가 되지 않고 최선을 다해서 미래의 정보통신분야 장관이 될 수 있도록 큰 꿈을 가진 인생을 살아가겠습니다. 교수님과 함께 했던 마라톤, 등산, 크리스마스 파티, 연구실 MT, 다양한 회식 자리들이 너무나 그리울 것 같습니다. I am extermely grateful to my supervisor, Prof. John Strassner, for his constance guidance, support, great friendship and for his insight.

학부 때부터 저의 박사학위 논문 심사를 해주시기까지 진심어린 가르침을 주신 김종 교수님, 저의 박사논문 연구주제를 시작하게 된 동기부여를 해주시고 많은 지도편달을 아끼지 않으신 서영주 교수님, 1년차때부터 저의 연구를 깊이있게 봐주시고, 언제나 격려를 아끼지 않으신 주홍택 교수님께 감사를 드립니다. 학부 지도교수님으로 시작해서 제가 전공분야에서 열정을 가지고 학자로서 살아가는 길을 제시해주시고, 저에게 더 넓은 연구분야로의 길을 위해 The University of Texas at Austin 방문을 소개해주신 강교철 교수님께 감사를 드립니다. 대학원 선배님이시자 저의 많은 연구들을 이끌어주시고, 대학원 생활에 대한 길을 제시해주신 고려대학교의 김명섭 교수님, 강원대학교의 최미정 교수님께 감사들 드립니다. I grateful acknowledge Prof. Raouf Boutaba for his good comments as a guest committee member. I grateful acknowledge Prof. Alberto Leon-Garcia from Univesity of Toronto and Prof. Don Batory from University of Texas at Austin for advising and supporting my research topics when I have been there.

지난 6년동안 제게는 가족들과도 다름없었던 DPNM 연구실 모든 선후배님들께 감사들 드립니다. 연구실 식구들이 없었다면 제가 지금 이 자리에 와 있을 거라는 생각을 하지 못할 것입니다. 우선 선배님들인 원영준 박사, 성철이, 소정, 선미, 형조, 룡권이형, Deepali, 대학원 동기이자 언제나 저의 고민을 들어주었던 은희 누나, 후배로 들어와 이미 졸업생이 된 창근이, 광본이, 성주, Suman, 진이에게 감사를 드립니다. 이제 저의 뒤를 이어서 랩장을 하고 있는 똑똑한 병철이, 언제나 연구

실의 스포츠맨으로 든든하게 자리잡은 씩씩이 성수, CMEST 프로젝트부터 다양한 연구들에서 저와 함께 열심히 연구를 해준 성실한 신석, 연구실의 홍일점으로 연구도 너무나 열심히 잘해주는 이쁜 아름이, 트래픽 연구의 새로운 주자로 떠오른 든든한 재윤이, 그리고 이제 석사 졸업하고 다시 든든히 박사로 진학할 얌전이 혁수, 묵묵히 맡은 일을 너무나 열심히 잘해주는 믿음직한 건이, ITCE를 든든하게 책임지고 있는 캡틴 영락이, KT 프로젝트를 하면서 너무나 수고해준 윤선과 효정, 신입생인 태현, Yongfeng, Do, 연구실의 하나하나 잡일부터 모든 살림살이를 잘 챙겨주는 착한 혜정이, 모든 우리 DPNM 연구실 식구들 너무 감사합니다. 어디를 가도 여러분은 절대 잊지 못할 겁니다.

그리고 제게 지금까지 많은 도움을 주셨던 분들께 감사를 드리고자 합니다.

특별히 소프트웨어 공학 연구실의 GDT 팀으로부터 알티캐스트에서의 ES 팀까지 너무나 많은 것을 도와주고 같이 즐겼던 이지영 박사님, 태호, 현호에게 감사를 드립니다. 그리고 다른 GDT 멤버였던 경진이 누나와 성구에게도 감사를 드립니다. 그리고 컴공과 97학번 동기들이 있어서 이곳에서의 생활이 너무나 즐거웠습니다. 모든 동기들에게 감사를 드립니다. 오영희 선생님, 이희조 박사님을 비롯한 모든 PLUS 식구들에게 감사를 드립니다. 학부 때부터 지금까지 PLUS의 한 일원이라는게 너무나 자랑스럽고, 든든한 선후배님들이 있어서 지금의 저도 열심히 하고자 하는 동기를 부여받습니다. 저의 대학원생활동안 힘이 되어주었던 상기형, 예하형, 현식이형 및 모든 선배님들께 감사를 드립니다. 그리고 학부 때 첫 룸메이트로 인연을 맺어 지금은 미네소타에서 박사학위를 마치신 훈정이형께 감사를 드립니다. Austin에 방문했을 때 저에게 많은 편의와 연구적인 동기부여를 심어주셨던 병철이형, 하이드팍 교회의 김한길 목사님, 정우형, 박영기 집사님께도 감사들 드립니다. 황주호 선생님을 비롯한 모든 고요독서회 식구들께도 감사를 드립니다. 2000년부터 4년동안 알티캐스트 회사에서 같이 지냈던 지승림 부회장님, 희수형, 문규형, 규호아저씨, 환효, 정동훈 전무님, 류주현 소장님, 김도형 팀장님, 김상수 팀장님, 이해철 팀장님을 비롯한 저와 함께 일했던 모든 분들께 감사를 드립니다. 회사생활에서의 너무나 좋은 추억과 경험이 있었기에 지금의 제가 있다고 생각이 듭니다.

끝으로 이공계 국가연구장학생으로 2009년 9월부터 2010년 8월까지 지원을 준 교육과학기술부 및 한국장학재단에도 감사드립니다. (S2-2009-000-00087-1)

이제 제 논문을 이 포항공대에 남기고 이제는 학생이 아니라 졸업생 신분으로서 학교의 명예를 더 높일 수 있도록 열심히 살아가도록 하겠습니다. 포항공대 출신이라는 것이 너무나 자랑스럽습니다. 모든 분들 감사합니다.

CURRICULUM VITAE

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EDUCATION

March 1997 – February 2005:
B.S. in Computer Science and Engineering
Pohang University of Science and Technology (POSTECH), KOREA

March 2005 – February 2011:
Ph.D. in Computer Science and Engineering
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Thesis title: Autonomic Management for Personalized Handover Decisions in Heterogeneous Wireless Networks (Defended on December 20, 2010)
Supervisors: Prof. James Won-Ki Hong and Prof. John Charles Strassner

RESEARCH INTERESTS

Autonomic Network and System Management, Mobile Device Management, Autonomic Resource Management, Handover Decision Management, Personalization, Context-Aware Computing, Interactive TV Platform & Service, Software Product Lines

AWARDS, SCHOLARSHIP & LEADERSHIP

September 2009 – August 2010: National Research Scholarship, Korea Student Aid Foundation grant funded by the Korea government (MEST), Research on an Efficient Decision Making Method in Autonomic Computing Systems, 12,000,000 KRW (S2-2009-000-00087-1)

December 2005 – October 2008: Lab. Leader, DPNM Lab. POSTECH, Korea.

March 2005 – February 2011: Brain Korea 21 Scholarship, Korea (Brain Korea 21: a major multi-year initiative by Korean Ministry of Education to enhance global competitiveness of graduate education in Korea).

August 1999: The Highest level in the Hackers Lab. (Korean Hacking contest)

March 1999 – February 2000: 11th Group Leader of CSE study group, POSTECH, Korea

June 1999: Prize in the Good Venture Item Contest (WizarDraw), Korea

EXPERIENCES

October 2008 – September 2009: Visiting Student, Dept. of Computer Science, The University of Texas at Austin, (Advisor: Prof. Don Batory) – Research on Feature Oriented Software

Development for Autonomic Management, Incremental Development of Software Architectures

September 2007 – December 2007: Teaching Assistant, Microprocessor Programming (CSED211), Department of Computer Science and Engineering, Pohang University of Science and Engineering (POSTECH)

January 2006 – February 2006: Visiting Student, Dept. of Electrical and Computer Engineering, University of Toronto, Canada, (Advisor: Prof. Alberto Leon-Garcia) – Research on Autonomic Mobile Terminal Management

September 2005 – December 2005: Teaching Assistant, Introduction of Computer Science (CSED101), Department of Computer Science and Engineering, Pohang University of Science and Engineering (POSTECH)

March 2004 – August 2004: Research student in Software Engineering Lab. (SE), Department of Computer Science and Engineering, Pohang University of Science and Engineering (POSTECH) – Research on Software Reuse and General Drawing Tool

January 2000 – January 2004: Software Engineer, Alticast Corporation, Seoul, Korea – Development of DVB-MHP middleware, EPG and DTV applications

June 1998 – December 1999: Research student in Software Engineering Lab. (SE), Department of Computer Science and Engineering, Pohang University of Science and Engineering (POSTECH) – Development of Security Injection System and General Drawing Tool

March 1999 – December 1999: Research student in High Performance Computing Lab. (HPC), Department of Computer Science and Engineering, Pohang University of Science and Engineering (POSTECH) – Research on System Security and Development of Hacking Simulator

June 1997 – present: Official member (PLUS016) of PLUS (POSTECH Security Group), POSTECH – Working on Windows and UNIX security

PUBLICATIONS

A. International Journal Papers

1. Chang-Keun Park, **Joon-Myung Kang**,James Won-Ki Hong, Mi-Jung Choi, Yong-hun Lim, Seongho Ju, and Moon-suk Choi. Development and Testing of an SNMP-based Integrated Management System for Heterogeneous Power Line Communication Networks. *International Journal of Network Management (IJNM)*, Vol. 20, Issue 1, January/February 2010, pp. 35-55. **(SCIE)**
2. **Joon-Myung Kang**, Hong-Teak Ju, Mi-Jung Choi, James Won-Ki Hong, and Jun-Gu Kim. OMA-DM Based Remote Software Fault Management of Mobile Devices. *International Journal of Network Management (IJNM)*, Vol. 19, Issue 6, November/December 2009, pp. 491-511. **(SCIE)**
3. Jae-Jo Lee, Choong Seon Hong, **Joon-Myung Kang**, and James Won-Ki Hong. Power line

communication network trial and management in Korea. *International Journal of Network Management (IJNM)*, Vol. 13, Issue 6, Special Issue, November/December 2006, pp. 443-457.

B. International Conference Papers

1. Sin-seok Seo, **Joon-Myung Kang**, Nazim Agoulmine, John Strassner, James Won-Ki Hong. FAST: A Fuzzy-based Adaptive Scheduling Technique for IEEE 802.16 Networks. *IFIP/IEEE International Symposium on Integrated Network Management (IM 2011)*, Dublin, Ireland, May. 2011 (Accepted to appear).
2. Arum Kwon, **Joon-Myung Kang**, Sin-seok Seo, Sung-Su Kim, Jae Yoon Chung, John Strassner and Jame Won-Ki Hong. The Design of a Quality of Experience Model for Providing High Quality Multimedia Services *The 5th IEEE International Workshop on Modelling Autonomic Communication Environments (MACE 2010)* Niagara Falls, Canada, Oct. 2010, pp. 24-36.
3. **Joon-Myung Kang**, Chang-Keun Park, Sin-Seok Seo, Mi-Jung Choi, and Jame Won-Ki Hong. User-Centric Prediction for Battery Lifetime of Mobile Devices. *11th Asia-Pacific Network Operations and Management Symposium (APNOMS 2008)*, LNCS 5297, Beijing, China, Oct. 2008, pp. 531-534.
4. Chang-Keun Park, **Joon-Myung Kang**, Mi-Jung Choi, James Won-Ki Hong, Yong-Hun Lim, and Seong-Ho Ju. Definition of Common PLC MIB and Design of MIB Mapper for Multi-vendor PLC Network Management, *IEEE International Symposium on Power Line Communications and its Applications (ISPLC 2008)*, Jeju Island, Korea, April 2-4, 2008, pp. 152-157.
5. Chang-Keun Park, **Joon-Myung Kang**, Mi-Jung Choi, James Won-Ki Hong, Yong-Hun Lim, and Munseok Choi. An Integrated Network Management System for Multi-Vendor Power Line Communication Networks. *The International Conference on Information Networking 2008 (ICOIN 2008)*, Busan, Korea, January 23-25, 2008.
6. **Joon-Myung Kang**, Hong-Teak Ju, Mi-Jung Choi, and James Won-Ki Hong. OMA DM Based Remote RF Signal Monitoring of Mobile Devices for QoS Improvement. *10th IFIP/IEEE International Conference on Management of Multimedia and Mobile Networks and Services (MMNS 2007)*, LNCS 4787, San Jose, CA, USA, Oct. 2007, pp. 76-87.
7. **Joon-Myung Kang**, Hong-Teak Ju, Mi-Jung Choi, and James Won-Ki Hong. OMA DM Based Remote Software Debugging of Mobile Devices. *10th Asia-Pacific Network Operations and Management Symposium (APNOMS 2007)*, LNCS 4773, Sapporo, Hokkaido, Japan, Oct. 2007, pp. 51-61.
8. **Joon-Myung Kang**, Chang-Keun Park, Eun-Hee Kim, James Won-Ki Hong, Yong-Hun Lim, Sungho Ju, Moonsuk Choi, Bum-Seok Lee, and Dukhwa Hyun. Design and Implementation of Network Management System for Power Line Communication Network. *IEEE International Symposium on Power Line Communications and its Applications (ISPLC 2007)*, Pisa, Italy, Mar., 2007, pp. 23-28.
9. **Joon-Myung Kang**, Hong-Teak Ju, and James Won-Ki Hong. Towards Autonomic Handover Decision Management in 4G Networks. *9th IFIP/IEEE International Conference on Management of Multimedia and Mobile Networks and Services (MMNS 2006)*, LNCS 4267, Dublin, Ireland, Oct., 2006, pp. 145-157 (SCIE)

C. Domestic Journal Papers

1. **강준명**, 고탁균, 서신석, 성백재, John Strassner, 김종, 박찬익, 홍원기. 상황인식 서비스를 위한 스마트 모바일 플랫폼 (Smart mobile platform for supporting context-aware services) *한국정보과학회 학회지*, 2010년 5월.
2. **강준명**, 박창근, 김은희, 홍원기, 임용훈, 주성호, 최문석, 이범석, 현덕화. 전력선 통신망을 위한 네트워크 관리 시스템의 설계 및 구현. *KNOM Review*, Vol. 9, No. 2, Jan 2007, pp 1-13.

D. Domestic Conference Papers

1. **강준명**, 서신석, 홍원기, John Strassner. 이종 이동 통신 네트워크에서의 이동 단말기의 이동성 관리를 테스트하기 위한 연구. *한국통신학회 하계학술대회*, 제주, June 23, 2010.
2. 서신석, **강준명**, 홍원기, John Strassner. 이동 통신 단말기를 위한 상황 정보 기반의 자동 응답 방법에 대한 연구. *한국통신학회 하계학술대회*, 제주, June 23, 2010.
3. 최혁수, **강준명**, 홍원기. 노인들을 위한 U-헬스 스마트 홈에 관한 연구. *한국통신학회 하계학술대회*, 제주, June 23, 2010.
4. 권아름, **강준명**, 홍원기, John Strassner. 인터넷 서비스의 QoE 측정을 위한 품질 지표 모델. *한국통신학회 하계학술대회*, 제주, June 23, 2010.
5. 최영락, **강준명**, 리건, 홍원기, John Strassner. 클라우드 컴퓨팅 기반의 통합 대중 교통 수단 검색 시스템. *한국통신학회 하계학술대회*, 제주, June 23, 2010.
6. 서신석, **강준명**, 홍원기. OMA DM 프로토콜과 Proc 파일 시스템을 이용한 모바일 단말 관리 정보 수집 방안. *한국통신학회 하계학술대회*, 제주, June 20, 2009.
7. **강준명**, 박창근, 최미정, 홍원기. 사용 패턴에 기반을 둔 이동 통신 단말기의 배터리 사용시간 예측 방법. *한국통신학회 하계학술대회*, 제주, July 3, 2008.
8. 박창근, 최미정, **강준명**, 홍원기, 임용훈, 주성호. 멀티 벤더 전력선 통신 망을 위한 통합 네트워크 관리시스템 설계 및 구현 *한국통신학회 추계학술대회*, 서울, November 17, 2007.
9. **강준명**, 최미정, 박창근, 홍원기. 모바일 단말기의 가용성을 높이기 위한 자율 관리 시스템의 설계 *한국통신학회 추계학술대회*, 서울, November 17, 2007.
10. 박창근, **강준명**, 최미정, 홍원기, 임용훈, 주성호, 최문석, 이범석, 현덕화. 전력선 통신 망(PLC 네트워크)을 위한 관리 정보(MIB) 설계. *통신망운영관리 학술대회 (KNOM 2007)*, 제주, April 2007, pp. 198-205.

E. Books and Book Chapters

1. **Joon-Myung Kang**, Windows NT Security, In: Security PLUS for UNIX,ISBN: 8931414900, Korea, pp. 439-490. (Korean).

F. International Patents

1. James Won-Ki Hong and **Joon-Myung Kang**. Method and Apparatus for Handover decision by using Context Information in a Next-Generation Mobile Communications Network. Patent No.: 4571663 (2007-271645), Japan, 2010.08.20 (Applicant: POSTECH)
2. James Won-Ki Hong and **Joon-Myung Kang**. Method for Predicting Battery Lifetime of Mobile Devices Based on Usage Patterns. Patent No.: 2009-118340, Japan, 2009. (Applicant: POSTECH) (FILED)
3. James Won-Ki Hong and **Joon-Myung Kang**. Method for Predicting Battery Lifetime of Mobile Devices Based on Usage Patterns. Patent No.:09005895.9, Europe(EPO), 2009. (Applicant: POSTECH) (FILED)
4. James Won-Ki Hong and **Joon-Myung Kang**. Method for Predicting Battery Lifetime of Mobile Devices Based on Usage Patterns. Patent No.:12/453,141, USA, 2009. (Applicant: POSTECH) (FILED)
5. James Won-Ki Hong and **Joon-Myung Kang**. Method and Apparatus for Detecting Abnormal Battery Consumption of Mobile Devices. Patent No.: , Japan, 2009. (Applicant: POSTECH) (FILED)
6. James Won-Ki Hong and **Joon-Myung Kang**. Method and Apparatus for Detecting Abnormal Battery Consumption of Mobile Devices. Patent No.:09005896.7, Europe(EPO), 2009. (Applicant: POSTECH) (FILED) (Accepted to Register)
7. James Won-Ki Hong and **Joon-Myung Kang**. Method and Apparatus for Detecting Abnormal Battery Consumption of Mobile Devices Patent No.:12/453,142, USA, 2009. (Applicant: POSTECH) (FILED)

8. James Won-Ki Hong and **Joon-Myung Kang**. Method and Apparatus for Handover decision by using Context Information in a Next-Generation Mobile Communications Network. Patent No.: 07020430.0-1249, Europe (EPO), 2007.10.18 (Applicant: POSTECH) (FILED)
9. James Won-Ki Hong and **Joon-Myung Kang**. Method and Apparatus for Handover decision by using Context Information in a Next-Generation Mobile Communications Network. Patent No.: 11/907,547, USA, 2007.10.15 (Applicant: POSTECH) (FILED)

G. Domestic Patents

1. 홍원기, **강준명** 사용 패턴 기반의 이동 통신 단말기의 배터리 사용시간 예측 방법. 특허 제 10-0981128, 2008.06.11, (출원인: 포항공과대학교 산학협력단)
2. 홍원기, **강준명** 이동 통신 단말기의 비정상적인 배터리 소모 검출 방법 및 장치. 특허 제 10-0886625, 2010.07.05, (출원인: 포항공과대학교 산학협력단)
3. 홍원기, **강준명** 차세대 이동통신 네트워크에서의 상황 정보를 이용한 핸드오버 결정 방법 및 장치. 특허 제 10-0809260호, 2008.02.25 (출원인: 포항공과대학교 산학협력단)
4. 홍원기, 존 스트라스너, **강준명** 이동 단말기의 개인화된 핸드오버 결정 방법 및 이를 수행하는 이동 단말기. 출원번호: 10-2010-0101906, 2010.10.19, (출원인: 포항공과대학교 산학협력단)
5. 홍원기, **강준명**, 서신석 이동 통신 단말에서 상황 정보를 이용한 자동 응답 방법 및 장치. 출원번호: 10-2010-0081790, 2010.08.24, (출원인: 포항공과대학교 산학협력단)
6. 홍원기, **강준명** 소프트웨어 시스템의 자율 관리 제공 방법, 이를 수행하는 프로그램을 기록한 기록매체 및 소프트웨어의 자율 관리 기능을 구비한 시스템. 출원번호: 10-2010-0032564, 2010.04.09, (출원인: 포항공과대학교 산학협력단)
7. 스트라스너 존 찰스, 홍원기, **강준명** 개인화 서비스 제공 및 관리를 위한 장치 및 방법. 출원번호: 10-2010-0033286, 2010.04.12, (출원인: 포항공과대학교 산학협력단)

H. Invite Talk & Tutorials

1. **Joon-Myung Kang**. Network Management for Power Line Communication Networks. Invite Talk, Workshop of u-City and Power IT Infra resource management, ETRI, August 21-22, 2008, Busan, Korea.
2. **Joon-Myung Kang**. OMA DM Based Remote RF Signal Monitoring of Mobile Devices for QoS Improvement. Conference presentation, *10th IFIP/IEEE International Conference on Management of Multimedia and Mobile Networks and Services (MMNS 2007)*, San Jose, CA, USA, Oct. 2007.
3. **Joon-Myung Kang**. OMA DM Based Remote Software Debugging of Mobile Devices. Conference presentation, *10th Asia-Pacific Network Operations and Management Symposium (APNOMS 2007)*, Sapporo, Hokkaido, Japan, Oct. 2007.
4. **Joon-Myung Kang**. Towards Autonomic Handover Decision Management in 4G Networks. Conference presentation, *9th IFIP/IEEE International Conference on Management of Multimedia and Mobile Networks and Services (MMNS 2006)*, Dublin, Ireland, Oct., 2006.
5. **Joon-Myung Kang**. Windows NT Security. Invite Talk, Workshop on Security (ConCERT 2000), Dongkuk University, Seoul, June 2000, Korea.
6. **Joon-Myung Kang**. Step by Step for Windows NT Security. Tutorial, Ahn Lab. Security Company, Seoul, May 2000, Korea.
7. **Joon-Myung Kang** Windows NT Security. Invite Talk, 6th Workshop of Internet Operation (WIO), ChoongNam University, August 1999, Korea.
8. **Joon-Myung Kang** Windows NT Security. Invite Talk, 5th Workshop of Internet Operation (WIO), Sookmyung Women's University, February 1999, Korea.

I. Software

1. James Won-Ki Hong, **Joon-Myung Kang**, Sin-seok Seo. HMNToolSuite (Emulator and Simulator for Heterogeneous Wireless Networks). (Java, XML-RPC) No. 2009-01-241-004298, Korea, 2009
2. 10 more registered software, available upon request

PROJECTS

A. Academic (POSTECH, http://www.postech.ac.kr, DPNM Lab., http://dpnm.postech.ac.kr)

1. June 2010 – November 2011: Development of Semantic Recommender System for IPTV VOD, KT.

   This research project develops a prototype of a semantic-based recommender system for IPTV VoD. We develops a movie database crawler (IMDB), user behavior monitoring by clicking through analysis, user modeling, and semantic reasoning based on ontology.
2. March 2010 – February 2011: HiMang (Highly Manageable Network and Service Architecture for Next Generation), Electronics and Telecommunications Research Institute (ETRI)

   This research project develops a novel autonomic and cognitive approach to providing a highly manageable network and service management architecture for current as well as future networks. It is based on using an innovative knowledge representation methodology that unifies disparate knowledge sources and greatly improves learning, decision-making, and reasoning in management systems.
3. May 2010 – October 2010: Self-Organizing Network Expert System, Samsung

   This research project analyzes how current wireless networks are managed, and develop a new approach that uses an expert system and production rules to self-configure and self-organize wireless network resource for Mobile WiMAX. We develop a policy language and compiler for covering business level SLA, system administrators command, and device instance level commands.
4. March 2010 – February 2011: Research on Decision Making for Autonomic Computing Systems, PIRL, POSTECH

   This research project develops a novel decision making for autonomic computing systems based on fuzzy logic and utility function. We develops it for access network selection for mobile devices.
5. November 2009 – October 2010: Cognitive Network Management System (CogNMS), EU FP Participation Activity Supporting Project, Korea Institute for Advancement of Technology (KIAT)

   This research project collaborates EU for CogNMS EU FP7 project.
6. October 2008 – September 2009: Feature-Oriented Software Development for Autonomic Management, Joint Research at The University of Texas at Austin (Prof. Don Batory)

   This join research project was achieved by collaborating Prof. Batory, UTAustin. His research area is Feature-Oriented Programming in Software Engineering. I wanted to apply Feature-Oriented method to we propose FOSDAM which is a feature oriented approach to develop Autonomic systems (ASs), which include AM, in terms of dynamic reconfiguration. We use two feature models for static configurations and dynamic reconfigurations of ASs, define a ranking metric for determining appropriate configurations based on a feature model at runtime, and develop a lightweight and fast decision maker.
7. January 2009 – February 2011: Research on Autonomics for IT Convergence, World Class University (WCU), Ministry of Knowledge and Economy (MKE)

   This is part of the research work proposed under our World Class University grant from the Korean government. My work involves investigating how autonomic mechanisms can be applied to manage new ubiquitous computing systems that use bio-informatics, nano-technologies, and networking technologies for building ubiquitous computing applications (called ubiquitous health and ubiquitous environment applications in Korea). I was a core member for preparing this project proposal and have been doing autonomic management research.

8. January 2007 – December 2007: Research on SNMP-based Military Strategy, Samsung Thales

   This research project develops an SNMP-based network management system for navy ships. We surveyed pros and cons of SNMP and developed an specific NMS for military strategies.

9. September 2005 – Debember 2011: Research on Embeded Software Technology for Network Convergence Mobile Platforms, ITRC (Information Technology Research Center), National IT Industry Program Agency (NIPA)

   This research is a part of Information Technology Research Center. In this project, we develops a middleware for mobile device. I developed a management system for mobile devices based on OMA-DM standards. I also developed a convergence framework for context-aware applications in mobile devices.

10. September 2005 – August 2008: Implementation of Manager for Broadband Power Line Communication Network Management System, Korea Electric Power Research Institute (KEPRI)

    This research project develops a prototype of a network management system for broadband power line communication networks. We developed an NMS and deployed it in the test field. We collaborated Xeline (PLC device manufacturer), Dongmin Information Communication company (NMS), and Kyunghee university (PLC Security).

11. June 1998 February 1999: Security Injection System for the nuclear power plant (SE Lab.)

    This research project developed a security injection system for the nuclear power plant. I developed a frontend using MFC and mailslot.

12. July 1999 December 1999: Implemented Hacking Simulator to Linux and Windows NT (Funded by KT, HPC Lab.)

    This research project developed a hacking simulator using known hacking script for Solaris, Linux, and Windows NT.

B. Commercial (Alticast Corporation, http://www.alticast.com)

1. September 2003 – December 2003: DTV Interactive Service Development Project for Skylife (Fortune service), Korea
   – This project is to develop DTV interactive services based on MHP API
2. November 2001 – April 2003: Skylife Data Broadcasting Service, Seoul, Korea (Development MHP Middleware for Satellite DTV) (commercialized)
3. November 2001 – September 2002: Shenzhen Data Broadcasting Service, Shenzhen, China (Development MHP Middleware for Cable DTV) (commercialized)
4. September 2002 – December 2002: Czech Data Broadcasting Service, Czech (Development MHP Middleware for Terrestrial DTV) (commercialized)
5. August 2001 – December 2001: AltiFusion (MHP Application Test Environment) (commercialized)
6. June 2000 – August 2001: AltiBrowser (MHP 1.1 Compliant Embedded Web browser for DTV)
7. March 2000 – June 2000: Task Force Project for Security Company called 4DSecure Corporation, Korea