SEAMLESS COMMUNICATIONS

SEAMLESS HANDOVER BETWEEN WIRELESS AND CELLULAR NETWORKS WITH FOCUS ON ALWAYS BEST CONNECTED

Lennart Isaksson

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To my family

Abstract

The evolution of today's wireless technologies and small hand-held devices has enabled the handling of the trade-off between mobility and performance. Things have, however, become more complex. Users demand high performance when using small and resource-efficient devices. Users also demand high-performance connectivity anywhere and anytime without having to care about transitions between different access networks. As of today, the absence of Mobile IP (MIP) support in most networks implies the need for a reconnection of the service as soon as the access network changes. That is why a new seamless communication concept is required.

In the thesis, a new seamless communication concept is proposed. The goal is to be Always Best Connected (ABC) even if the conditions change. Initially, a network link has to be selected and a connection has to be established. The service used should be maintained as long as the conditions are fulfilled. First, a set of Generic Services (GSs), each related to a specific communication task, is defined. Furthermore, a deep performance investigation of some of the wireless technologies available is summarized and used. Based on the combination of a GS and a wireless technology selected criteria are used. The data extracted from our measurements have the option of later being fed into statistical algorithms. The translation of the extracted information through the statistical methods could be non-linear and for that reason the Fuzzy Set Theory (FST) is used. The FST provides us with the tool needed for the next step, the decision aiming at ABC. To be able to handle the large amount of data, the Multi-Criteria Decision Making (MCDM) is used. This decision model requires a linguistic 9-point scale which suits the FST tool perfectly. A judgment between different criteria can then be made.

Moreover, the thesis describes a couple of important issues regarding the Internet protocol address problem. Each problem is discussed and solutions are presented in the context of having seamless communication without today's constraints. The result is a seamless communication concept that is more flexible than other solutions. Both the FST and the MCDM tools have been successfully implemented into a running prototype.

Preface

This thesis consists of research in the area of seamless communications. The work was done at the School of Engineering at Blekinge Institute of Technology (BTH). The thesis is also a part of the Personal Information for Intelligent Transport Systems through Seamless Communications and Autonomous Decisions (PIITSA) project funded by the Swedish Agency for Innovation Systems VINNOVA (project number 2003-02873), www.vinnova.se. Other partners have been Saab Communication in Växjö; the Technical Research Institute of Sweden (SP), and the Swedish National Road Administration (Vägverket). I would like to thank them all for a good collaboration. It has been a pleasant experience to work with You all.

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Lennart Isaksson
Karlskrona, February 2007

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Chapter 1

Introduction

The test of true science is not whether men of genius have revealed some of nature's mysteries but whether men of lesser talent can learn to use their methods and reveal more.

Howard Scott Gordon

This chapter presents the background and motivation of the thesis. The definition of seamless communications together with the problem statements and the focus of the thesis are then given. A view on research methodology and the actual use of this methodology in the thesis follow. The presentation of the structure of the thesis concludes the chapter.

1.1 Background and Motivation

Personalized communication and information technology has steadily grown in importance during the recent years. Today, a user has the ability to choose the way of communication compared to a few years ago. Instead of using one telephone connected to only one provider, one has the option to choose between several providers and services. So, the dilemma presents itself when there is a need to choose an acceptable network link for a selected service. In case of several available network links, a selection has to be made in such a way that the desired Quality of Service (QoS) is met. In highly dynamic wireless and mobile environments, involving varying numbers of users and volatile transmission conditions, the characteristics of streams of data packets change all the time, which imposes the need of end-to-end monitoring. Also, the amount of simultaneous users who could be connected to the same Access Point (AP) does have some major impact on the overall performance. Moreover, the problem with interference in the 2.4 GHz Industrial Scientific and Medical (ISM)-band, shared amongst Wireless Local Area Network (WLAN), ZigBee, Bluetooth and microwave ovens, needs to be addressed [1]. Today, several other technologies are competing in transferring information in the same frequency band and with that comes interference.

No matter the conditions and obstacles, the main goal for any end-user is to be Always Best Connected (ABC): "he or she is not only always connected, but also connected through the best available device and access technology at all times" [2]. However, an average user does not necessarily comprehend the offerings and implications of different access networks for different Generic Services (GSs) such as streaming, messaging and interactivity [3]. Given the growing mobility of users and the volatility of conditions, necessary changes of access networks need to be carried out during ongoing sessions. This is not enabled by the Internet Protocol (IP) which is *the* most spread networking protocol today. A change of network means a change of the IP address and thus breaking the session, entailing data loss and the necessity to start over.

The dream scenario from the end-user point of view is, however, *seamless communications* implying switching or roaming between access networks (also called *vertical handover*) which should be hardly noticed by the end-user. So, the challenge is to choose an acceptable network link for the selected service so that a reasonable "performance-cost-accessibility" compromise is yielded.

This automatically lead us to the next issue, the criteria. Depending on the service used the type of criteria changes. A set of criteria (measurement points) and a predefined metric value (primary parameter) for a particular criterion, which is not changed during a session, is defined as a *static* criterion. If the changes occur within a session the criterion is defined as *dynamic*. Based on the monitored information, a decision is made from the end-user perspective. The hand-held device, with the End-to-End (E2E) connection, tries to preserve its expectations even if a switch between two connections is done. All types of dynamic inputs will be fed into a Multi-Criteria Decision Making (MCDM) tool which makes the switch more or less *seamless* from the end-user point of view. Still, the future goal is to reach a complete absence of packet losses caused by the roaming.

What does a true seamless communication concept look like? A (wireless) technology and its network link together with a specific service have to be identified first. There are different types of services available, so-called Generic Services (GSs), which are similar in their characteristic and needs in order to be perceived as functioning in an acceptable way. Depending on the services selected, an appropriate quality has to be maintained. True seamless communication should also have the option of selecting different technologies in both directions. The end-user expects that all efforts are put into the selection of the best link (network and connection) to provide the best QoS. And all this should be carried out in a seamless context way, i.e. without any disruptions.

1.2 Decision Framework for Seamless Communications

In Fig. 1.1 the flow chart of the seamless communications concept is presented. Seamless communications is enabled by three components as follows: *Generic Services*, *Seamless Connectivity*, and the *Switch Control Unit*. Between the *Seamless Connectivity* and the *Switch Control Unit* there are the *criteria*, *metric values*, *statistics*, *transformation*, *decision method* and *roaming strategy*. If these steps are carried out and in this order, true seamless communication is possible to obtain. Before going any further, each subsection is shortly introduced together with a few guiding questions.

1. Generic Service, detailed in Section 2.4. Before using a particular service, which could be video or messaging, a hand-held device has to be chosen. The application together with the service selected perceives a combination of its own characteristics together with the wireless technology used. So, the opening question is: *which types of services could we expect?* This also leads us to the question: *when are these types of services supposed to be used and under which circumstances?*

2. Seamless Connectivity, detailed in Section 2.5. By using *seamless communications* well-known wireless technologies such as the Universal Mobile Telecommunications System (UMTS), the General Packet Radio Service (GPRS), and the Wireless Local Area Network (WLAN) have to be investigated. The Digital Audio Broadcast (DAB) technology was also investigated, but the low interest of implementation of the new technology and the high cost of using it made it less interesting to go any further in investigating its behavior and characteristics. So, the UMTS, GPRS, and WLAN were used. Thus, the questions are: *which type of behavior and characteristics does each wireless technology have, and how do those relate to the service in question?*

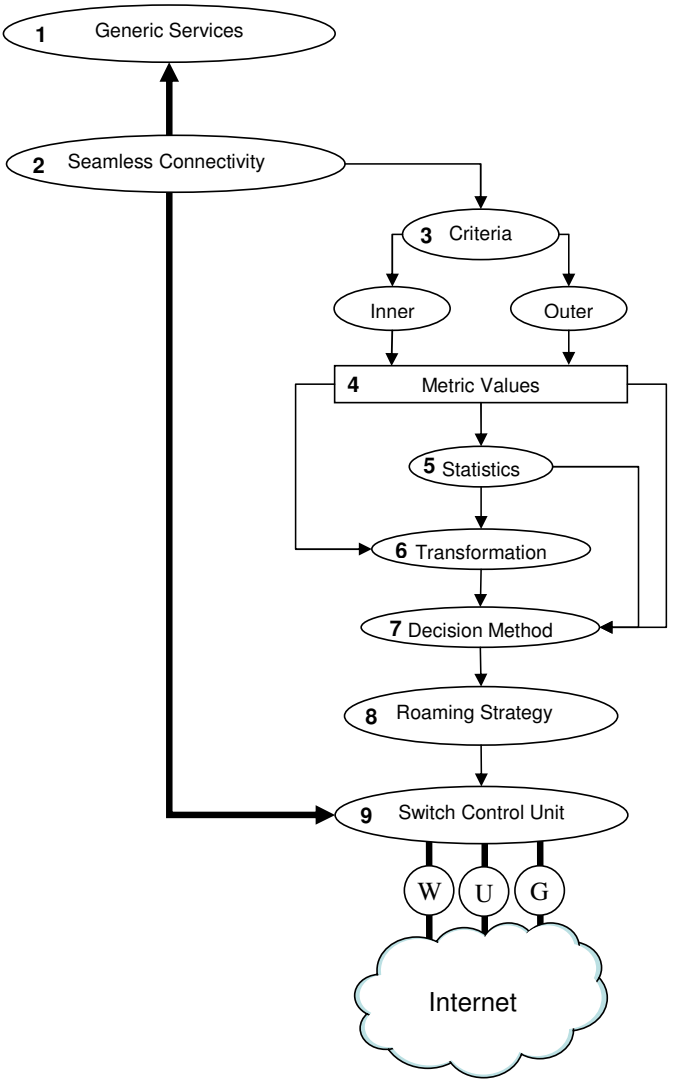


Figure 1.1: Seamless communications concept

3. Criteria, detailed in Section 2.6 and Chapter 3. Different services and different wireless technologies do show different types of behavior. Sometimes it is not only the performance itself that matters. To simplify the distinction between the different criteria, a division into two groups was made which are defined as the *inner* and *outer* groups. This leads us to the question: *which types of criteria should be used in each group?*

4. Metric Values, detailed in Section 2.7. When a metric value has been established into a so-called *primary parameter* it has to be linguistically interpreted due to input requirements from the decision tool. Before the metric values are translated into a linguistic scale these metric values could take different paths such as: the cognitive translation of a value which is directly fed into the Analytic Hierarchy Process (AHP), and in this case a scale between 1 (equal importance) and 9 (extreme importance) is used. This step is the only step that involves no mathematical tools; metric values are translated with help from *statistics* before being fed into the AHP; the third way goes through statistics and a subsequent translation before entering the AHP. Such a translation can be a simple threshold-based one or based on the Fuzzy Set Theory (FST). In the latter case, they are called "fuzzy quantities". Finally, the pure user perception and rating is fed into the AHP. The data could be measured in different time scales, as in hours, minutes, seconds, or milliseconds etc. It could also be measured in energy or numbers aiming at a specific time frame, for instance the power level of a wireless technology in dBm or a frame size in bytes. So, the question is: *which type of metric unit and scale could be used?*

5. Statistics, detailed in Section 3.6. There are several ways of processing data. These could include: calculating the average, standard deviation, histogram, or autocorrelation of the data. It all depends on what is adequate and usable for the final decision. So the question is: *which type of statistics could be used?* When the data has been processed it

should be sent further either to be used by (d) FST or directly to the (e) decision method.

6. Transformation, detailed in Section 2.8 and Chapter 4. A measurement which produces metric values needs to be mapped into a multi-point scale suitable for decision making. This can be done by the Fuzzy Set Theory (FST) which is called an "approximate reasoning" process. The linguistic values are later sent to the decision method. This leads us to the question: *how should the fuzzy functions and rules be defined?*

7. Decision Method, detailed in Section 2.9 and Chapter 6. In an application, real-time decisions have to be made constantly. A straightforward approach is to use the Multi-Criteria Decision Making (MCDM) suitable for any multi-point scale. The decision method collects data from the previous stages of *metric values*, *statistical* module, or the *transformation* module. This leads us to the question: *what type of decision methods could handle the amount of quality variations reflecting the structure of our criteria?*

8. Roaming Strategy, detailed in Section 2.10 and Chapter 8. This is the procedure which handles the roaming strategy, addressing the switch from one wireless network over to another wireless network. The strategy is to have predefined priorities to make a better decision when a switch is requested. So, the question is: *which types of components are required in a roaming strategy?* And, *how are these connected to each other?* Finally, a suitability presentation of the monitored network links is needed. A simple presentation of the condition of the network links could be sufficient for most of the end-users, e.g. a presentation in colors green (G), yellow (Y), or red (R). Still, if required, the decimal representation could also be presented. This leads us to the question: *what type of scale should be used and how should this be presented?*

9. Switch Control Unit (SCU), detailed in Section 2.11 and Chapter 9.

Finally, a decision is made. Upon this decision the SCU is able to carry out the switch between the network links between W(LAN), U(MTS) or G(PRS), see Fig. 1.1. Another issue of concern is the IP address architecture: *how could a switch between two different connections be carried out in a seamless manner without losing the E2E connectivity?* This leads us to the question: *could a switch be carried out so that the E2E connection for the selected service is preserved?*

The primary focus of the thesis is to describe a seamless communication concept. The goal of ABC must first be defined for each part of the concept in terms of performance and interoperability. The inner part of the seamless communication concept consists of components that are important to reach this goal. This is described and motivated in detail. To achieve the goal of ABC, statistical methods, fuzzy logic and a decision model have to work together. Next, previous work on performance characteristics of wireless networks, e.g. WLAN, UMTS and GPRS, should be used to define the criteria needed for showing the characteristics of each network link. Based on the service selected through a wireless network link a roaming strategy must also be defined. It is equally important to have a strategy for when to change over to another network link as for the use of a specific network link itself. Finally, the accessibility issue for WLAN due to the amount of other technologies using the same frequency band needs to be considered. The accessibility impact of a decision could play a major role in the final implementation of ABC. The secondary focus is to describe the enabler of a seamless solution because of the IP-addressing issues in mobility situations. So, the steps needed are the following:

- A seamless communication concept will be defined.
- A-priori performance investigations of each technology will be summarized and used to get the correct priority of each network link for a given service. The complete description of each network link and its

characteristics is shortly described and referenced [4].

- Each criterion and its structure will be presented. Due to the complexity of the structure a division of subgroups is required which will be defined.
- Several statistical methods are used together with piecewise linear and non-linear mapping. The measurement mapping will translate any metric scale to a 9-point scale suitable for the decision model which will be presented.
- A decision tool should be able to transform the data into a possible comparison between different alternatives. The amount of criteria or perceived data has to be judged fast and a fair comparison between two completely different types of criteria has to be made. So a usable decision tool will be motivated and presented.
- The specific issue of accessibility in the 2.4 GHz ISM-band will be motivated and described. A classification approach for technologies currently using the ISM-band will be presented.
- After a decision is made between different network links, a roaming strategy will be defined. All the pieces are now put together for the presentation of a solution of seamless communications. With a-priori measurements and characteristics of each network link and real-time monitoring of data packets and a predefined roaming strategy as a basis, the goal of ABC will finally be achieved.

1.3 Research Methodology

Research methodology addresses the process used to carry out research. The methodology comprises the use of different types of sources of information to gain knowledge, e.g. articles, papers etc. Furthermore, a main part of research

work is to verify and validate gained knowledge and from there define new hypotheses.

Today, a more refined distinction is made between basic scientific research and applicable scientific research, as stated in, for example, Ackoff's "Scientific Method" [5]. Basic scientific research is conducted more for its own reason, and applicable scientific research expects fast results. Therefore, scientific research depends on which direction the research is taking. For the basic scientific research three steps are defined; (1) observations; (2) generalizations; and (3) experiments. And for the applicable scientific research there is a more refined ladder with six steps: (1) formulation of the problem; (2) definition of a model; (3) test of the model; (4) deduction of a solution from the model; (5) test and control of the solution; and (6) implementation of the solution. An additional way of conducting research is using the case study method. This was summarized and presented by Tellis [6–8].

Therefore, the conclusion has to be that the paradigm used in this thesis is applicable scientific research.

1.4 Thesis Structure

Chapter 2 – The Concept. In this chapter a definition of Generic Services is given. For each service a description of how the service could be used is described. Also, a detailed description of the statistics used in the model is presented. In general, an elaborate description of each part of the proposed seamless communication concept is given. In some cases a further description is needed which can be found in the referenced chapters.

Chapter 3 – Criteria and Measurement Techniques. In this chapter our criteria are defined. To better support the characteristics of the seamless communication concept, each wireless technology, e.g. WLAN, has to be carefully examined. Different statistical methods are used to better understand the behavior of each technology. These statistical methods are also a part of the inputs to the final decision tool used. From these findings different types of criteria are defined and presented.

Chapter 4 – Linguistic Translation of Metric Values. In this chapter the Fuzzy Set Theory (FST) is presented. It also shows the state of the art in the subject of decision-based algorithms in the fields of the FST. The basic steps of Fuzzy Logic Control (FLC) are given. The chapter ends with a case study of how the FST is used to transform the metric data of packet losses.

Chapter 5 – Accessibility in WLAN. In this chapter the problem of other interfering technologies in the Wireless Personal Area Network (WPAN) area is discussed. Also, a case study is given. A part of the overall decision inputs depends on the used channels and/or energy inside the range of 2.4 GHz ISM band for WPAN and WLAN. This could have an important impact on the final decision. By using the FST, a classification method is also presented.

Chapter 6 – Multi-Criteria Decision Making. The Analytic Hierarchy Process (AHP) tool is motivated and described. Also the setup parameters are described. A description of the Mean Random Consistency Index (MRCI) together with new findings are provided. Finally, the measurement mapping is given.

Chapter 7 – Case Study. A case study is given of both Streaming Service (SS) and Messaging Service (MS). The information gained could now be fed into a Multi-Criteria Decision Making (MCDM) tool to obtain the preference ratios of the alternatives. The ratios are sorted into a list of all technologies used in the Network Selection Box (NSB). The linguistic level for each criterion is motivated and described.

Chapter 8 – Roaming Strategy. The roaming strategy is the main concept of handling the seamless communication functionality inside the Network Selection Box (NSB). The interface to and from the NSB is described as well as the functionality inside the NSB. The NSB is described to give the necessary input to the following chapters. Also two different types of the Network Selection Algorithm (NSA) are presented. Finally, a pseudo-code is given as an aid to better illustrate the seamless communications concept.

Chapter 9 – Switch Control Unit. In this chapter the Switch Control Unit (SCU) is described. First, the state of the art is presented together with some problems regarding the IP-address issue. Five main issues within mobility are listed for the Internet system. Finally there is a presentation on how these issues can be solved, with the focus on the concept of seamless communications.

Chapter 10 – Conclusions. In this chapter, the conclusion of the thesis work is presented. In addition, a description of the contributions is given. Finally, a discussion of future work ends the thesis.

Appendix A – Abbreviations and Acronyms. The acronyms used in the thesis are presented here.

Appendix B – Lightweight ABC for WPAN. Additional figures for lightweight decisions using Always Best Connected for Wireless Personal Area Network which did not fit into Chapter 4 are shown in this Appendix.

Appendix C – WPAN Classification. Additional figures for Wireless Personal Area Network classification which did not fit into Chapter 4 are shown in this Appendix.

Appendix D – Real- and Pseudo-Code Examples. Additional code examples which did not fit into the main text body are shown in this Appendix.

Chapter 2

The Concept

Science is best viewed, not as a body of knowledge, but as an activity - the search for truth, not the possession of it.

Howard Scott Gordon

The chapter begins with an introduction. Next, the state of the art is given. The following sections provide the reader with a short introduction to each part of the seamless communication concept.

2.1 Introduction

What could be expected from a hand-held device? Looking at mobile phones, according to Wood [9], the consumer could expect two types of platforms; smart phones and feature phones. By presenting the difference between the two types of phones, Wood gives 20 scenarios which are listed in favor of the smart phones. Seven main scenarios are presented here:

- Multitasking
- Messaging and entertainment
- Mobile knowledge access
- Organizers and finance
- Pocket consolidators
- Social tools
- Personal development

Wood also emphasizes that the underneath technologies are a part of the success of today. Some of them are *security*, *Internet protocols* and *high-bandwidth data communications*.

At the Macworld Conference & Expo (January 10, 2007) presented by Steve Jobs, something revolutionary happened in the area of hand-held devices. Apple Inc. launched a new type of device which seamlessly integrates music, video, phone and Internet into one device which is called iPhone. Also, inside the iPhone a revolutionary User Interface (UI) is found which makes the device simple and intuitive to use.

One thing one might notice, however, about all these features and devices is the absence of seamless communications, because: *how could the involved feature(s) and service(s) be used if the user does not have a connection available?* The answer is: *hardly!* So, seamless communications would be highly

motivated for these types of devices, as for example the iPhone. The seamless communications component could stretch every service in general to be used even further by the end-user, which could be the turning point when purchasing "that particular expensive application" in mind. The main point is to use an application with less constraints which automatically leads to a more satisfied end-user. On the other hand, Personal Digital Assistants (PDAs) are currently offered with built-in GPRS, UMTS and WLAN. However, the connectivity offered is not seamless; network switches have to be initiated by the user. So, the goal is to be seamlessly ABC.

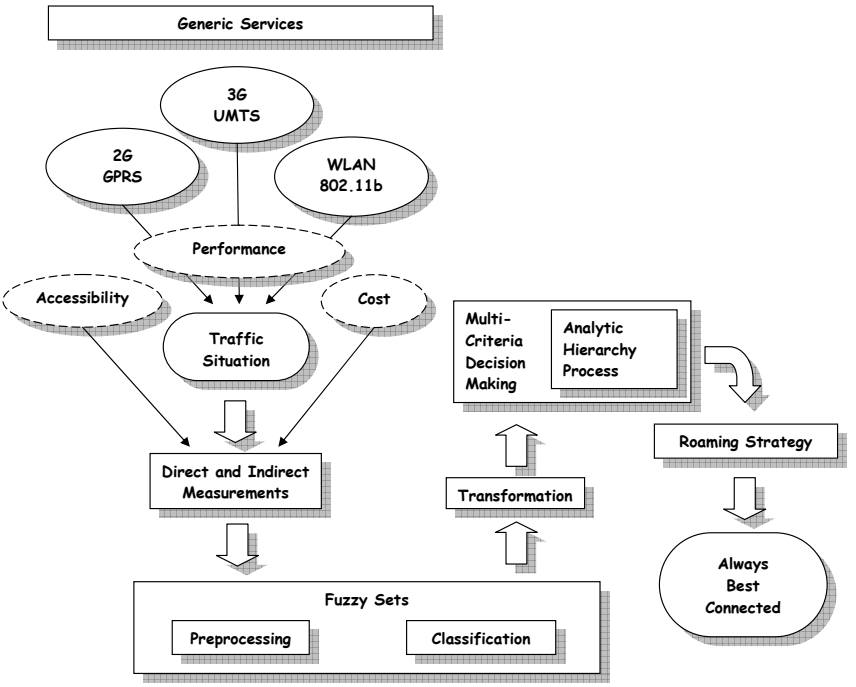


Figure 2.1: The concept

In the thesis a new concept of seamless connection is presented, see Fig. 2.1. The *performance*, *cost*, and *accessibility* criteria of several wireless technologies, e.g. WLAN, UMTS and GPRS, have to be monitored. Through these wireless technologies our GS is used, see Section 2.4. The data is measured directly or indirectly, using statistical methods, depending on the situation, see Section 2.7. In some cases the information needs to be preprocessed and classified before transformed into a decision tool, see Section 2.8. The outcome from the decision tool, see Section 2.9, is finally fed into a roaming strategy, see Section 2.10. The goal is always to be ABC. The concept of ABC is now further presented in this chapter.

2.2 State of the Art

Today, there exist only a few papers in the area of seamless communication. Bakshi *et al.* [10] are looking at cost effective solutions during active handover for WLAN with Transmission Control Protocol (TCP). Also, handover performance on UMTS networks was measured and presented by Bhatti *et al.* [11]. Indulska *et al.* [12] investigate the context-aware vertical handover between WLAN and 3G networks. This work was based on Mobile IP (MIP). The prototype was developed to demonstrate vertical handover between WLAN/GPRS and GPRS/WLAN using streaming Joint Photographic Experts Group (JPEG) video. Their results show low delays and low packet losses due to a disconnection and a reconnection which is required in MIP scenario. Floroiu *et al.* [13] have looked at seamless handover using both User Datagram Protocol (UDP) and TCP in MIP for WLAN/GPRS. The results show that the Round Trip Time (RTT) is one of the important parameters indicating performance degradation. All these papers have used a maximum of two different types of (wireless) technologies being semi-simultaneously connected based on the well-known constrained MIP concept. Ylianttila *et al.* [14] focus on handover between WLAN and GPRS. In their work they have used

fuzzy logic and neural networks. The output is still rough with only three levels of output, i.e. stable, unstable and poor. Still, nothing in detail is presented for how these thresholds should be defined. Another work by Hou *et al.* [15] uses a decision making algorithm based entirely on fuzzy logic which belongs to the group of dynamic programming. Next, a paper by Åhlund *et al.* [16] shows a model of a simultaneously connected network link using Multihomed Mobile IP (M-MIP). The paper also describes a model of handling interference in an access point using Signal-to-Noise Ratio (SNR). However, the metric values used are not related to any generic service. Another interesting paper by Qingyang *et al.* [17] describes a network selection scheme for an integrated cellular/WLAN system. In this system two decision methods are used, the Analytic Hierarchy Process (AHP) and the Grey Relational Analysis (GRA). What makes this paper interesting is that their research is based on being ABC which relates directly to the end-user. Also, the variation and the amount of criteria used is also highly inventive. Still, the issues of the IP-address are not considered.

The main problem which needs to be solved, however, is to find the Holy Grail of Always Best Connected. In [18], we presented a true end-to-end solution for seamless communications, based on a so-called Network Selection Box (NSB) and leaving both the IP-stack and the network untouched.

2.3 Subjective versus Objective Quality

To reach the goal of true seamless communications the objective quality is always used. Still, the subjective quality has to be considered as well.

When it comes to subjective quality, Miller [19, 20] as early as 1956, stated an upper limit of short-term memory based on human capacity which is referred to as the "*channel capacity* of the observer". The outcome is to use a seven-point scale, plus or minus two. To remember these numbers a range of 10–30 seconds is needed and is referred to as the *duration*. A few years ago

Miller wrote an interesting article on the historical perspective on the cognitive revolution [21]. Before this, in 1932, Likert [22] was able to define different scales like a three-point, and a five-point scale. In 1971, Jacoby [23] was satisfied with the three-point scale. Finally in 1994, Chang [24] was looking into scales in-between the four-point and six-point scale.

The subjective quality combines the human perceptive and the objective quality as stated by Sutinen *et al.* [25], see Fig. 2.2. The objective quality consists of four components, the *transport* being one of them. The transport could be any wireless system, e.g., the Universal Mobile Telecommunications System (UMTS), the General Packet Radio Service (GPRS), or the Wireless Local Area Network (WLAN). Each wireless system has its own characteristic which needs to be considered when working toward Always Best Connected (ABC). Different criteria should be considered, e.g. *initial delays* of a connection, *link capacity* which differs depending on the direction, *directional loss* which also differs depending on the direction, *coverage* which is different depending on telephone provider and user location, *Time-Based Fee* for the subscription, *Volume-Based Fee* charge per payload size, etc. Not every criterion is applicable in the same way to different GSs.

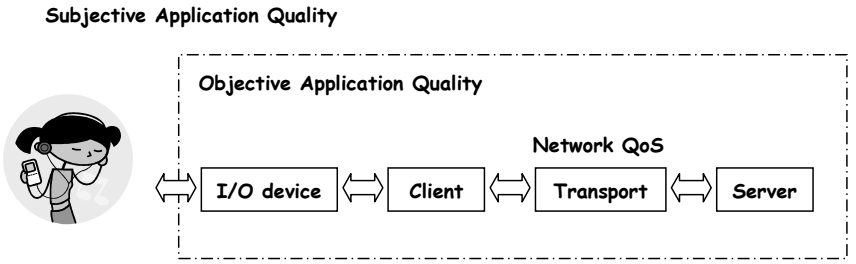


Figure 2.2: Subjective Quality of Service

In general, different persons handle the perceived impression received differently. According to Zadeh [26], the end-user could be facing a fuzzy situa-

tion:

> As the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics.

Further, this is related to the characteristic of the real world perceived by the end-user as stated by Zimmermann [27]:

> Real situations are very often uncertain or vague in a number of ways. Due to lack of information, the future state of the system might not be known completely. [...] We shall call this type of uncertainty or vagueness *stochastic uncertainty* in contrast to the vagueness concerning the description of the semantic meaning of the events, phenomena, or statements themselves, which we shall call *fuzziness*.

The real world constraints could be listed as: *probability*, *fuzziness*, *uncertainty* and *incompleteness*.

A detailed discussion on the selected criteria in the context of seamless communications is found in Chapters 4, 6 and 7.

2.4 Generic Services

GSs are used in different situations, see Fig. 2.3. In the following subsections each type of a GS and abbreviations are described together with a particular service in mind. The GS is also based on the desired degree of availability, performance, security and cost according to Fiedler *et al.* [3] which are taken from the Intelligent Transport Systems and services (ITS) domain. The different types of GSs expected have different characteristics and needs. Against this background, the GSs have been defined as follows: *Streaming Service*, sending

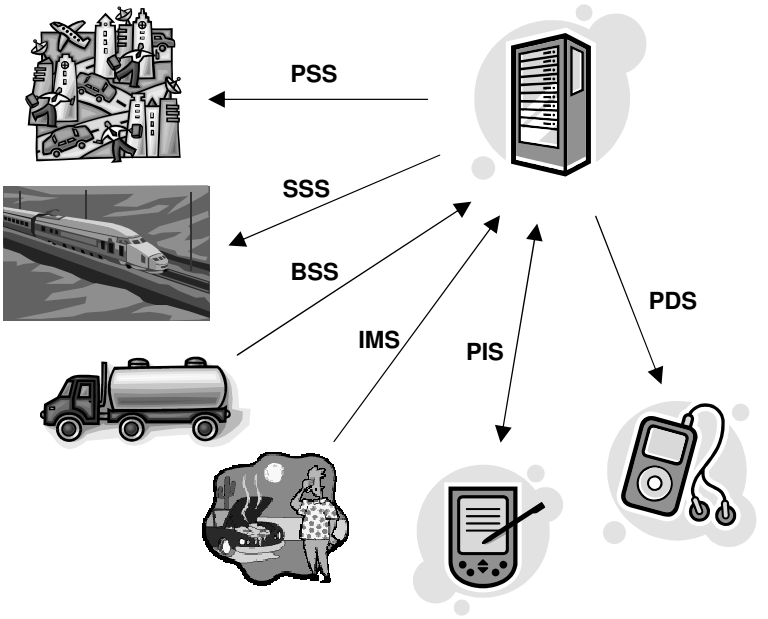


Figure 2.3: Generic Services

information mainly in one direction on a regular basis, i.e. periodically; *Messaging Service*, sending information essentially in one direction when required; and *Interactive Service*, sending information in both directions in a request / response manner.

2.4.1 Streaming Service

A Streaming Service needs constant throughput. Generally data packets are constantly being sent with a relatively constant Inter Packet Delay (IPD). In the ITS context, Fiedler *et al.* [3], have identified the following examples:

Public Streaming Service (PSS). This type of broadcast service is broad-

cast to everybody. The end-user needs to listen or subscribe to a specific channel to receive the information. The service is selected at the receiver's site by choosing an information channel (cf. broadcast radio). Apart from that, the receiver does not have any influence on intensity or contents of the broadcast information. Such service is initiated by some instance (e.g. an authority) being interested in reaching as many people as possible. Correspondingly, the need for availability is high. Usually, this kind of information is provided at low cost (or even free-of-charge) and at a low level of security. Examples include regular messaging about traffic conditions, radio broadcasting via DAB, etc. The amount of data to be streamed depends very much on the need of the application.

Selective Streaming Service (SSS). Selective Streaming Service relates rather to groups than to the broad public. It is "a stream of messages" to "members" who actively subscribe to a group or just belong to it by sharing a common situation or location (e.g. a delayed train). The latter case can be seen as a location-based PSS. It is important to notice that information is not sent upon requests from single users. Depending on the content and the target group, using such a service might be charged and need special precautions with regards to security. As pointed out before, there might be some conceptual overlap with PSS. Examples include traffic information to certain groups of users, e.g. traveling by train or using a certain motorway; group news; weather information services; etc.

Backwards Streaming Service (BSS). This type of service is used to send positions to a central server. Such service might be useful for tracking vehicles (rescue service; dangerous loads; etc.). The message is of the type unicast and is generally small in volume. This service is a variant of the Individual Messaging Service (IMS) described below with the difference that information is sent on a regular basis, i.e. streamed.

2.4.2 Messaging Service

A Messaging Service needs a small Initial Delay (ID), i.e. the initiation of the data transport should happen immediately. In general terms, data packets are few or in some cases only one. The type is unicast, and a message is in general not acknowledged in any way. Obviously, the ID is more interesting than the throughput.

Individual Messaging Service (IMS). This type of messaging is quite frequently used and probably better known as Short Message Service (SMS). When an accident occurs the information should fast and safely be transmitted to an aid server for help of some kind. The message is of the type unicast and generally consists of small data like the position of the accident. Considering safety-critical aspects, such a service needs high levels of availability and security. The amounts of data sent are expected to be rather small (e.g. positioning- and event-related data).

2.4.3 Interactive Service

An Interactive Service (IS) consists of a request by a client which is processed and answered by a server. Depending on the nature of the information to be fetched from the server, the answer can be very different in response and volume. Also the ID has to be considered which will be different depending on the type of wireless technology used.

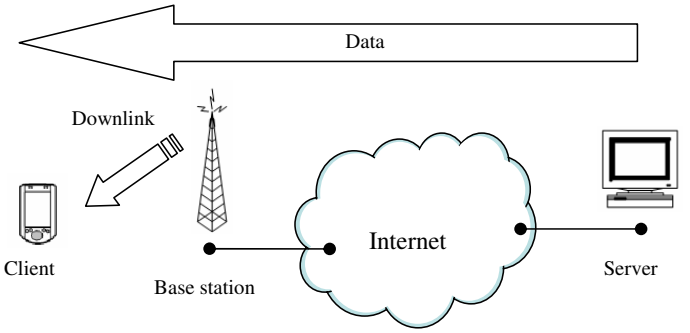
Personal Interactive Service (PIS). This type of service addresses the user's need for information. The user sends a request in form of a message, which is processed and answered by the server in form of another message. From the viewpoint of the user, the response should happen within a reasonable time frame, which involves the need for sufficient throughput and small delays (both ID and processing time) along the round trip, see Chapter 8.

Personal Download Service (PDS). The difference to PIS consists of the fact that the user's request initiates a streaming of a (larger) file, typically involving a considerable number of data packets. This service is a combination of two basic services, the interactive and the streaming service. This service offers a means for the user to download a bulk of data in advance, i.e. before the information is needed. There are probably a lot of situations when this could be advantageous, for instance when the user is about to leave a high-speed network and knows that a specific map, time table or drawing will be needed soon. This service poses high demands regarding throughput in order to minimize the download time.

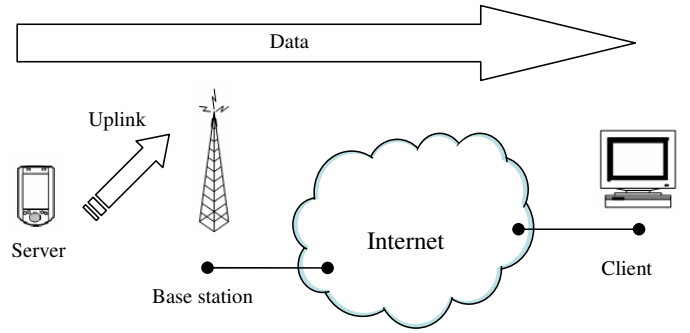
2.5 Wireless Technologies

Cellular phone technologies such as the UMTS and the GPRS are heavily regulated regarding each frequency band and for that reason they depend on the parameter settings by the phone provider, such as code or time slot assignments and scheduling, scheduling in each cell and related Base Station (BS) equipment. This is not the case if using the WLAN. Besides of AAA (Authentication, Authorization and Accounting), WLANs are generally not controlled as hard as mobile access networks, which leaves more control to the end-user. Still other types of problems are addressed for this type of technology, like interference and accessibility due to the amount of devices and available channels, see Chapter 5.

The influence of the GPRS and the UMTS networks in both downlink (a) and uplink (b) direction, see Fig. 2.4, on relevant statistics can be quite different. The throughput-related statistics have shown to be capable of visualizing critical network impacts on application performance. Using the concept of an equivalent bottleneck, it is also possible to derive bounds for the first packet due to the need of setting up a *temporary block flow* via causality arguments. Thus, we have been able to derive these kinds of delays from throughput



(a) Downlink scenario



(b) Uplink scenario

Figure 2.4: Mobile scenarios

statistics, see [3, 4, 28–30].

In general, both the UMTS and the GPRS networks are capable of introducing enormous amounts of jitter, which is seen from throughput deviations based on one-second averages. The impacts of these mobile channels on throughput histograms and autocorrelation functions are clearly visible. While the UMTS is almost transparent in terms of throughput as long as the application uses only a small share of the nominal capacity, the behavior of the GPRS with regards to throughput jitter has shown to be quite unforesee-

able, which is a result of the interaction of application, time slot allocation and scheduling inside the BS related equipment.

In the *downlink* direction, see Fig. 2.4 (a), there is a certain risk of data loss even if the nominal capacity of the mobile link is not reached yet. It was observed that the GPRS network in use had considerable problems in delivering packets in the downstream direction. Loss ratios of 10 to 20 % were not uncommon, which jeopardizes the performance of streaming applications.

In the *uplink* direction, see Fig. 2.4 (b), the burstiness also rises as long as the nominal capacity of the wireless link is not reached. This effect is reversed as soon as the nominal capacity is surpassed: In case the sending application transmits datagrams too fast, the send function itself acts as a shaper by holding packets until they can be sent, which can be considered as some kind of "force feed-back". Loss is avoided that way, but timing relationships within the stream can differ substantially from the ones imposed by the streaming application.

Summarizing, the UMTS seems to be suitable for streaming services as long as the service uses merely a part of the nominal link capacity. The GPRS, on the contrary, does not seem to be feasible for Streaming Services unless the desired throughput is low and exact timing relationships are not that important. The GPRS might even fail to support elastic services such as file transfers because of the large amounts of loss and jitter.

Based on the above analysis and knowledge gained, an application could gain more throughput and be more efficient if the datagrams are sent with some inter-packet delay instead of sending all datagrams as fast as possible. This IPD, i.e. the nominal throughput, should be well-adapted to the throughput supported by the weakest communication link. As the available capacity could be changed during an ongoing connection due to cross traffic, it might be important to adaptively change the inter-packet delay to the new conditions. In general, the application programmer considering the use of mobile channels should be conscious of these throughput variations. Moreover, these

results are aimed at optimizing the network selection based on requirements provided by users and applications.

Particular performance issues relate to the ISM-band (2.400–2.4835 GHz) which is used by several technologies by sharing the same communication band. Several standards are available, e.g. Institute of Electrical and Electronics Engineers (IEEE) 802.11b WLAN, IEEE 802.15.1 Bluetooth, IEEE 802.15.3a Wireless Universal Serial Bus (USB), and IEEE 802.15.4 ZigBee. An additional non-standard interfering technique needs to be considered, which is the microwave oven. As part of the interference mitigation techniques, the issue was investigated by Lansford *et al.* [31] who looked at the coexistence between 802.11b and Bluetooth.

A detailed discussion on the coexistence of WLAN and Wireless Personal Area Network (WPAN) wireless systems in the context of seamless communications is found in Chapter 5.

2.6 Criteria

The basic idea is to express the overall goal based on the selected criteria. A collection of performance criteria is listed in RFC 4148 [32], e.g. one-way delay, one-way packet loss, round-trip delay, etc.

In RFC 2678 [33], the measurement of one-way and two-way connectivity is defined. The parameter N is the number of packets being sent to determine the connectivity which is set to $N = 20$ packets. The parameter W is the "waiting time" before sending the packet again. The parameter is set to $W = 20\,\mathrm{s}$. This is carried out for a period of $dT = 60\,\mathrm{s}$. The required constraints are: $W \leq 255\,\mathrm{s}$ and $dT > W$. Based on this the measurement period of 60 s was adopted and used in our own measurements. In RFC 2679 [34], the motivation for measuring the one-way delay is; (1) the path between source-destination compared to destination-source could be different, a so-called asymmetric path; (2) if the path is the same the queuing behaviors

in both directions could still be different. In RFC 2680 [35], the motivation for measuring packet loss is given as follows: (1) monitor bad application performance up to a threshold value; (2) a large amount of packet loss makes it difficult to support real-time applications; (3) the transport-layer requires low packet loss due to the maintenance of high bandwidths. A typical example would be a PDS, for which each packet loss means a reduction in throughput due to the TCP. Also messaging services are susceptible to losses. These facts motivate the measurement of packet losses in general.

The ITU-Telecommunication Standardization Sector (ITU-T) and its Study Group 12 is responsible for "Performance and quality of service" and is the "Lead Study Group on Quality of Service and Performance" [36]. Several recommendations are presented, e.g. Y.1540 (previously I.380) [37] and Y.1501 [38] which was summarized by Seitz *et al.* [39, 40]. The recommendation Y.1540 specifies three types of criteria, namely speed, accuracy and dependability, and three functions, namely access, user information transfer, and disengagement, which are represented by a 3×3 matrix. Still, it is only the user information transfer function that is applicable for *primary parameters*. The process recommended, in the Y.1540 standard, is as follows: (1) define the interface which is called *measurement points*; (2) define a set of *primary parameters*; (3) define a set of *availability decision parameters*. Also, the recommendations, in the Y.1540 standard, for the IP packet transfer performance parameters are as follows: IP packet delay variations, IP Packet Error Ratio (IPER), IP Packet Loss Ratio (IPLR), Spurious IP Packet Rate (SIPR) and flow-related parameters. Another set of recommendations, in the Y.1540 standard, is regarding material relevant to IP performance measurement methods. The standard specifies five conditions that should be required to meet the basic requirements in IP performance measurements. They are: E2E measurements, measurement time, traffic characteristics, type of measurements, and summaries of the measured data.

One major limitation regarding the standard are other types of, e.g. outer

criteria such as cost and accessibility. None of these criteria are mentioned in the ITU-T recommendations which are important in the overall decision of ABC. Regarding cost and accessibility more information can be found in Chapter 3.

2.7 Direct and Indirect Measurements

There are two types of measurements, *direct* and *indirect*. Direct measurement is applied directly to the attribute e.g., length of an object. Indirect measurement is applied to an attribute by measuring two different types of direct measurements, or using mathematical methods which are described in Section 3.6. So, the selection of direct measurements and combinations of the measured data is important.

We are interested in the E2E characteristics of the networks. The throughput is the ultimate enabler of network communication. The throughput variation combined with delay and losses are important indicators. Our metric values could also have different units. E.g. throughput is measured in bits per seconds (bps), loss is measured in percent, delay is measured in seconds, power level is measured in dBm, and in currency. These basic entities could be refined further by using different statistical methods. More information can be found in Chapter 3.

2.8 Measurement Mapping

Now we have our numerical values together with subjective values from the end-user. These mixed values with their corresponding scales have to be fed into our decision model. The mapping tool selected needs to be flexible with a linguistic ability. This concludes the necessity of Fuzzy Sets (FS), see Fig. 2.5 [41]. *Fuzzy inputs* X are first collected and fed into the fuzzification box. The *fuzzification* box, the *defuzzification* box, and the *rule*

base box are connected to the *inference* box. A membership function is defined by the grade $\mu_{\widetilde{A}}(x_i)$ with a value between $[0,1], i = 1,2,\cdots,N$, together with $\widetilde{A} = \{\mu_{\widetilde{A}}(x_1), \mu_{\widetilde{A}}(x_2), \cdots, \mu_{\widetilde{A}}(x_N)\}$, with the multiple input $X = \{x_1, x_2, \cdots, x_N\}$. Each membership function is connected to a rule which is transformed into a certain linguistic value. A membership function could be of the type triangular, trapezoidal, Gaussian, generalized bell, sigmoidal, Z curve, S curve, or Pi curve [42]. The final step is the *fuzzy output U* which is now suitable for further use as an input for Multi-Criteria Decision Making.

A detailed discussion on the Fuzzy Sets in the context of seamless communications is found in Chapter 4.

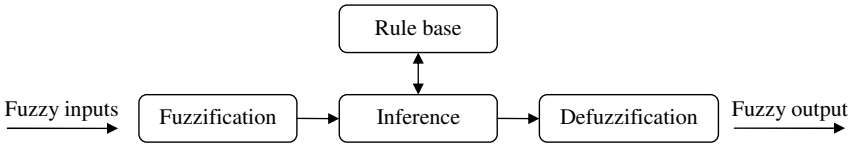


Figure 2.5: Fuzzy procedure

2.9 Decision Method

The seamless communication concept presented is complex due to the many aspects that need to be taken into account. The decision method selected needs to be flexible, measuring intangibles due to the information from the end-user, and it needs to have the ability of measuring the consistency of our decisions.

A known branch of decision making is the Multi-Criteria Decision Making (MCDM). The decision making branch could further be divided into the Multi-Attributive Decision Making (MADM) and the Multi-Objective Decision Making (MODM). In this decision branch, Pohekar *et al.* [43] have made an overview of available methods: the Weighted Sum Method (WSM),

the Weighted Product Method (WPM), the AHP, the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), the Elimination and Choice Translating Reality (ELECTRE), the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), the Compromise Programming (CP), and the Multi-Attribute Utility Theory (MAUT).

The WSM and the WPM commonly solve single dimensional problems. They do not provide any tool for testing, e.g. the consistency of judgments which is one of the main components required in the seamless communication concept. The PROMETHEE and the ELECTRE have the ability to rank the index to some extension. The ELECTRE, e.g. only eliminates less favorable alternatives. The favorable alternatives have to be further processed by another method to get the final results. The TOPSIS uses the concept of shortest distance according to Euclidean distance. Still, the method is concentrated on mathematically solving a problem. Also, the CP aims at solving the shortest distance. The MAUT considers preference of attributes with different scales factors. Also in this case they do not provide any tool for, e.g. consistency of judgments or the measuring of intangibles.

According to Pohekar *et al.* [43], the findings of the AHP method is the most popular compared to the other named methods, closely followed by the PROMETHEE and the ELECTRE methods.

A detailed discussion on the proposed Decision Support System (DSS) in the context of seamless communications is found in Chapter 6.

2.10 Roaming Strategy

The decision of finding a switch between two or several wireless/non-wireless technologies and to maintain the goal of being ABC tends to be complex. A strategy must be defined. One part of the strategy is to *maintain the service*, (i.e. switch between network technologies involving different IP addresses without breaking the session), and *monitor each network and link*

simultaneously. The other part is the presentation of the information in an understandable way. So, instead of always using a very fine scale (more than a seven-point scale) the information should be understandable by every end-user. The questions are: *which scale should be used and how should this be presented?*

A detailed discussion on the proposed roaming strategy in the context of seamless communications is found in Chapter 8.

2.11 Switch Control Unit

The handling of several connections simultaneously is difficult or in some cases impossible due to the implementation of the IP stack. The original design of Internet was aimed at a stationary environment. For that reason mobility issues were not considered [44]. One way of solving the mobility issue is to divided the IP address into an *identity* and a *location* part. The location part hides the connection from the identity part by encapsulating the IP packet between each endpoint, RFC 1853 [45]. Another solution could be using the MIP, which however does not have the possibility to handle several connections simultaneously, see RFC 3344 [46] and RFC 4433 [47].

Still, we might need several (more than two) connections in order to enable a fast switch between them. Also, we need some hard- and/or software to handle several connections simultaneously. If a solution was found, the E2E connectivity can be sustained well-adapted to the generic service in question.

A detailed discussion on the proposed Switch Control Unit in the context of seamless communications is found in Chapter 9.

Chapter 3

Criteria and Measurement Techniques

Knowledge is not a loose-leaf notebook of facts. Above all, it is a responsibility for the integrity of what we are, primarily of what we are as ethical creatures.

Jacob Bronowski (1908 - 1974)

In this chapter an introduction of standards and recommendations regarding performance parameters is given together with the state of the art. Also, a detailed description of each measurement point is given. Finally, a description of the statistical method used in the thesis is provided.

3.1 Introduction

Now, the Generic Services are defined and our wireless technologies are depicted. The next step is to find the criteria for our measurements. The main goal is to be ABC for a given type of service. The goal is also to give the end-user the best possible QoS even if this is hard to archive [48]. This puts the need for criteria that are related to the service used and that target ABC in an objective user-independent manner. In this chapter, the basis of our discussion is Streaming Service.

The criteria must be related to the service used in a way that they contribute to the overall decision of ABC, not necessarily the exact requirements which could vary from person to person.

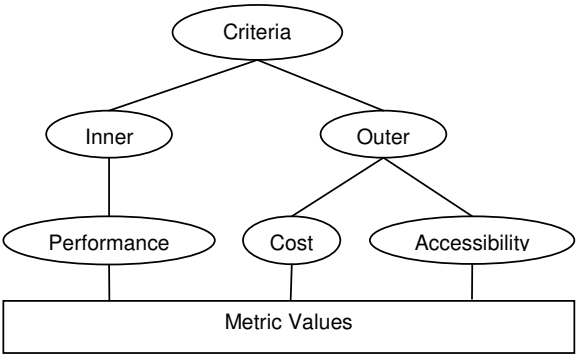


Figure 3.1: Taxonomy of criteria

In our seamless communication concept three groups of criteria are defined next to the metric values, see Fig. 3.1. Those are: *performance*, *cost* and *accessibility*. Above those groups two new groups are defined which are the *inner* (aimed at the characteristic of the data flow inside the network link) and *outer* (aimed at other types of criteria) groups. The inner group is the connection between the main criteria group and the performances group. The

outer group is connected with both the cost and the accessibility groups, and together they form the main group of criteria. One type of attributes could be found in the information flow of the connection itself, like *packet loss* and *packet delay* in a one-way or two-way connectivity. Another could be the range of the technology or the cost for using a particular service. It could also be a performance issue of the hardware. Together, they have something to contribute and are therefore able to provide a decision model with the information to perform the service selection as well as possible.

Some parameters are more important than others. To capture the information of the criteria in a better way, two additional sub-groups are defined; (1) dynamic and (2) static, see Fig. 3.2. A static criterion addresses static values such as: *Initial Delay*, *Link Capacity* and *Directional Loss*. These values do not change over a long period of time. Typically, they are determined based on a-priori or initial measurements, experience and evaluations. Dynamic criteria compare the dynamic changes within the system such as: *throughput*, *losses* and *Round Trip Time* variations; these values do change over a short period of time, e.g. during the use of a service.

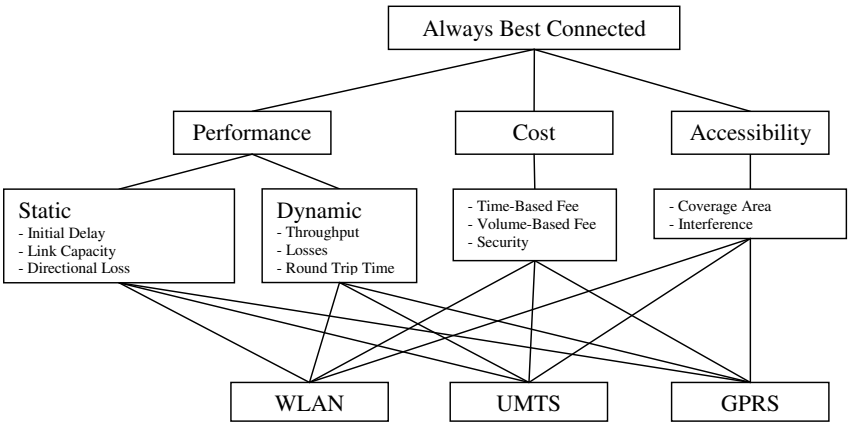


Figure 3.2: Always Best Connected hierarchy for Seamless Communications

3.2 State of the Art

When it comes to the estimation of the throughput of a network link, three related metrics are suggested by Dovrolis *et al.* [49] which are: *capacity*, *available bandwidth*, and *bulk transfer capacity*. Dovrolis focuses on bandwidth estimation with a TCP scenario. The first metric *capacity* is related to *throughput* in the thesis. The second metric is the *available bandwidth* which is related to Link Capacity (LC). Dovrolis relates these two metrics to "both individual links and end-to-end paths". The last metric is the *bulk transfer capacity* which could not be related to any metrics in the thesis.

There are also several Bandwidth Estimation Techniques (BET) listed by Dovrolis *et al.* [49, 50], which are: Variable Packet Size (VPS), Packet Pair Train Dispersion (PPTD), Self-Loading Periodic Streams (SLoPS) and Trains of Packet Pairs (TOPP). This was also presented by Lidong *et al.* [51]. Every BET tries to measure the bandwidth available with active probing. In our measurements active probing is also used but for one reason only, to be able to sense if a connection is up or down. This means that the packet overhead is a minimum because these packets are sent with a few seconds in-between.

Reinemo *et al.* [52] refer to the three significant important properties *bandwidth*, *latency*, and *packet loss*. These properties are more related to single data streams than to aggregates of traffic.

Interference was investigated amongst others by de Vendictis *et al.* [53]. The fairness index, defined by Jain *et al.* [54], decreases and the capture effect increases as the number of monitor stations increases.

In some cases the momentarily "transmission greed" is reduced near to zero, and the SNR is considerable lower than the SNR of the competitors. Another issue is the number of available channels, see Fig. 3.3. In the case of the IEEE Std 802.11 [55] and IEEE Std 802.11b [56], there are 13 available channels inside the 2.4 GHz ISM-band, but only three non-overlapping ones to choose between. The Federal Communications Commission (FCC) allows channels 1–11 (1, 6 and 11) within the U.S. (FCC part 15.247 [57]), channels 1–13 (1,

7 and 13) within Europa (European Telecommunications Standards Institute (ETSI) 300 328 [58]), and only channel 14 in Japan. Another interesting observation is the different maximum output power allowed. In the U.S., the maximum output power is 1000 mW and in Europe 100 mW. This means that less interference could be expected using equipment in Europe.

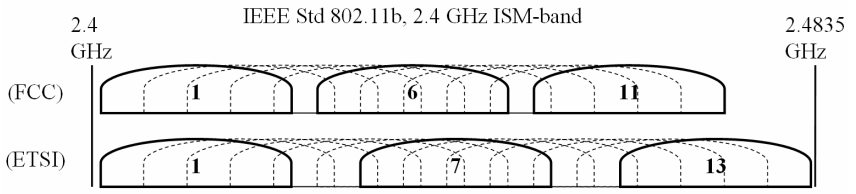


Figure 3.3: Wireless Local Area Network 802.11b

Other research performed by Bianchi [59] implemented a performance analysis of the IEEE 802.11 Distributed Coordination Function (DCF). The DCF consists of two types of mechanisms: basic access using a two-way handshake and request-to-send/clear-to-send using a four way handshake. A general formula of normalized system throughput was stated regardless of the mechanism used.

One interesting observation is that when using two simultaneous connections the total throughput performance increases (two nodes: ~ 5.6 Mbps) even if the corresponding device senses a decreased throughput. As expected when using several nodes, the overall throughput decreases (20 nodes: ~ 5.0 Mbps).

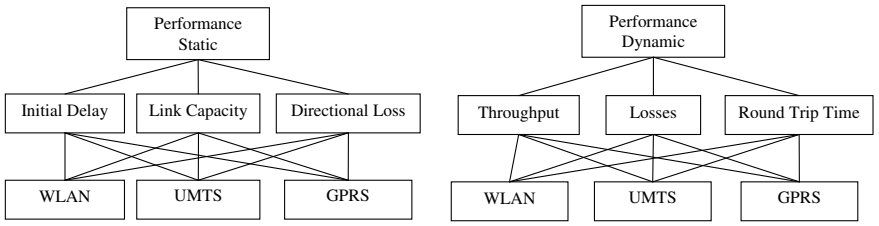
It is also important to account for different interference characteristics, as e.g. the different bit rate technologies. Research on this was done by Heusse *et al.* [60]. The conclusion of his work was that a lower bit rate has a very high performance impact on other higher bit rate technologies. Still, this type of problem is possible to overcome, see Chapter 5.

When it comes to simulating true network characteristics this is difficult.

According to Miura *et al.* [61] using a M/H2/1/K queuing model, it is possible to simulate the behavior of i-mode characteristics very closely. The accuracy of these simulations versus actual values is around 90 %.

3.3 Performance

The sub-group *performance* is dedicated to performance issues regarding how packets are handled as a data stream, e.g. delay, capacity, losses etc., see Fig. 3.4. In the *static* (a) sub-group a proactive approach is given. The criteria are evaluated in an a-priory manner based on previous measurements by Fiedler *et al.* [4, 29, 30] and Chevul [62]. In the *dynamic* (b) sub-group a reactive approach is given. The measurement is an ongoing process which gives indications of the behavior of a network link in a real time manner.



(a) Static (b) Dynamic

Figure 3.4: The Performance group

In the following chapter a detailed description and motivation is given regarding our selected criteria.

3.3.1 Initial Delay

The setup of a connection takes time, in some systems more than in others. According to Fiedler *et al.* [30], the uplink for GPRS has the lowest Initial Delay ($\tau_0^T \sim 0.2\,\mathrm{s}{-}1.5\,\mathrm{s}$) followed by the uplink UMTS ($\tau_0^T \sim 3.0\,\mathrm{s}{-}4.3\,\mathrm{s}$),

the downlink UMTS ($\tau_0^T \sim 1.0\,\text{s}-6.9\,\text{s}$), and finally the downlink GPRS ($\tau_0^T \sim 0.8\,\text{s}-2.1\,\text{s}$) for mobile wireless cellular networks. This gives us a very important indication of how the behavior differs depending on the technology used. More information can be found in Chapter 8.3.2.

3.3.2 Link Capacity

Throughput, which is heavily dependent on the link capacity is the most important enabler for networked applications. While in general throughput is defined on the network or transport level e.g. for TCP, the *application-perceived throughput* reflects the perspective of the application, i.e. it captures the behavior of all communication stacks in-between the endpoints. Streaming multimedia applications require some amount of throughput on a regular basis. For an elastic application such as file transfer, the achieved throughput determines the download time. For situation-dependent services, e.g. for ITS, short response times are of utmost importance, which are enabled by high throughput values as well.

The WLAN is the natural choice for obtaining the highest throughput compared to the UMTS and the GPRS. Still, if several WLAN units are available this could be a problem since the number of available channels is limited [53].

In case of the UMTS, the Spreading Factor (SF) decides the throughput at the end-user. A low value of the SF means high throughput for few users and a high value of the SF means low throughput for many users, see Tab 3.1. For the uplink scenario the SF ranges from 4 to 256, and for the downlink scenario the SF ranges between 4 and 512.

The GPRS throughput depends on four components: the chosen Coding Scheme (CS), the number of assigned time slots, Global System for Mobile Communications (GSM) networks (900 / 1800 MHz or 1900 MHz), and whether uplink or downlink is used. The GPRS follows another approach than the UMTS as it allocates different numbers of time slots. First, there exist four

Table 3.1: UMTS, bit rates in different cells

Cells	Data Rate
Pico cell	2.048 Mbps
Medium-sized cell	384 kbps
Large macro cells	144 kbps and 64 kbps
Very large cells	14.4 kbps
Speech	4.75 kbps - 12.2 kbps
Satellite	9.6 kbps

types of CS $\in \{1, 2, 3, 4\}$, today only the first two are usually implemented due to the implementation cost, see Fig. 3.2. The error correction for those CS are {high, medium, low, none}. Second, there are maximum eight slots available per frame. These factors together determine the perceived throughput. The number of slots used may vary. For the downlink, the usual scenario is 4 slots depending on the capacity of the base station which could be reduced to only one slot. If the base station has a capacity problem, voice has priority over data.

Besides the selection of CS and time slots, GPRS standards have stated 29 handset classes. Two of the handset classes are typically implemented, class 4 and class 10. A class 4 handset can only use a maximum of 4 slots, 3 slots for the downlink (3D) and 1 slot for the uplink (1U). A class 10 could only use maximum 5 slots, with the following combinations: 4D + 1U or 3D + 2U, see Tab. 3.3, Classes 13 to 18 have more than 5 active slots. Classes 19 to 29 have up to 8 active slots in half-duplex mode.

3.3.3 Directional Loss

The packet loss for the UMTS ($\sim 0\,\%$) and the GPRS ($\sim 0.0-0.6\,\%$) uplink is very low according to Fiedler *et al.* [30], and the packet loss high for the UMTS

Table 3.2: GPRS, bit rates, a combination of coding schemes and slots

Coding Scheme #Slots	CS1 [kbps]	CS2 [kbps]	CS3 [kbps]	CS4 [kbps]
1	9.05	13.40	15.60	21.40
2	18.10	26.80	31.20	42.80
3	27.15	40.20	46.80	64.20
4	36.20	53.60	62.40	85.60
5	45.25	67.00	78.00	107.00
6	54.30	80.40	93.60	128.40
7	63.35	93.80	109.20	149.80
8	72.40	107.2	124.80	171.20

($\sim 0.0 - 8.7\,\%$) and the GPRS ($\sim 0.0 - 19.9\,\%$) downlink. Considerably high loss such as indicated in the last case happens if there is a mismatch between capacity demand and availability. As the allocation strategy of the GPRS is hidden to the user (with exception of the feedback in the uplink case), the GPRS has the potential to introduce significant loss especially in the downlink direction. Other potential problems of the high packet losses were identified by Sarker *et al.* [63] to be increasing on call intensity, maximum number of admitted calls and activity factor. Another factor is if both directions are used simultaneously which also increases the delay. In the WLAN case both the uplink and the downlink scenarios show hardly any packet loss at all.

3.3.4 Throughput

The monitored throughput during small time intervals of received packets at the application layer should stay almost constant, given a constant sending rate. This indicates a normal behavior in the link. If not, the link could experience congestions and for that reason indicate a much higher variation

Table 3.3: GPRS handset classes

Class	Downlink	Uplink	Max. slots
1	1	1	2
2	2	1	3
3	2	2	3
4	3	1	4
5	2	2	4
6	3	2	4
7	3	3	5
8	4	1	5
9	3	2	5
10	4	2	5
11	4	3	5
12	4	4	5

of the measured values than normal.

3.3.5 Losses

The observed message or packet losses are also very important. This could give an indication to search for another link which has lower packet losses. To this end, control packets are sent in each connection to control if everything is connected and working as expected. This is done in the same manner as the ”ping” command, which generates echo packets at the network level and evaluates loss and round-trip delays. However, the *Netstat* messages used in the context of this work are generated and evaluated at the application level.

3.3.6 Round Trip Time

Monitoring the Round Trip Time (RTT) is the way of measuring the delay in both directions summarized. Some types of GSs require a specific time frame and for that reason requires information about the RTT. In some cases the individual direction could be interesting to measure. One reason is that our solution of seamless communication does not require the same technology in both directions. However, the main and non-trivial issue for such measurements is clock synchronization. More information can be found in Chapter 8.3.2.

3.4 Cost

The sub-group *cost* is dedicated to outer types of constraints, see Fig. 3.5. Internet subscription costs money. Depending on the provider the subscription cost could vary.

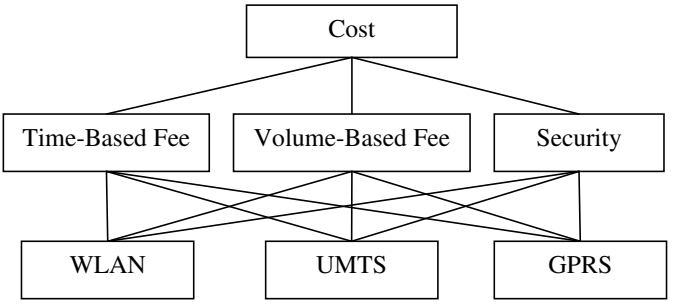


Figure 3.5: The Cost group

3.4.1 Time-Based Fee

In new and expensive infrastructures with sparse capacities providers have price tags on the amount of data being sent. This is the case for most of the current technologies such as the UMTS and the GPRS. In the case of free APs for the WLAN this is not an issue. The criterion for cost that is identified as important and of consideration is the Time-Based Fee (TBF) such as a monthly subscription.

3.4.2 Volume-Based Fee

A Volume-Based Fee is typical in mobile scenarios, especially when roaming. The cost is low as long as the user stays within the network of "its" provider. The criterion for cost that is identified as important and of consideration is the Volume-Based Fee (VBF), which is typical for mobile connectivity. An additional cost that has to be counted for is the security in form of overhead.

3.4.3 Security Overhead

Adding security comes at the cost of performance, cf. Johnson [64]. The security issues have many faces. One is the throughput overhead caused by security measures, actually not the general case. Another is the execution performance. Security calculations can have a heavy impact on hand-held platforms with low processing capacity. In general, the negative effect of adding security features on performance grows as capacity decreases, which speaks against the GPRS and in favor of the WLAN. This motivates the inclusion of security in the cost group.

3.5 Accessibility

The *accessibility* of a technology is also important, see Fig. 3.6. It depends among others on the *Coverage Area* of a particular network and its neighbors

using the same frequency band. In the wireless context, the *interference* issue is an increasing factor nowadays; other technologies are using the same 2.4 GHz ISM-band and for that reason the probability for obtaining a durable connection is reduced.

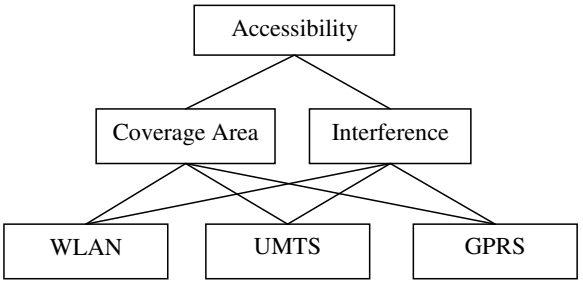


Figure 3.6: The Accessibility group

3.5.1 Coverage Area

The frequency band used, its width and the power level constitute the coverage area. The UMTS and the GPRS cover larger areas compared to the WLAN which uses lower power as it has been designed for local scenarios.

3.5.2 Interference

When using a WLAN channel, interference issues must be considered. Many other technologies use the same frequency band. That is why the particular use of that band needs to be classified and the characteristic of each present wireless technology needs to be found. For instance the energy in each ZigBee channel is measured inside the 2.4 GHz ISM-band. These channels also cover all WLAN channels and by measuring the energy in these ZigBee channels it is possible to estimate the energy and classify each used WLAN channel, which will be detailed in Chapter 5.

3.6 Statistics

Of particular interest is the focus on the traffic flow properties, and the *discrete-time fluid flow traffic model* [30]. In this subsection the statistical parameters that are used in the context of the thesis are listed, see Section 3.6.4 and Chevul *et al.* [62].

3.6.1 Throughput Time Series

The contributions of packets observed during short averaging intervals ΔT are collected. The first packet of the trace ($p = 0$) is used as a synchronization packet both at sender and receiver, which is observed at T_0, respectively. This is motivated as the receiving application begins to act upon reception of this packet. Then, the corresponding throughput time series $\{R_{\mathrm{A},s}\}_{s=1}^{n}$ is calculated as

$$R_{\mathrm{A},s} = \frac{\sum_{\forall p: T_p \in]T_0+(s-1)\Delta T, T_0+s\Delta T]} L_p}{\Delta T} \tag{3.1}$$

containing $n = \Delta W/\Delta T$ values. As point of reference, the application level (index $_{\mathrm{A}}$) was used. On this level, L_p reflects the payload sent by a server application (index $^{\mathrm{in}}$) or received by a receiver application (index $^{\mathrm{out}}$). The time stamp is taken just before a packet is sent or just upon reception.

The second step consists of calculating selected summary statistics such as average (3.2) and standard deviation (3.3), which is detailed in the following subsections.

3.6.2 Average Throughput

Definition:

$$\bar{R}_{\mathrm{A}} = \frac{1}{n}\sum_{s=1}^{n} R_{\mathrm{A},s} \tag{3.2}$$

A change of this parameter between server ($\bar{R}_{\mathrm{A}}^{\mathrm{in}}$) and client ($\bar{R}_{\mathrm{A}}^{\mathrm{out}}$) reflects missing traffic at the end of the observation interval:

$$L = \max\left\{(\bar{R}_{\mathrm{A}}^{\mathrm{in}} - \bar{R}_{\mathrm{A}}^{\mathrm{out}})\,\Delta W, 0\right\}\ .$$

That share of traffic might be overdue (i.e. appear during the next observation intervals) or might have been lost. The use of the max-operator is motivated by the fact that there might be overdue traffic from an earlier interval reaching the receiver in the current observation interval, yielding $\bar{R}_{\mathrm{A}}^{\mathrm{out}} > \bar{R}_{\mathrm{A}}^{\mathrm{in}}$. The corresponding loss ratio is obtained as:

$$\ell = \frac{L}{\bar{R}_{\mathrm{A}}^{\mathrm{in}} \cdot \Delta W}\ .$$

3.6.3 Standard Deviation

Definition:

$$\sigma_{R_{\mathrm{A}}} = \sqrt{\frac{1}{n-1}\sum_{s=1}^{n}\left(R_{\mathrm{A},s} - \bar{R}_{\mathrm{A}}\right)^2} \tag{3.3}$$

A rising standard deviation ($\sigma_{R_{\mathrm{A}}}^{\mathrm{out}} > \sigma_{R_{\mathrm{A}}}^{\mathrm{in}}$) reflects a growing burstiness of the traffic between sender and receiver, while a sinking standard deviation ($\sigma_{R_{\mathrm{A}}}^{\mathrm{out}} < \sigma_{R_{\mathrm{A}}}^{\mathrm{in}}$) means a reduction of burstiness. The latter case is typical for a shaper [65].

3.6.4 Monitoring Algorithm

Many statistic algorithms used for real-time monitoring may have performance issues. One way of minimizing possible constraints is to implement efficient algorithms. One example is to use a ring buffer in combination with an update of first and second moment in order to perform fast calculation of *averages* or *standard deviations*. The parameters and their initiated values are presented in Tab. 3.4. The constant parameter `n` is the buffer size and the time period is measured in seconds (line 2). The vector `Rs`, together with the time samples,

Table 3.4: Ring buffer

```
1  // size buffer
   const int n = 60;
3
   // containing time series
5  double[ ] Rs = new double[n];

7  // first moment
   double m1n;
9
   // second moment
11 double m2n;

13 // index that was used before
   int i_before = 0;
```

are saved (line 5). The first moment parameter `m1n` and second moment parameter `m2n` are saved in these parameters (line 8 and 11). Finally the index parameter `i_before` which takes care of the position of the previous sample (line 14).

Next comes the registration of the data received which is done by using the register function, see Tab. 3.5. First, the location of the index must be calculated. This calculation is based on the initial time of the measurement and time duration ($\mathtt{n} = \Delta\mathtt{w}/\Delta\mathtt{T}$), see lines 3 and 6. The new value has to be calculated based on size `rcvdSize`, see line 9. If the calculation is within the same time frame (line 12), the contribution may be added, see lines 13–16. If not (line 20), the old values should be replaced with the new value, see lines 21–26. In any case, `m1m` and `m2m` need to be adjusted accordingly

Now, both the `get_average`(), see lines 1–2, and `get_stdev`(), see lines 4–5, function with statistical methods could be used, see Tab. 3.6.

Table 3.5: Register function

```
1   int i; // index
    double newval; // new value
3   long t = DateTime.Now.Ticks - socket.quality.T_start;

5   // calculate current index
    i = ((int)(t / (Delta_T * SEC_MULTIPLIER ))) % n;
7
    // contribution
9   newval = socket.quality.rcvdSize / Delta_T;

11  // if the index has not moved, just add the contribution
    if (i == i_before){ // has to be updated, remove
13    m2n -= Rs[i] * Rs[i]; // the previous indexed value
      Rs[i] += newval; // add new value
15    m1n += newval; // add new value
      m2n += Rs[i] * Rs[i];} // add new value
17
    // if the index has moved, throw out the old values
19  // and initialize with the (one and only) new value
    else{
21    m2n -= Rs[i] * Rs[i]; // has to be updated, remove
      m1n -= Rs[i]; // the previous indexed value
23    Rs[i] = newval; // init with new value
      m1n += newval; // add new value
25    m2n += newval * newval // add new value
      i_before = i;} // save current index
```

Table 3.6: Statistical functions

```
1  private double get_average(){
     return (m1n / n);}
3
   private double get_stdev(){
5    return (Math.Sqrt((m2n - m1n * m1n / n) / (n - 1)));}
```

Chapter 4

Linguistic Translation of Metric Values

The fact that all Mathematics is Symbolic Logic is one of the greatest discoveries of our age; and when this fact has been established, the remainder of the principles of mathematics consists in the analysis of Symbolic Logic itself.

Bertrand Russell (1872 - 1970)

In this chapter an introduction to the Fuzzy Set Theory (FST) is given. After that, the state of the art is presented. Next comes an example of the fuzziness level comparing a "crisp value" with a "fuzzy value". The steps needed to use the FST itself are also given. Finally, a case study is provided to make it clearer how to use the FST in the transformation of metric values.

4.1 Introduction

Our metric values are now measured and saved. Still, those metric values are not directly usable. They must be refined before they can be used for making a decision. More information could be extracted if statistical methods are applied on the raw measured data. Later on in the thesis a decision model is used which uses a linguistic scale with discrete levels. So, to be able to map the measured metric values to such a scale, a mapping tool is required.

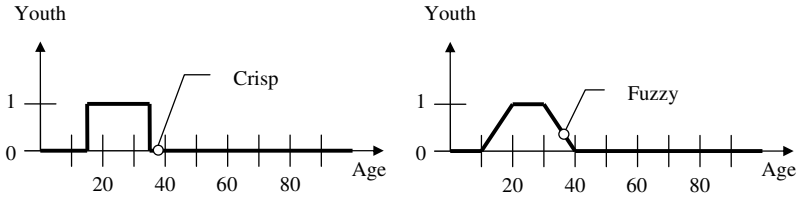
4.2 Fuzzy Sets

In 1965, Zadeh presented the first publication on the FST. Now it was possible to handle uncertain or vague situations in a different way. Previously, probability theory and statistics were the only tools available for this type of problems which are known as the Kolmogoroff-type probability set-theory and Koopman's probability for the truth of statements defined as *stochastic uncertainty*. With the new FST the statements themselves could be called *fuzzy sets* [41].

The knowledge of a dynamic system generally consists of a differential equation as $\dot{x} = f(x, u)$ with $x(t_0) = x_0$. In the case of fuzzy control, when the dynamics of a system is known, it could be described by the FST, see Fig. 2.5. In the next section a few examples are given regarding the new paradigm. The paradigm change toward fuzzy logic is also described by Bih [66].

There are different levels of fuzziness. The two main differences are between a non-fuzzy or "crisp value" and a "fuzzy value". One example could be age and how to translate this to a linguistic scale. Let us consider the linguistic value "young". In Fig. 4.1 (a) the definition of being "young" is crisp between age 15 and age 35. In Fig. 4.1 (b) the definition of being "young" is fuzzy between age 10 to 20 and age 30 to 40, [67]. Between age 20 and 30 it is crisp. So, if someone is at age 38, in this example, in the crisp version you are not young and in the fuzzy version you are young to a degree of 0.4.

Through the FST the uncertainty could be given a degree of a level between 0 and 1 instead of only the crisp values of 0 or 1. So, the angle of the slope matters and determines the area of fuzziness.



(a) Crisp value (b) Fuzzy value

Figure 4.1: Fuzziness level

4.3 State of the Art

Wong *et al.* [68] have used a fuzzy decision-based algorithm and put it into a routing protocol for mobile ad hoc networks. The motivation of using a decision-based algorithm in this case is that at the network layer all packets are treated equally, regardless of scenario which is important in mobile ad hoc networks. Three types of network protocols were mentioned which treat the packets with no priority: the Dynamic Source Routing (DSR) protocol, the Ad Hoc OnDemand Distance Vector (AODV) protocol, and the Destination Sequenced Distance Vector (DSDV) protocol. The new protocol, the DSR, supports service differentiation and QoS routing. The implementation basically depends on four steps: input-output system, rule-base and fuzzy table, membership functions, and defuzzification, see Fig. 2.5. The first step depends on three inputs: end-to-end delay, node loss, and node speed. The output is called *fitness*. The fitness indicates the condition of the route. The fitness scale is later mapped toward a scale based on traffic characteristics. The second step is a set of rules which defines the behavior between the in-

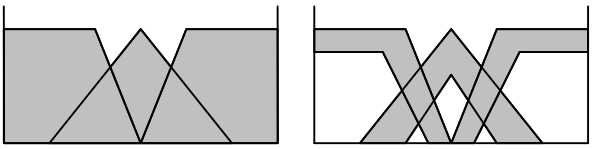
put metrics. These rules are based on ”common sense”. Step number three handles the mapping of the membership functions. The fuzzy logic translates the linguistic terms into a graph representation. Finally, the defuzzification translates the fuzzy output into a real number output.

The fuzzy logic is also being used in intuitive expert systems for weaning a patient with respiratory insufficiency from mechanical ventilation in a medical procedure as presented by Adlassnig *et al.* [69]. The information obtained from the Patient Data Management System (PDMS) has a time interval of one minute and therefore the received data and the corresponding data rate are very small. This information is considered enough to reach the main goal of delivering improved quality of patient care as efficiently as possible. In order to avoid cardiac failure and respiratory muscle fatigue the arterial O_2 and CO_2 are measured. The CO_2 consists of three member functions with the linguistic levels low, normal, and high. The results indicated a more rapid response if the decision making was used compared to when the clinical staff made the decision. It may be observed, however, that the staff, according to the study, was ”reluctant to follow a machine that does not exactly show the decision process”.

Chen *et al.* [70] proposed an information fusion method based on interval-valued fuzzy numbers for handling multi-criteria fuzzy decision making problems. The FN-IOWA [71] operator is used to determine the weights of linguistic options which is later aggregated into different linguistic constraints. The conclusion is that the proposed information fusion method is able to handle multi-criteria fuzzy decision making problems in a more intelligent way.

Cheng [72] has used the fuzzy Delphi method which uses a normalized fuzzy decision matrix $\tilde{X} = [\tilde{x}_{ij}]_{m \times n}$. Every criterion is tagged with a linguistic value based on a seven-point scale. The fuzzy attribute weights are later multiplied by the fuzzy decision matrix and the result is a vector with its ranked values. Finally, an algorithm has been proposed to obtain the best solution.

A fuzzy decision making handoff situation for wireless communication sys-



(a) Fuzzy sets type-1 (b) Fuzzy sets type-2

Figure 4.2: Fuzzy groups

tems was proposed by Lee *et al.* [73]. In this situation a grey prediction method is used. The word "grey" in this case means that not all information is available. Three objectives have to be met: link quality maintenance, interference reduction, and the keeping of the number of handoffs low. Two groups of member function were used, Type-1 and Type-2, see Fig. 4.2. In contrast to Type-1 functions, Type-2 functions also exhibit lower thresholds regarding the size of the fuzzy sets. Finally, a decision on whether to carry out the handover or not was taken based on a threshold.

Cheng *et al.* [74] presented a fuzzy traffic controller for ATM networks which involves both call admission control and congestion control. They then used a Generic Algorithm (GA) to further optimize the result. In general two types of member function were used, the *triangular* function (4.1) and the *trapezoidal* function (4.2). These functions are highly motivated and suitable for real-time operations according to Zimmermann [27]. The simulation results show an improvement compared to the original algorithm. One conclusion mentioned is that there is no general technique for mapping existing knowledge regarding traffic control.

$$f(x; x_0, a_0, a_1) = \begin{cases} \frac{x-x_0}{a_0} + 1 & \text{for } x_0 - a_0 < x \leq x_0 \\ \frac{x_0-x}{a_1} + 1 & \text{for } x_0 < x \leq x_0 + a_1 \\ 0 & \text{otherwise} \end{cases} \tag{4.1}$$

$$g(x; x_0, x_1, a_0, a_1) = \begin{cases} \frac{x-x_0}{a_0} + 1 & \text{for } x_0 - a_0 < x \leq x_0 \\ 1 & \text{for } x_0 < x \leq x_1 \\ \frac{x_1-x}{a_1} + 1 & \text{for } x_1 < x \leq x_1 + a_1 \\ 0 & \text{otherwise} \end{cases} \tag{4.2}$$

Lee *et al.* [75] proposed a "[...] criteria trade-off analysis approach based on relationships analysis for fuzzy decision making [...]". Current analysis approaches like the Fuzzy Multiple Objective Programming (FMOP) and Decision Making based on Relationships between Goals (DMRG) can show a contradiction between some of the criteria. Lee *et al.* propose a trade-off analysis between criteria called Criteria Trade-off Analysis (CTA). Three conclusions were stated: (1) it was easy to identify a unique relationship for a criterion, (2) the selected operators better reflect the situations, (3) a better structure helps alleviate the associations between the operators.

Kroll *et al.* [76] use a non-linear controller design methodology in a fuzzy network. This was demonstrated for a hydraulic drive situation. During this research four issues were stated: (1) detailed robustness studies are further required, (2) the concept is applicable for other processes, (3) more theoretical examinations on stability and convergence would provide further insight, (4) the fuzzy networks are useful in a prediction model.

4.4 Basic Steps for Fuzzy Logic Control

The FLC is a complex process. In the thesis a short description is presented in seven steps, see Fig. 4.3:

1. The traffic situation is first perceived and measured $x_i^{\text{input}}; i = 1, \ldots, N$ of the measured value is saved for further analysis;

2. Next comes the *fuzzification* which refers to the type of membership function. Based on the membership function the crisp values are trans-

lated into a fuzzy stage. The function $\mu_{\widetilde{A}}(X_i)$ is called the membership function of X in $\widetilde{A}$. A linear approach is preferred as it tends to be more computationally efficient than non-linear approaches;

3. Each membership function is later connected with a *rule*. It could be an arbitrary number of rules and the structure of the rule base could be non-linear. Each rule can also be individually weighted between zero and one;

4. An *aggregation* of individual rules and operators are put together with the IF-THEN logic;

5. The $\wedge$ operator is used on the rule, $\alpha_r = min_{i=1,\cdots,n}\{\mu_i^{ji}(x_i^{input})\}$;

6. Several methods of defuzzification exist, in this case the singleton sets are used, see Equation (4.3);

7. Finally, the level of the crisp *output*, u_1, is determined.

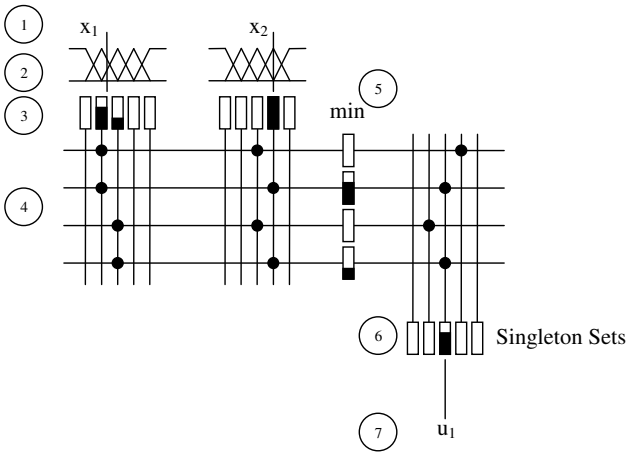


Figure 4.3: Programmable Fuzzy Logic Array data flow

$$u^{\text{Sugeno}} = \sum_r \alpha_r \cdot f_r(x_1, x_2) / \sum_r \alpha_r \tag{4.3}$$

4.5 Case Study: Netstat Losses

In this case the losses of *Netstat* messages are depicted, cf. Section 3.3.5. Netstat messages provide a functionality similar to ping packets, but at the application layer. One advantage is that the impact of the entire Operating System (OS) and in particular of the whole network stack is involved. In Fig. 4.4 (top) three membership functions of the type triangular and trapezoidal are chosen. The y-axis is the membership degree and the x-axis is the number of losses of subsequent messages. In Fig. 4.4 (bottom) the x-axis is the output of the linguistic level. The following membership functions are used: (1) Trapezoidal with the parameters $\mu_{low} = [-2, -1, 1, 2]$; (2) Triangular with the parameters $\mu_{middle} = [1, 2, 6]$; (3) Trapezoidal with the parameters $\mu_{high} = [2, 6, 8, 9]$. The rule is then defined as $\alpha_r = min_{i=1,\cdots,n}\{\mu_i^{ji}(x_i^{input})\}$:

- rule 1: if Netstat = "low" then Level = "low"
- rule 2: if Netstat = "middle" then Level = "average"
- rule 3: if Netstat = "high" then Level = "high"

Netstat "low" means 0 to 1 losses in any case, "middle" means 2 to 5 losses, and "high" means 6 or more losses. There are transition areas between these sets. This gives us a translation of a metric value to a linguistic level suitable for a decision model. The later can be archived by using irregular polygons. Each polygon is described according to Equ. (4.4). The parameter $\alpha \in$ [0.6, 1.1, 1.8, 2.3, 5.6, 6.2, 8.0] represents the coordinates of the x-axis and $\beta \in$ [1.0, 1.5, 3.8, 5.2, 8.6, 9.0, 9.0] represents the corresponding coordinates of the y-axis, see Fig 4.4 (bottom).

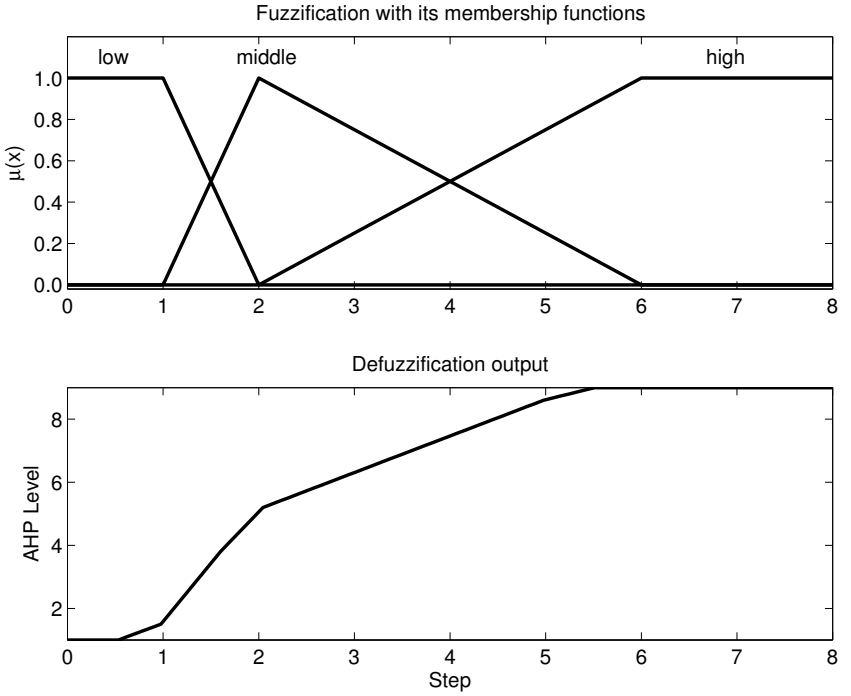


Figure 4.4: Netstat packet losses

$$y = \begin{cases} \beta_1 & \text{for} \quad x < \alpha_1 \\ \frac{\beta_2 - \beta_1}{\alpha_2 - \alpha_1} \cdot (x - \alpha_1) + \beta_1 & \text{for} \quad \alpha_1 \leq x < \alpha_2 \\ \frac{\beta_{max} - \beta_2}{\alpha_{max} - \alpha_2} \cdot (x - \alpha_2) + \beta_2 & \text{for} \quad \alpha_2 \leq x < \alpha_{max} \\ \beta_{max} & \text{for} \quad \alpha_{max} \leq x \end{cases} \tag{4.4}$$

4.6 Summary

A metric scale is not necessarily directly fitted into another type of scale. In this chapter we show the possibility of having a solution of a non-linear, in this case, step-wise translation between different types of metric scales. The goal is to transform the metric scale into a decision making tool for which the FST is perfectly suited.

Chapter 5

Accessibility in WLAN

All traditional logic habitually assumes that precise symbols are being employed. It is therefore not applicable to this terrestrial life but only to an imagined celestrial existence.

Bertrand Russell (1872 - 1970)

In this chapter, an application and adaptation of the FST for classification of the WLAN and the WPAN is given. A passive and non-interfering probe monitors power levels in the 2.4 GHz ISM-band. Now, it is possible to decide if a certain WLAN channel can be used or not. A case study is carried out. First, the power level in the 2.4 GHz ISM-band has to be measured. Second, a decision whether to use a specific WLAN channel or not has to be made. Third, if other technologies are present it would be of interest to know about their nature and which channels are being used. For that reason a classification is required and presented.

5.1 Introduction

What about interference? Certainly, the presence of other technologies in one and the same frequency area could have an effect on the final decision with regards to ABC. Such artificial sources of noise – the technologies perceive each other as noise – could be operating in the same frequency band. The FST tool, which was previously introduced, is now used to identify and classify other artificial source technologies in the 2.4 GHz ISM-band which is being used by 802.11b, Bluetooth, ZigBee and microwave ovens, see Fig. 5.1.

Cellular phone channels are ruled by strict regulations. In the WLAN scenario, the case is different. Several technologies could disturb each other within the same ISM-band. In general, the end-user is tethered to the cellular infrastructure providers and to phone companies, which deploy the UMTS and GPRS systems. However, it is up to the end-user to decide when to use the WLAN technology. If nobody is currently using a WLAN channel the choice is simple; use one of the three WLAN channels available. In the case of someone else using the same WLAN channel, the strongest signal (probably the closest) might have all the throughput. In the worst case scenario, if the connection is very weak, we could experience less throughput, or none at all. Other types of technologies could also contribute to interference in the same 2.4 GHz ISM-band which could for instance be a microwave oven, Bluetooth or ZigBee, see Fig. 5.1. Several standards are available for the IEEE 802.15.x WPAN; IEEE 802.15.1 Bluetooth; IEEE 802.15.2 coexistence of WLAN and WPAN; IEEE 802.15.3a Wireless USB; IEEE 802.15.4 ZigBee. All these standards have the (2.400–2.4835 GHz) ISM-band in common. As they use the same 2.4 GHz ISM-band, an additional non-standard interfering technique needs also to be considered, i.e. the microwave oven.

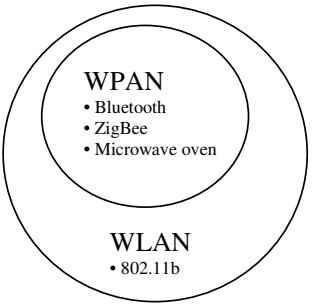


Figure 5.1: Interfering technologies in the area of WLAN and WPAN

5.2 State of the Art

Bluetooth uses the Frequency Hopping Spread Spectrum (FHSS), which means that several channels are used during a transmission. It uses 79 channels with a bandwidth of 1 MHz without any space between the channels, see Fig. 5.2. Medical monitoring is one of the important issues and one that challenges Bluetooth [77]. The bit rate of the Bluetooth technique version 1.1 and lower is at maximum 723 kbps. For versions 1.2 and 2.0 the highest bit rate is 2.1 Mbps.

The coexistence of WLAN (802.11b) and WPAN is essential, and a vast amount of research is undertaken, e.g. [31, 78–81]. Also a huge amount of research is undertaken regarding the use of same wireless technology, e.g. 802.11b, described by Vendictis *et al.* [53]. The WLAN specification mentions 14 channels, of which 13 are inside the 2.4 GHz ISM-band using the Direct Sequence Spread Spectrum (DSSS) or the FHSS technique. These channels overlap with each other and therefore only a few of the channels are usable, see Fig. 5.2. The specified bit rate of the WLAN (802.11b) technique is 1, 2, 5.5 and 11 Mbps, depending on the implementation.

The Wireless Universal Serial Bus (WUSB) uses the DSSS in the same place as Bluetooth's 79 channels together with Code Division Multiplexing

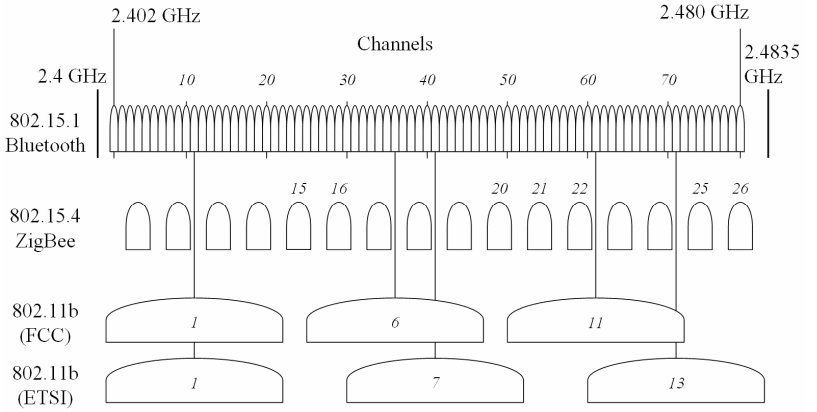


Figure 5.2: 802.11b, Bluetooth, and ZigBee in the 2.4 GHz ISM-band

Access (CDMA) spreading sequences called *Gold codes* [82]. This is a new technology to be considered in the future.

ZigBee uses several free bands like the 868 MHz band with one channel (number 0), the 915 MHz band with 10 channels (number 1−10), and the 2.4 GHz ISM-band with the DSSS technique. In the 2.4 GHz area, ZigBee uses 16 non-overlapping channels (number 11–26), see Fig. 5.2. The bit rates offered by the ZigBee technique are 20 kbps, 40 kbps and 250 kbps.

5.3 Passive and Non-Interfering Probing

How could we detect wireless traffic? One way is to measure the energy emitted, see Isaksson *et al.* [1]. Our measurements are based on an affordable hardware, the Freescale^{TM} MC13193 2.4 GHz DSSS radio frequency transceiver and the Freescale MC9S-08GT60 micro controller using IEEE 802.15.4, ZigBee^{TM}. The probing technique is passive and non-interfering. In our workbench a dedicated ZigBee device probes all the 16 channels in the 2.4 GHz ISM-band very close to the source device. The device is con-

nected to COMPORT 4 and to device board ID 0004, see Fig. 5.3 (top left). To the right all ZigBee channels between 1–16 show the power sensed in the air. On the left below a 3D figure shows the power and the 30 latest batch-samples in real time. The measurements are executed by sending a command in hex code: `0x0500020003a8`, the response is retrieved and the power levels of each 16 channels are translated into dBm or in milliwatt, where $P/\text{dBm} = 10 \times \log(P/\text{mW})$. This is executed 40 times per seconds in each batch. For each of the 16 channels the highest value during this second is depicted and saved in a log file together with the date and time. All samples are analyzed off-line. This is the initial step of the knowledge-based classification using the FST.

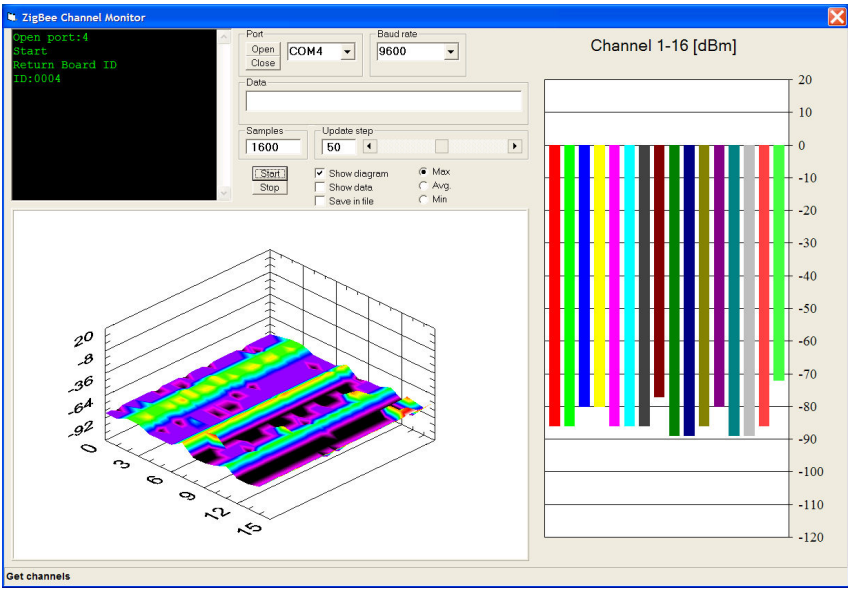


Figure 5.3: ZigBee channel monitor

5.3.1 ZigBee Packet Structure

The ZigBee protocol is uncomplicated compared to many other protocols, e.g. the Bluetooth protocol. The structure is based on the most significant byte first and consists of: *size of the packet* (1 byte); *destination* (2 bytes); *source* (2 bytes); *command* (1 byte) and in some cases *payload* (1 to 119 bytes).

5.3.2 Power Level

First, a ZigBee device has to be connected to a computer via a USB-port. Second, the application has to know the identity of the ZigBee device to be able to communicate with it. This is done by sending a command `0x0500000000b7` which is responded by `0x0700000000cf00004`. If `0xcf` was received the answer `0x0004` is the correct identity of the connected ZigBee device. Now, the specific command to retrieve the power of all the ZigBee channels could be sent with the correct identity `0x05`**`0004`**`0000a5`. This command should be replied by `0x...c3...` together with 16 bytes of data of the power level from each channel. Each resulting byte B, which is delivered by the device, is unsigned and represents the power in dBm, see Equ. (5.1).

$$P/\mathrm{dBm} = -\frac{B}{2} \tag{5.1}$$

5.3.3 Traffic Generator

To generate WLAN traffic a device from Lucent Technologies was used. During the measurements an arbitrary file was transmitted over the air using the File Transport Protocol (FTP). The nominal output power for the ORINOCO AP-500[1] is -15 dBm.

For ZigBee, a packet generator was constructed to simulate traffic between two devices. The default output power of -7.2 dBm was used.

[1] ORINOCO PC24E-H-FC with a maximal output power of 15 dBm.

Finally, the Bluetooth device uses the power class 2 which is 2.5 mW (0 dBm) with the built-in antenna.

5.3.4 Standard Deviation

For each sample five batches collected previously ($\delta = 5$) – Fig. 5.4 illustrates this – are used to calculate the standard deviation by using Equ. (5.2) which is plotted in Fig. 5.5. These two input parameters are used to classify and quantify the output. N is the size of the vector which is the number of samples (batches). P is the power measured. S is the standard deviation.

$$S_{P,WLAN}(i) = \sum_{i=1}^{N-\delta+1} S(P(i+\delta)) \tag{5.2}$$

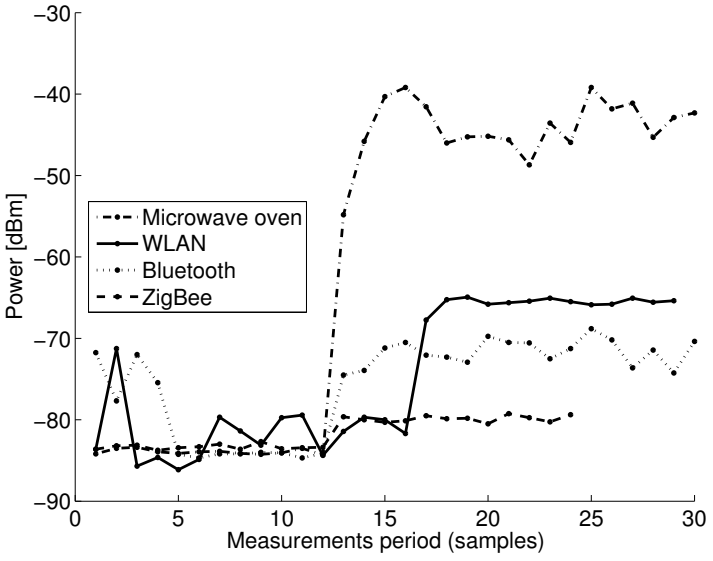


Figure 5.4: Power samples in various WPAN scenarios

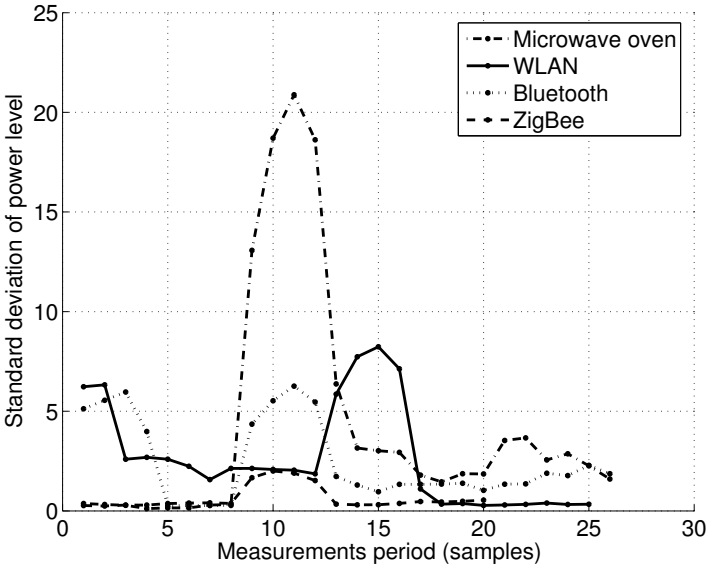


Figure 5.5: Standard deviation of WPAN measurements of the power level

5.3.5 Channel Characteristics

Each technology has its own characteristics. WLAN uses a bandwidth of 22 MHz with a channel spacing of 25 MHz (peak-to-peak) and covers 4 ZigBee channels as well as 22 Bluetooth channels. To test the behavior of a WLAN channel, in this case channel 6, an access point was set up. The minimum and maximum power levels in dBm are presented on the right side of the figure, see Fig. 5.6 (a). The WLAN traffic is scattered all over the ZigBee channel 5, 6, 7 and 8 during samples 1 to 7. This behavior is natural because the WLAN access point broadcasts information periodically during this time. From sample 8 to 16, the impact of the FTP traffic is seen from a distinct pattern: the WLAN channel character is like a lobe, higher in the middle and lower at both sides, see Fig. 5.6 (b). This is the transmission power of -37 dBm. The power levels are between -37 dBm and -95 dBm for the entire

plot, see Fig. 5.6 (a).

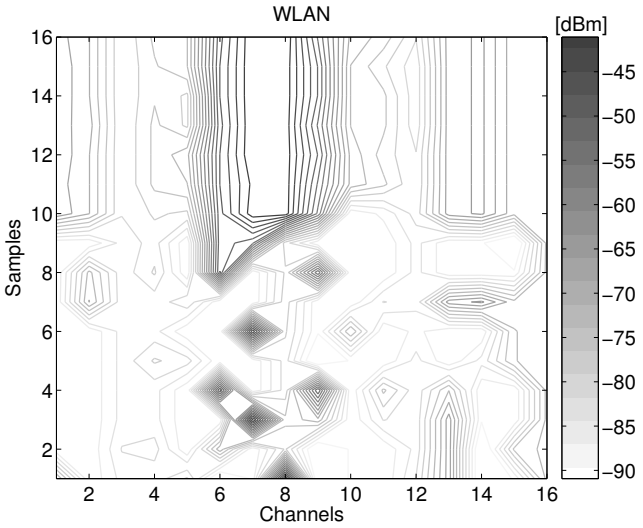
Bluetooth has a bandwidth of 1 MHz per channel with a channel spacing of 1 MHz (peak-to-peak) and uniquely uses the FHSS. This characteristic reflects the behavior of using both Time Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM). Fig. 5.7 (a) shows initially no traffic in any channel from samples 1 to 6. From samples 7 to 16 the figure shows a random transmission behavior at −57 dBm at maximum. The power levels are between −48 dBm and −89 dBm for the entire plot. Fig. 5.7 (b) shows the power levels at sample 12.

ZigBee itself has a small bandwidth of only 3 MHz which covers 3 Bluetooth channels with a channel spacing of 5 MHz (peak-to-peak), see Fig. 5.8. The figure shows initially no traffic in any channel from samples 1 to 8. From samples 9 to 16 the ZigBee channel 8 shows a transmission behavior at −44 dBm with a relatively moderate transmission power. The power levels are between −42 dBm and −89 dBm for the entire plot. Fig. 5.8 (b) shows the power levels at sample 12.

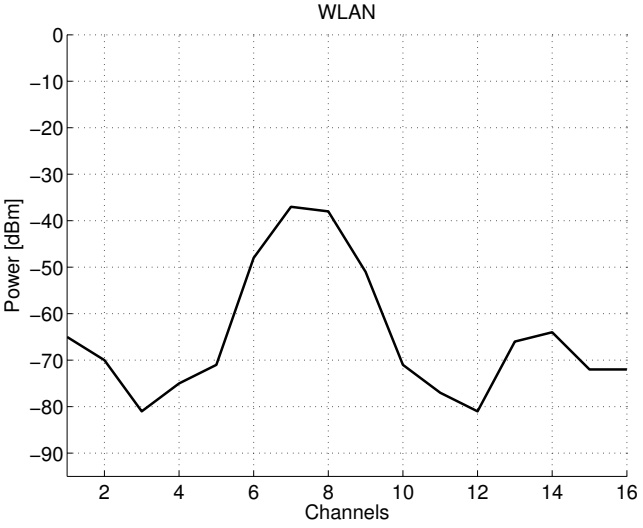
A standard microwave oven with 900 W power and with the probe in front of the oven shows a similar behavior as in the Bluetooth case. The deviations between the microwave oven and Bluetooth are as follows: the power is more concentrated at the beginning of the 2.4 GHz ISM-band, and the power level of the microwave oven is much higher, see Fig. 5.9. Between samples 1 and 7 the power is insignificant. From sample 8 the power is a lot higher as compared to other technologies. The power levels are between −14 dBm and −89 dBm for the entire plot. Fig. 5.9 (b) shows the power levels at sample 12.

5.3.6 Power Averaging

Now, all sixteen channels have been taken into consideration. The power in each channel $P(1)$ to $P(16)$ is used to calculate the arithmetic mean for each sample, see Equation (5.3).

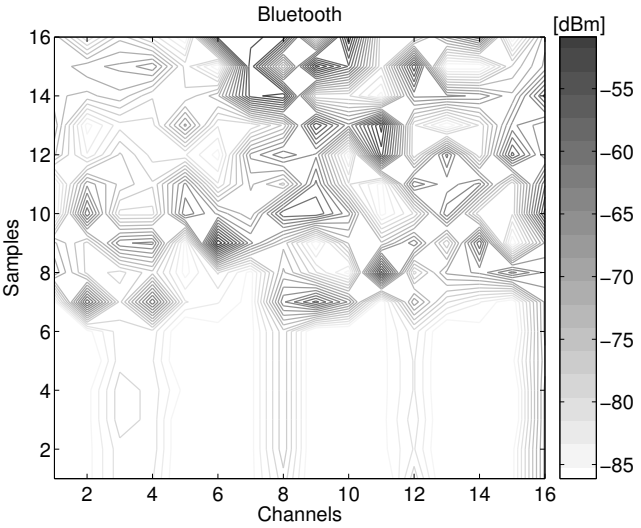


(a) Contour plot

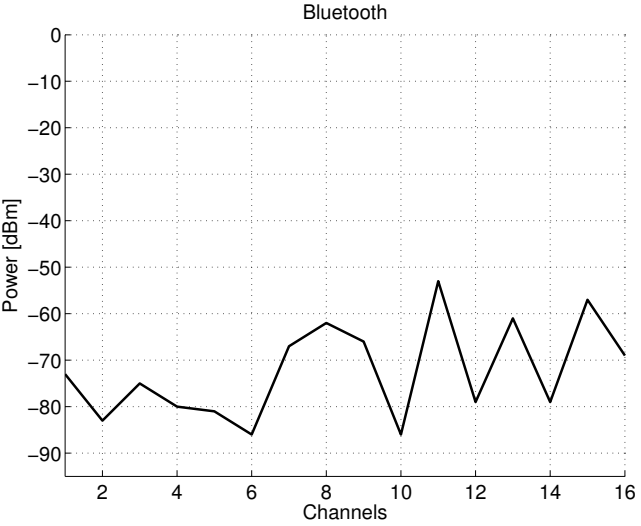


(b) Sample 12

Figure 5.6: Power levels in a WLAN scenario with the obtained throughput using 802.11.4 channel detection

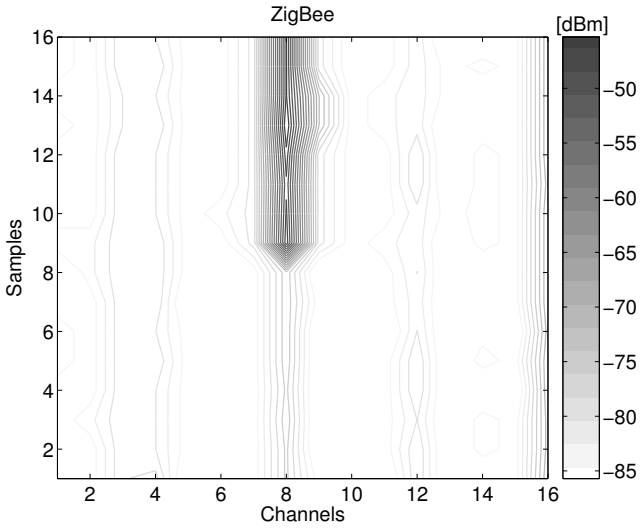


(a) Contour plot

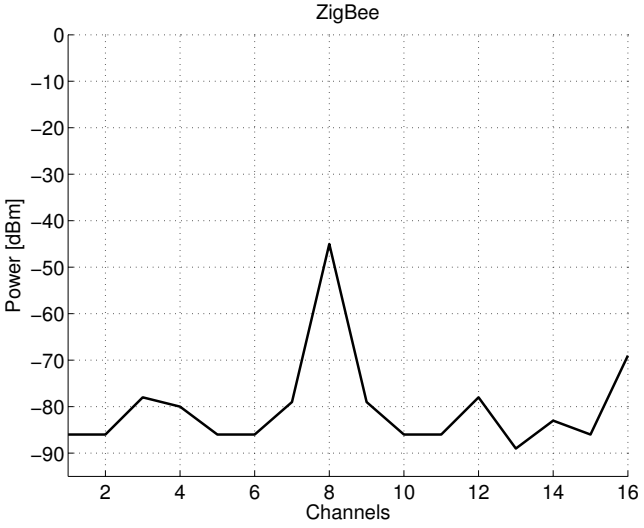


(b) Sample 12

Figure 5.7: Power levels in a Bluetooth scenario with the obtained throughput using 802.11.4 channel detection

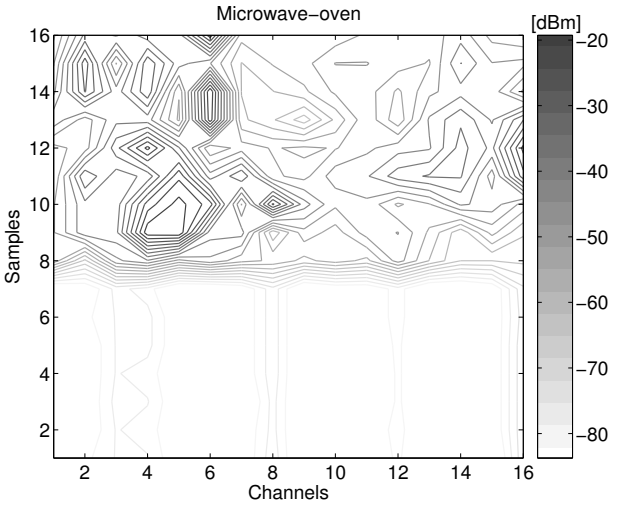


(a) Contour plot

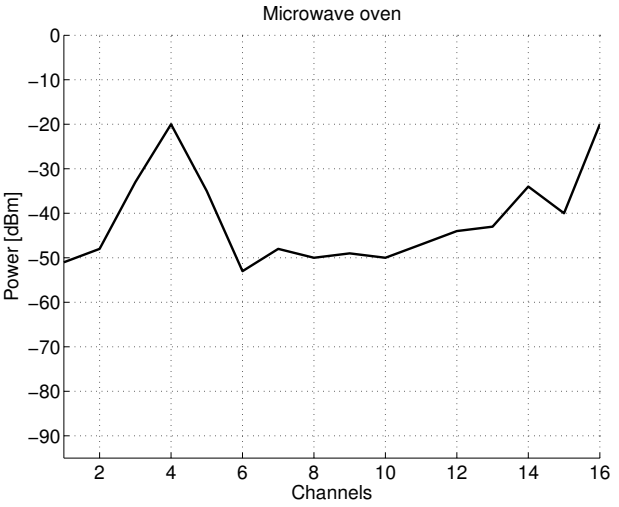


(b) Sample 12

Figure 5.8: Power levels in a ZigBee scenario with the obtained throughput using 802.11.4 channel detection



(a) Contour plot



(b) Sample 12

Figure 5.9: Power levels in a microwave oven scenario with the obtained throughput using 802.11.4 channel detection

$$\bar{P} = \frac{1}{16} \sum_{i=1}^{16} P(i) \tag{5.3}$$

The power levels are not equal to each other, see Fig. 5.4, depending on the pre-defined setting of a device. In the case of WLAN, the average power in standby mode is $\sim -82\,\text{dBm}$ up to sample 16. After that the power level increases to $\sim -65\,\text{dBm}$. In standby mode WLAN has a scattered behavior compared to the action mode which changes the behavior and makes it a lot smoother. For ZigBee the power level increases from $\sim -84\,\text{dBm}$ to $\sim -80\,\text{dBm}$. The behavior is the same as for the WLAN in action mode, still at a lower power level. Bluetooth ends up using the power level between $\sim -75\,\text{dBm}$ and $\sim -70\,\text{dBm}$. In action mode Bluetooth shows a scattered behavior which is natural because it uses the FHSS. Finally, the behavior of the microwave oven is similar to Bluetooth except in one aspect, the power level is a lot higher. In this case the power level lies between $\sim -50\,\text{dBm}$ and $\sim -40\,\text{dBm}$.

The characteristics can be filtered out by looking for a scattered behavior together with the power level. In all these cases only one technology was used. The characteristics can now be classified using the FST, and the result can be fed into a MCDM model.

5.4 Fuzzy Set Tools

Now, our input metrics are defined, i.e., the power levels and the standard deviations. These metrics are our so-called fuzzy input. The definition of all membership functions and rules needed is a rather complicated task. So, something simpler and more intuitive is desired.

The Fuzzy Inference System (FIS) structure together with a Graphical User Interface (GUI)[2] tool editor makes it possible to change all parameters

[2]Matlab Fuzzy Logic Toolbox.

graphically. The structure includes e.g. variable names, membership functions, the fuzzification method, the defuzzification method with different sections i.e. *system*, *input1*, *input2*, *output1*, and *rules*. All data are saved in a file with the name e.g. `WLAN.fis`. The function `fuzzy()` calls the function `readfis()` to be executed e.g. `fuzzy(readfis('WLAN.fis'))`. The *System* section, see Tab. B.1, consists of general information on how to use the script. The "Type" describes the method being used, in this case the *sugeno* method is depicted, see Chapter 4. The defuzzification method is called *wtaver* or *wtsum* which is the summary method used [42]. The *input1* section, see Tab. B.2, describes the first group of membership functions and its shape. The *input2* section, see Tab. B.3, describes the second group of membership functions and its shape. The *output1* section, see Tab. B.4, describes the sugeno parameters. Finally, the membership function with the IF-THEN condition is given. The *rules* section describes a rule with a match toward two membership functions, see Tab. B.5.

5.4.1 Fuzzy Membership Functions

Several types of membership functions are available. The trapezoidal shape for WLAN (Fig. C.1 and C.2), the microwave oven (Fig. C.3 and C.4), Bluetooth (Fig. C.5 and C.6) and ZigBee (Fig. C.7 and C.8) are depiced. The output parameter is based on Singleton sets. Also in this case the trapezoidal shape is chosen.

5.4.2 Rules

Each membership function is connected to a rule. The first rule selects the standard deviation membership function **A** using the AND operator selecting the next power level membership function **B** whose output is the membership function **C**. Second, the rule is inverted to exclude all other situations, see Tab. B.6, lines 3–4.

5.4.3 Defuzzification

As mentioned in Chapter 4, the Sugeno model is depicted using singleton sets with the linguistic output levels of *low*, *middle* and *high* (three linguistic levels). The *low* value is set to 0, the *middle* is set to 4 and the *high* is set to 8. The output scale, which uses the singleton sets, is simpler to handle compared to other methods like the mean of max or the center of gravity method, suggested by Mamdani [42], in the case of transforming the linguistic output to a fixed x-point scale. That is why the minimum boundary is set to represent the value of zero and the maximum boundary is set to represent the value of eight, which leads us to the 9-point scale required by the decision method.

5.4.4 Classification Degree

How good is the classification? If we look between sample 1 and 17 nothing can be filtered out for the WLAN case, see Fig. 5.6 and 5.10. After sample 17, WLAN climbs to separate the category from other categories. This shows that the method could distinguish categories from each other.

5.5 WLAN and WPAN Accessibility

All power level measurements are executed by using a ZigBee device which is able to retrieve the power in all 16 specified ZigBee channels in the 2.4 GHz ISM-band. The lightweight ABC is used as a simpler decision method compared to other more advanced MCDM tools. Once a non-interfering channel or non-used channel is found, it will simply be chosen by using a knowledge-based classification method.

The initial step for the knowledge-based classification is to use the Fuzzy Set Theory (FST) [27]. Data, *metric values*, are first collected which are to be divided into *linguistic values* using Multiple-Input Single-Output (MISO).

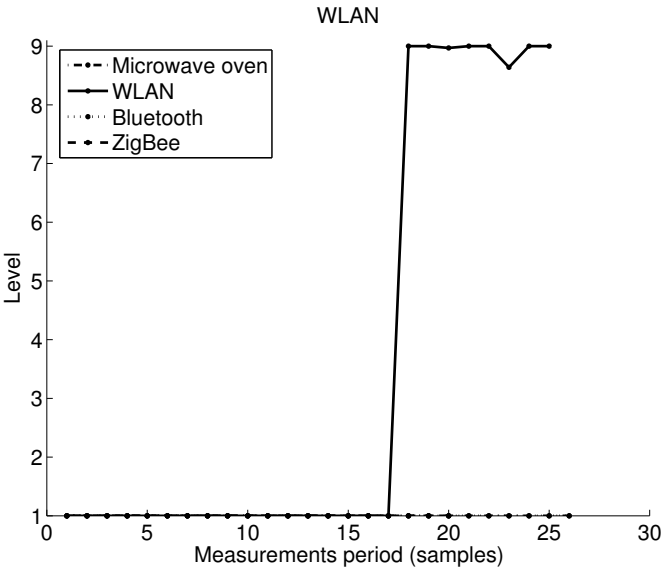


Figure 5.10: WPAN classification

The multiple-input is defined as $X = \{x_1, x_2, \cdots, x_N\}$, and the membership function as $\widetilde{A} = \{\mu_{\widetilde{A}}(x_1), \mu_{\widetilde{A}}(x_2), \cdots, \mu_{\widetilde{A}}(x_N)\}$, and the grade $\mu_{\widetilde{A}}(x_i)$ found in the interval $[0, 1], i = 1, 2, \cdots, N$. Each membership function is connected to a rule which is transformed into a certain linguistic value. Now, two options are possible. The first option is to use the linguistic values without changing its interpretation. The second option is to translate the linguistic values into metric values. The final step inside the knowledge-based box is to do a match of the linguistic values or the metric values. Based on the fuzzy outcome a class or a category is depicted. These classes or categories with their fuzzy levels are later transformed into a suitable scale used as an input for Multi-Criteria Decision Making. More information can be found in Section 6.

5.5.1 WLAN

In the case of WLAN, each WLAN channel covers four ZigBee channels, see Equ. (5.4). The first WLAN channel $P_{\mathrm{W}}(1)$ covers four ZigBee channels $P_{\mathrm{Z}}(1)$ to $P_{\mathrm{Z}}(4)$. For each WLAN channel an average power is calculated, see Equ. (5.5). All 13 channels are sorted in the order of decreasing average power over 15 samples and plotted, see Fig. 5.11 and 5.12. It is interesting to see that channels 5 and 7 are also affected – which is definitely the case due to the overlap of the WLAN channels. The conclusion from the data is that channel 6 is likely to be used which means that the standard specified for the U.S. market is used in Europe.

The opposite is also possible to get which in this case is the lowest power. All 13 channels are sorted in the order of ascending average power over 15 samples and plotted, see Fig. 5.13 and 5.14. In this case the lowest value provides the choice of transmission channel. If one follows the specification for the U.S. the choice will be channel number 1 followed by channel number 11. For the Europe standard only channel number 1 is possible to choose.

$$\begin{aligned} P_{\mathrm{W}}(1) &\in \{P_{\mathrm{Z}}(1), P_{\mathrm{Z}}(2), P_{\mathrm{Z}}(3), P_{\mathrm{Z}}(4)\} \\ P_{\mathrm{W}}(2) &\in \{P_{\mathrm{Z}}(2), P_{\mathrm{Z}}(3), P_{\mathrm{Z}}(4), P_{\mathrm{Z}}(5)\} \\ &\vdots \\ P_{\mathrm{W}}(13) &\in \{P_{\mathrm{Z}}(13), P_{\mathrm{Z}}(14), P_{\mathrm{Z}}(15), P_{\mathrm{Z}}(16)\} \end{aligned} \tag{5.4}$$

$$\bar{P}_W(i) = \frac{1}{4} \sum_{j=0}^{3} P_Z(i+j), \quad i = (1, \ldots, 13) \tag{5.5}$$

5.5.2 ZigBee

All 16 ZigBee channels are sorted in descending order and plotted, see Fig. B.1 and B.2. In this case the interest is to know the highest measured power level.

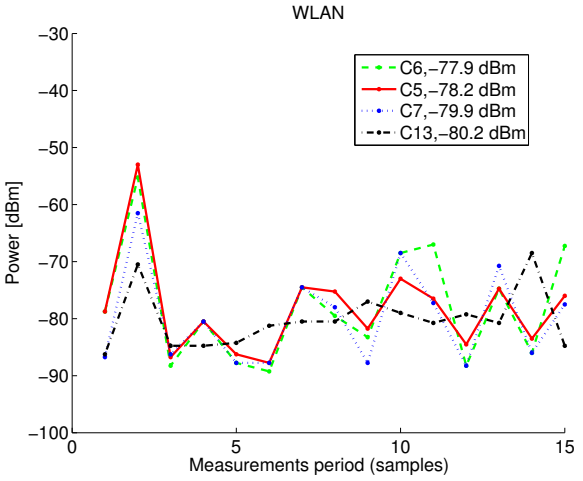


Figure 5.11: WLAN channels sorted in descending order, first four channels shown, samples 1 to 15, i.e. the four channels with highest average signals

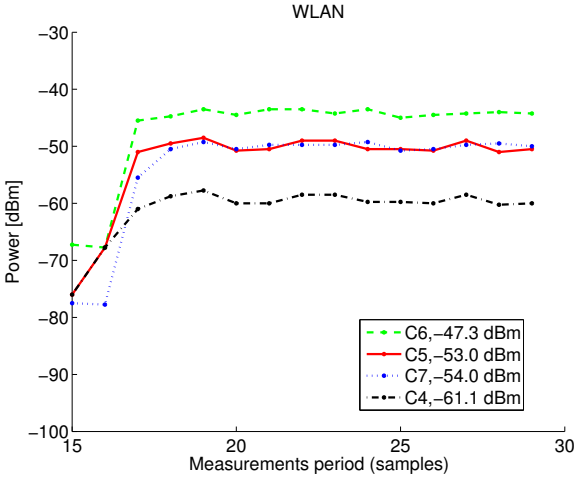


Figure 5.12: WLAN channels sorted in descending order, first four channels shown, samples 15 to 29, i.e. the four channels with highest average signals

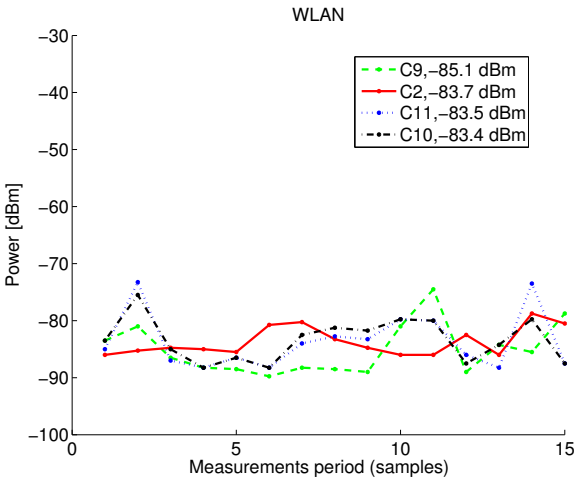


Figure 5.13: WLAN channels sorted in ascending order, first four channels shown, samples 1 to 15, i.e. the four channels with lowest average signals

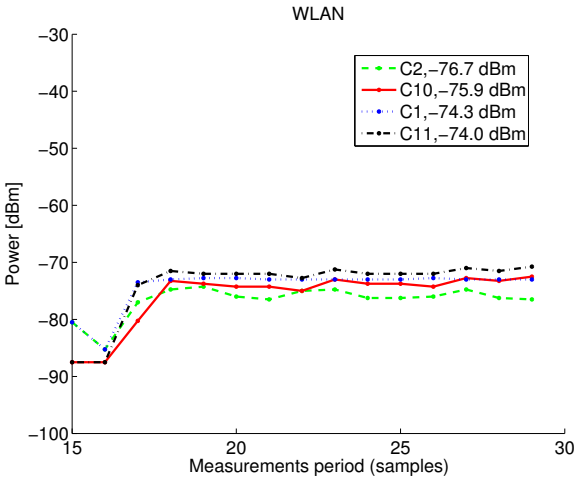


Figure 5.14: WLAN channels sorted in ascending order, first four channels shown, samples 15 to 29, i.e. the four channels with lowest average signals

Channel number 8 is above −50 dBm and depicted and classified as occupied.

The opposite is also possible to get. All 16 ZigBee channels are sorted in ascending order and plotted, see Fig. B.3 and B.4. In this case the lowest value is also the choice of a free transmission channel number 13. If WLAN traffic was present the choice would be channel number 15 which is between the WLAN channel 1 and WLAN channel 6.

5.5.3 Bluetooth

The latest version of the Bluetooth specification version 2.0 [83] includes the higher bit rates, up to 3 Mbps, at the physical layer. Also, version 1.2 of the specification includes an extended version of the frequency hopping to Adapted Frequency Hopping (AFH) which was investigated by Isaksson [84]. The difference between the two versions of the specifications 1.1 [85] and 1.2 [86], regarding input parameters, is that the 23- and 79-frequency switch is removed. This is not needed any longer because of the Channel Map (CM). With the channel map there is a possibility to choose all combinations of the channels between $N_{min} \leq N \leq 79$ instead of only two main options (23 and 79). The minimum number of channels is $N_{min} = 20$.

Basically, the selection box is extended to handle two situations; the original with all 79 channels used and the new AFH using between 20 and 78 channels, see Fig. 5.15. If the derived frequencies match the AFH channel map, which is based on the allowed frequencies used in the selection box, the frequency is derived as before and becomes f_k. If the frequency is not within the allowed frequencies, a new frequency $f_{k'}$ has to be calculated with help from Equation 5.6, 5.7 and 5.8. Parameter N is the number of channels (probably less than 79). $PERM5_{out}$ is the output result from a permutation algorithm inside the selection box. Parameter E and F are based on parts of the Bluetooth address. Parameter CLKN and Y2 are based on parts of the Bluetooth clock.

Finally, a decision could be made to exclude certain channels for Blue-

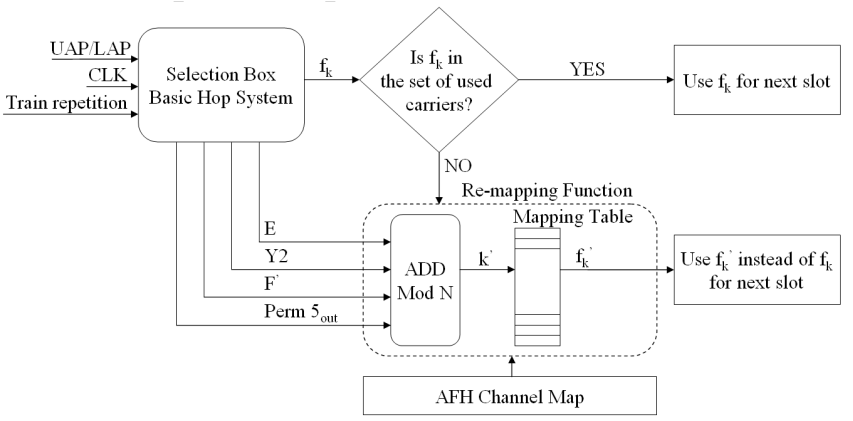


Figure 5.15: Block diagram of Basic and Adapted Frequency Hopping Scheme for Bluetooth version 1.2

tooth to increase the probability of a transmission, see Equation (5.9), denoting which channels to *avoid* in case a certain WLAN channel is on air, see Tab. D.2. Equation (5.10), denotes the channels to *avoid* in case a certain ZigBee channel is on air, see Tab. D.3.

$$\mathrm{F}^{'} = \mathrm{MODULO}(16 \cdot \mathrm{CLKN}_{27-7}, \mathrm{N}) \tag{5.6}$$

$$\mathrm{k}^{'} = \mathrm{ADD_mod_N}(\mathrm{PERM5}_{\mathrm{out}}, \mathrm{E}, \mathrm{F}^{'}, \mathrm{Y2}) \tag{5.7}$$

$$\mathrm{f}_{\mathrm{k}'} = \mathrm{RegisterBank}(\mathrm{N}) \tag{5.8}$$

$$\begin{aligned} P_{\mathrm{W}}(1) &\in \{P_{\mathrm{B}}(23), \cdots, P_{\mathrm{B}}(79)\} \\ P_{\mathrm{W}}(2) &\in \{P_{\mathrm{B}}(1), \cdots, P_{\mathrm{B}}(4)\} \text{ and } \{P_{\mathrm{B}}(28), \cdots, P_{\mathrm{B}}(79)\} \\ P_{\mathrm{W}}(3) &\in \{P_{\mathrm{B}}(1), \cdots, P_{\mathrm{B}}(9)\} \text{ and } \{P_{\mathrm{B}}(33), \cdots, P_{\mathrm{B}}(79)\} \\ &\vdots \\ P_{\mathrm{W}}(13) &\in \{P_{\mathrm{B}}(60), \cdots, P_{\mathrm{B}}(79)\} \end{aligned} \tag{5.9}$$

$$
\begin{aligned}
P_{\mathrm{Z}}(1) &\in \{P_{\mathrm{B}}(1), \cdots, P_{\mathrm{B}}(2)\} \text{ and } \{P_{\mathrm{B}}(6), \cdots, P_{\mathrm{B}}(79)\} \\
P_{\mathrm{Z}}(2) &\in \{P_{\mathrm{B}}(1), \cdots, P_{\mathrm{B}}(7)\} \text{ and } \{P_{\mathrm{B}}(11), \cdots, P_{\mathrm{B}}(79)\} \\
&\vdots \\
P_{\mathrm{Z}}(16) &\in \{P_{\mathrm{B}}(78), P_{\mathrm{B}}(79)\}
\end{aligned}
\tag{5.10}
$$

5.6 Summary

The use of the FST in combination with a simple ZigBee-based monitoring tool makes it possible to classify the type of technology and channel(s) by sensing the energy for a particular technology and channel. The WPAN technology Bluetooth, e.g., could now be instructed to change its use of channels to avoid interference with WLAN channels, thus improving the probability of a successful transmission.

Chapter 6

Multi-Criteria Decision Making

[...] comparative judgment is the identification of some relation between two stimuli both present to the observer.

Arthur L. Blumenthal (1977)

This chapter presents an illustration of how the Analytic Hierarchy Process (AHP) can be used for choosing between different wireless networks, in terms of metrics and constraints. The chapter starts, however, with an introduction of the subject of Multi-Criteria Decision Making (MCDM). Then there is a description of how the AHP works. Also the Mean Random Consistency Index (MRCI) is described and validated for some cases. Finally, the measurements mapping and how this is used and implemented is also given.

6.1 Introduction

At this point we have all the input parameters in order for us to use a decision tool. The reason for using a decision tool is the large amount of data that has to be compared and judged. The decision for selecting Always Best Connected

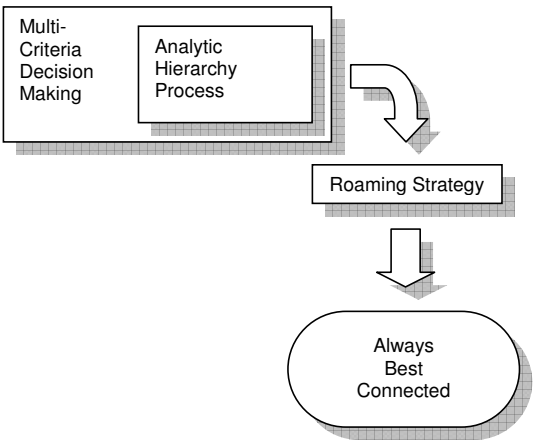


Figure 6.1: Multi-Criteria Decision Making with the goal of Always Best Connected

(ABC) by selecting a network link tends to be complex and depends upon a whole range of criteria, most of which relate to the conditions and efficiency within each considered device and environment. Normally, the criteria are not easy to quantify and the most critical task in the decision process is to define those criteria that are of importance. Our metric values are the input to the Multi-Criteria Decision Making (MCDM) process in which the transformed 9-point scale is being used. The outcome from the decision process is a weighted priority list which is fed into the roaming strategy box with the final goal of being ABC, see Fig 6.1.

The Decision Support System (DSS) is of great interest and importance

today because fast and accurate decisions could make a difference. The DSS classifies the process models of cognitive support for human decision makers. Nancy Green Hall [87] summarized, in 1986, several research areas within Fuzzy DSS. A framework in the area of cognitive perceptions using fuzzy DSS was categorized by Zachary [88]. His work was formalized before the common use of fuzzy logic, in which he categorized the cognitive support based on non-fuzzy tools needed for a human decision maker. Six general classes of cognitive perceptions were given:

1. process models – e.g. forecasting and econometric models;
2. choice models – e.g. analytical hierarchy and expected value models;
3. information control techniques – e.g. database management systems and knowledge-based meta systems;
4. analysis and reasoning methods, numerical and symbolic – e.g. optimized, statistical analysis, goal-based inference;
5. representation aids – e.g. linguistic and spatial representation;
6. human judgment amplifying/refining techniques – e.g. human-aided optimization, Bayesian updating.

The first three categorizes are commonly used in fuzzy tools. Especially the MCDM benefits from these types of categorization. In category four a combination of both numerical and analytical models are represented. The natural language is represented in category five. One advantage is that the user is able to interact with the fuzzy tool as naturally as possible in a linguistic way. Finally, category six tries to make the best of the human's intuitive ability to interpret the information produced by a computer.

As proposed, the AHP method will be used to select the best network link alternative with the Quality of Service (QoS) level in mind. The AHP has many advantages [89]: easily understood and flexible, integrates deductive

approaches, interdependence of elements of systems, hierarchic structuring, measures intangibles, tracks logical consistency, overall estimation, consideration of the relative priorities, and improvement of the judgment.

This was originally proposed by Saaty in [90] to support decisions in Management Science [91]. The AHP method has further been accounted for by Saaty in other publications like [92–96]. It has also been used in several software engineering settings [97–100] and several pieces of software have been developed using AHP as a foundation [101–105]. In general the structure is illustrated as in Fig. 6.2. In some literatures *features* is only a subgroup to *criteria*, still it means the same and *alternatives* is the same as *attributes*.

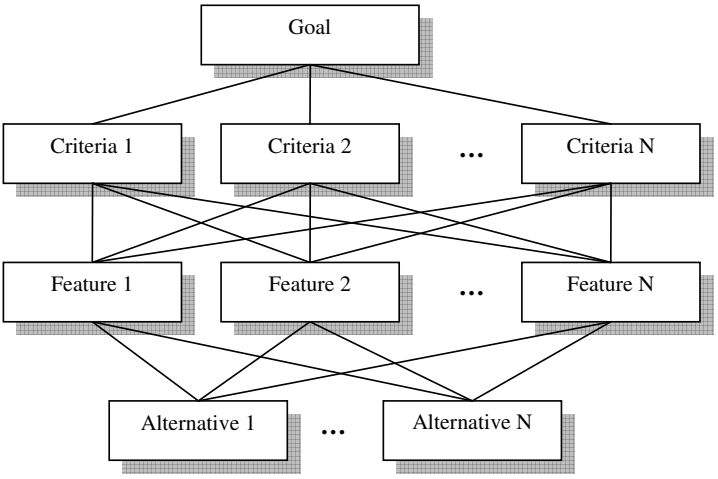


Figure 6.2: Decomposition with four levels

6.2 Definition of the Overall Goal

The objective is to find a network link efficient enough for the selected service, see Tab. 6.1. Several alternatives could be used: the Digital Audio

Table 6.1: Setup parameters for the AHP

Goal		
Always Best Connected (ABC)		
Alternatives		
WLAN (Europe, America), UMTS, GPRS		
Attributes		
	Static	Dynamic
Performance	Initial Delay (ID) Link Capacity (LC) Directional Loss (DL)	Throughput Losses Round Trip Time (RTT)
Cost	Time-Based Fee (TBF) Volume-Based Fee (VBF) Security	
Accessibility		Coverage Area (CA) Interference

Broadcast (DAB), the Wireless Local Area Network (WLAN), the Universal Mobile Telecommunications System (UMTS), and the General Packet Radio Service (GPRS). In this case the last three are used. The attributes are divided into three sub-groups: *performance*, *cost*, and *accessibility*. Some groups are further divided into two sub-groups: *static* and *dynamic*. Finally, the criteria / attributes are defined. All groups are later put together and the final *preference ratios* are found. The highest preference ratio denotes the best link according to the weighted criteria from the AHP. More information can be found in Section 7.

6.3 The Analytic Hierarchy Process

This section describes, in detail, the AHP for decision making. The AHP was also used in a technical research report by Isaksson *et al.* [106]. The AHP

method for solving decision problems includes five major steps:

- Step 1: Construct the hierarchical structure by breaking down and decomposing the decision problem into several decision elements.
- Step 2: Create the input values by pair-wise comparisons of decision elements.
- Step 3: Estimate the relative weights of the decision elements.
- Step 4: Check for consistency.
- Step 5: Synthesize the priorities and combine the relative weights to determine the final set of ratings for the different decision alternatives.

6.3.1 Step 1

The critical part of decision making is the structuring. This includes the decomposition of the problem into several elements according to their characteristics. In order to model complex decisions correctly and efficiently the following guidelines should be kept in mind:

- Try to cluster elements so that they include elements that are comparable, or that do not differ too much from each other. This was taken into account when defining the hierarchy shown in Fig. 3.2. Its basic form consists of a hierarchy structure with the goal at the top level, in-between the clustered criteria, and last the alternatives.
- Do not include more than nine elements in any set. Experiments have shown that it is challenging for human beings to deal with more than nine factors at one time and this can result in less accurate priorities, demonstrated in [107]. Moreover, as the number of elements being compared increases, the measure of inconsistency decreases so slowly that there is insufficient space for improving the assessment as well as the consistency.

- When it comes to subjective quality, Miller [19, 20] as early as in 1956 stated an upper limit of short-term memory based on human capacity. It is recommended to use a seven-(plus-minus-two-)point scale [19].

To make comparisons possible, the goal has to be established first. A useful way is to use the following suggestions in [96] for a hierarchical design:

- Identify the overall goal and subgoals of the overall goal. What are you trying to accomplish? What is the main question?
- Identify criteria that must be satisfied in order to fulfill the subgoals of the overall goal.
- Identify, if necessary, sub criteria under each criterion. Note that criteria or sub criteria may be specified in terms of ranges of values of parameters or in terms of verbal intensities such as high, medium, and low.
- Identify actors involved.
- Do benefit/cost analysis. Because we are dealing with dominance hierarchies, ask which alternative yields the greatest benefit; for costs, which alternative costs the most.

Therefore, the basic form consists of a hierarchy structure with the goal at the top level, in between the criteria, and last the alternatives. In many cases the AHP is based on one complex constructed hierarchy [89].

6.3.2 Step 2

The judgments in the AHP are made in pairs a_{ij}, relating the importance of criterion i to that of criterion j. The scale used is represented by the intensities between each other according to the *fundamental scale*. The fundamental scale is validated according to effectiveness and theoretical justifications according to Saaty [90]. The scale consists of nine levels. To make it even easier to judge,

one can use a more restricted scale with five levels: 1 is *equal importance*, 3 is *moderate importance*, 5 is *strong importance*, 7 is *very strong or demonstrated importance* and 9 is *extreme importance*.

Table 6.2: The fundamental scale for AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the object
2	Weak	*Between Equal and Moderate*
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	*Between Moderate and Strong*
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	*Between Strong and Very Strong*
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	*Between Very Strong and Extreme*
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

First, the criteria are compared pair-wise with respect to the goal. A $i \times j$ matrix, denoted as $\mathbf{A}$, is created using the comparisons with elements $a_{ij} > 0$, indicating the importance of criterion i relative to criterion j as shown in Equation (6.1). Obviously, $a_{ij} = 1$ when $i = j$, while $a_{ji} = 1/a_{ij}$, which reflects the reciprocal importance of criterion j relative to criterion i.

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1j} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2j} \\ \vdots & & & & \\ a_{i1} & a_{i2} & a_{i3} & \cdots & a_{ij} \end{bmatrix} \tag{6.1}$$

6.3.3 Step 3

After constructing the matrix of comparison, the next step is to determine the weights of the criteria, in which w_i is the weight of objective i in the weight vector $\mathbf{w} = [w_1, w_2, \cdots, w_n]$ for n criteria. The objective is to recover vector $\mathbf{w}$ from matrix $\mathbf{A}$ by finding the solution for some value u of

$$\mathbf{A} \cdot \mathbf{w}^T \quad = \quad u \cdot \mathbf{w}^T \,. \tag{6.2}$$

The matrices $\mathbf{A}^{\mathrm{C}k}$ contain judgments of the importance of *criteria* against each other per group $k \in \{1 = \text{performance}, 2 = \text{cost}, 3 = \text{accessibility}\}$. The matrices $\mathbf{A}^{\mathrm{A}kl}$ contain judgments of the importance of *attributes* per criterion k. Index k and index l together form the following combinations: 11 = Initial Delay (ID), 12 = Link Capacity (LC), 13 = Directional Loss (DL), 14 = Throughput, 15 = Losses, 16 = Round Trip Time (RTT), 21 = Time-Based Fee (TBF), 22 = Volume-Based Fee (VBF), 23 = Security, 31 = Coverage Area (CA), 32 = Interference.

In order to determine w_i a numerical solution is used [90] that starts with normalizing each column j in $\mathbf{A}$ such that

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \,.$$

Next, each row i in a' is summarized into a vector with elements

$$a''_i = \sum_{j=1}^{n} a'_{ij} \,.$$

Finally, the vector **w** is obtained as

$$w_i = \frac{a_i''}{\sum_{j=1}^{n} a_j} ,$$

where w_i is the weight of criteria i in the weight vector.

6.3.4 Step 4

The next step is to check for consistency. According to [90] four steps are used as follows:

1. Compute λ_{max}, which is the largest eigenvalue of matrix **A**.
2. Compute the Consistency Index CI(n) = ($\lambda_{max} - n$) / ($n - 1$).
3. Compute the Mean Random Consistency Index, MRCI(n) = ($\bar{\lambda}_{max} - n$) / ($n - 1$).
4. Compute the Consistency Ratio CR(n) = CI(n) / MRCI(n) and evaluate the consistency, observing $\varepsilon \simeq 0.052$ for a 3×3 matrix; $\varepsilon \simeq 0.089$ for a 4×4 matrix; and $\varepsilon \geq 0.1$ for a larger matrix, see Section 6.3.6.
   - If CR(n) = 0 then **A** is consistent;
   - If CR(n) $\leq \varepsilon$ then **A** is consistent;
   - If CR(n) $> \varepsilon$ then **A** is not consistent.

One could compare the alternatives pair-wise by studying the satisfaction of each criterion on the level above. Thus there will be n matrices of judgments since there are n criteria. Each matrix contains the weight for each alternative and is determined in a similar way as described above for w_i in Formula 6.4.

6.3.5 Step 5

Finally, the last step is to select the alternative that best satisfies the goal, and synthesize the priorities. This is done by multiplying vectors $\mathbf{w}^{Ck}$ and $\mathbf{w}^{Akl}$ according to

$$\mathbf{w}^{Dk} = \left[w_l^{Ck} \cdot \mathbf{w}^{Akl}\right]_l . \tag{6.3}$$

In our context, the vectors $\mathbf{w}^{D1}$, $\mathbf{w}^{D2}$ and $\mathbf{w}^{D3}$ represent the ranking of the alternatives WLAN, UMTS and GPRS with regard to performance, cost and accessibility. Finally, the average ranking of these alternatives is computed as

$$\mathbf{w}^{D} = \frac{1}{3}\sum_{k=1}^{3} \mathbf{w}^{Dk} . \tag{6.4}$$

The alternative with the largest value is then selected. This way of synthesizing the priorities is called the *distributive mode* [90]. There is another alternative which is called the *ideal mode*. In this case only the matrix of each criterion, and not the alternatives, is used. A guideline, by Millet *et al.* [108], is summarized as follows:

> *The Distributive (dominance) synthesis mode should be used when the decision maker is concerned with the extent to which each alternative dominates all other alternatives under the criterion. The Ideal (performance) synthesis mode should be used when the decision maker is concerned with how well each alternative performs relative to a fixed benchmark.*

6.3.6 Mean Random Consistency Index

The *consistency index* is randomly calculated, Saaty [90, 109]. So, the question of trustworthiness arises.

The MRCI is the average value of CI for randomly chosen entries in $\mathbf{A}$, given by Tab. 6.3. The set $\Omega_{17} = \{1, 2, \ldots, 9, 1/2, 1/3, , \ldots, 1/9\}$ was used.

Several other papers have shown simulation results of the Mean Random Consistency Index (MRCI), see Tummala *et al.* [110]. Still, simulations do not show the exact value. Lane and Verdi [111] could in 1989 show the exact Mean Consistency Index (MCI) value for the MRCI(3) by solving all $17^3 = 4913$ equations, 17 combinations for $a_{12} = 1/a_{21}$, 17 combinations for $a_{13} = 1/a_{31}$, and 17 combinations for $a_{23} = 1/a_{32}$ see Tab. 6.3. That value was confirmed in the thesis by emulating all solutions for the MRCI(3), see Tab. 6.3. In Fig. 6.3 the solid line is our emulated values which finally reaches 0.5245, and the dashed horizontal line shows the simulated value (0.52). An exact value for MRCI(4) was also emulated, solving MCI(4) $17^6 = 24137569$ combinations, see Tab. 6.3 and Fig. 6.4. The solid line is our emulated values which finally reaches (0.8842) and the dashed horizontal line is the simulated value (0.89). Finally an exact value for MRCI(5) was emulated, solving MCI(5) 17^{10} combinations, see Tab. 6.3 and Fig. 6.5. The solid line is our emulated values which finally reaches (1.1086) and the dashed horizontal line is the simulated value (1.11). The script used can be found in Tab. D.1. Line 5 is the Ω_{17} vector. Line 7 is the size of the matrix and line 9 is the number of the combinations expected. Lines 14 to 16 produce the input of the emulation. Lines 19 to 26 create the matrix which is later used in line 28 to reveal the largest eigenvalue λ_{max} of the matrix. The calculations are completed at line 31 which finally show the value of $\bar{\lambda}_{max}$.

Table 6.3: Mean Random Consistency Index (MRCI) and Mean Consistency Index (MCI)

n	3	4	5	6	7	8	9
Saaty [109]	0.52	0.89	1.11	1.25	1.35	1.40	1.45
Lane and Verdi [111]	0.5245*	-	-	-	-	-	-
Isaksson	0.5245*	0.8842*	1.1086*	-	-	-	-
	* this value is not based on random numbers						

The number of combinations increases rather fast with the size of the matrix. The MCI(3) was executed in seconds and MCI(4) in less than one hour. Emulating larger matrixes is another story. If using a computer with a capacity of 2 GHz the MCI(5) would approximately take 2.5 years to execute. The solution was to build a client/server program in order to carry out computations in parallel. The server hands out a unique batch sequence to a client after a request. The client executes the batch and uploads the results to the server. This continues until the number of batches is exhausted which is estimated to take 2.5 months, if using approximately 20 computers. The algorithm is based on the same script used before, see Tab. D.1. In this case the Matlab script was compiled into C code using MATLAB Component Runtime (MCR) instead of executing the script directly in Matlab. The client/server script was developed in Perl with TCP/IP connection ability. Inside the client program it calls the compiled Matlab code. This client/server solution was used to execute the MCI(3) (Fig. 6.3), the MCI(4) (Fig. 6.4), and the MCI(5) (Fig. 6.5), see Tab. 6.4. The MCI(5) used at most 21 computers simultaneously to reduce the total emulation time.

Table 6.4: Data from Mean Consistency Index (MCI) emulations based on varying batch sizes

n	Sample size	Batch size	Number of batches	Total [%]	Variance s^2	Std. Dev. s	MCI
3	17^3	1	4913 of 4913	100	1.94	1.39	0.524457
4	17^6	5000	4828 of 4828	100	0.99	0.99	0.884112
5	17^{10}	$1 \cdot 10^8$	20159 of 20159	100	0.85	0.92	1.108683

The conclusions show that the MRCI(4) is not exactly correct. Based on our emulations of MCI(4) the value should be 0.884112 which is slightly lower than 0.89 found by Saaty. The next case, which is the MRCI(5), is correct. Based on our emulations of MCI(5) the value is 1.108683 which is only slightly lower than 1.11 found by Saaty.

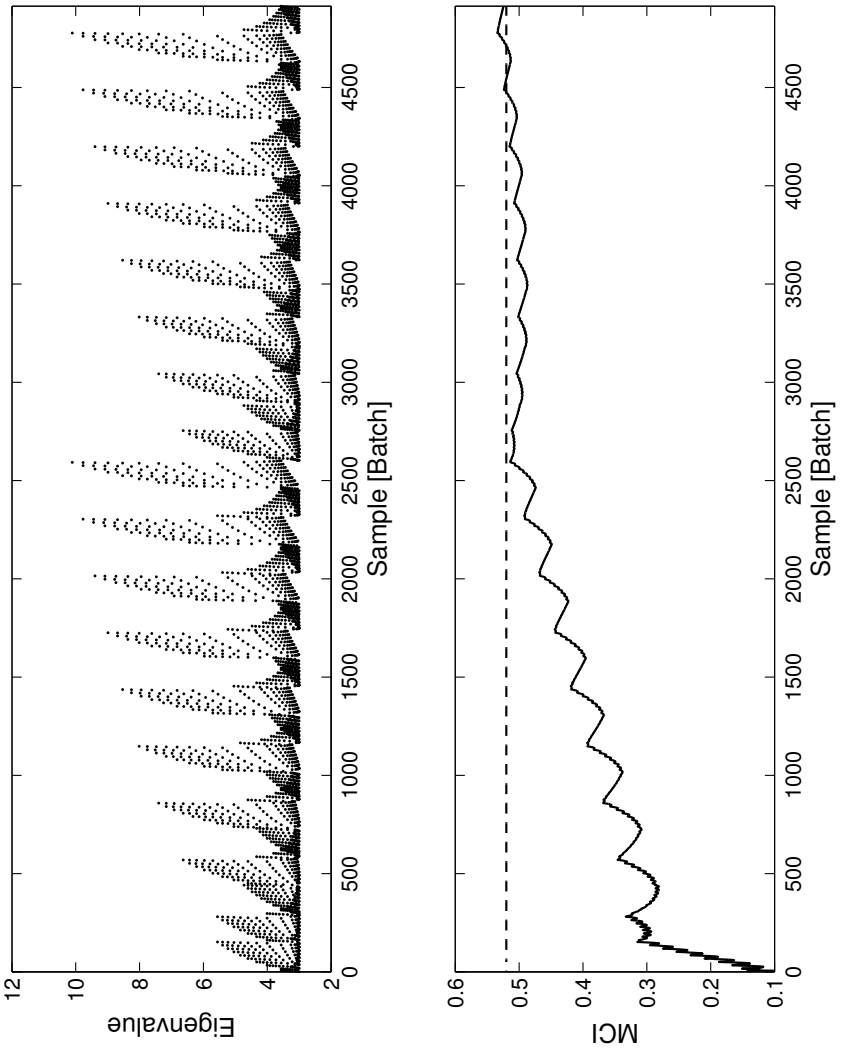


Figure 6.3: MCI calculations for a 3x3 Matrix, Eigenvalue (top), Mean Consistency Index (bottom)

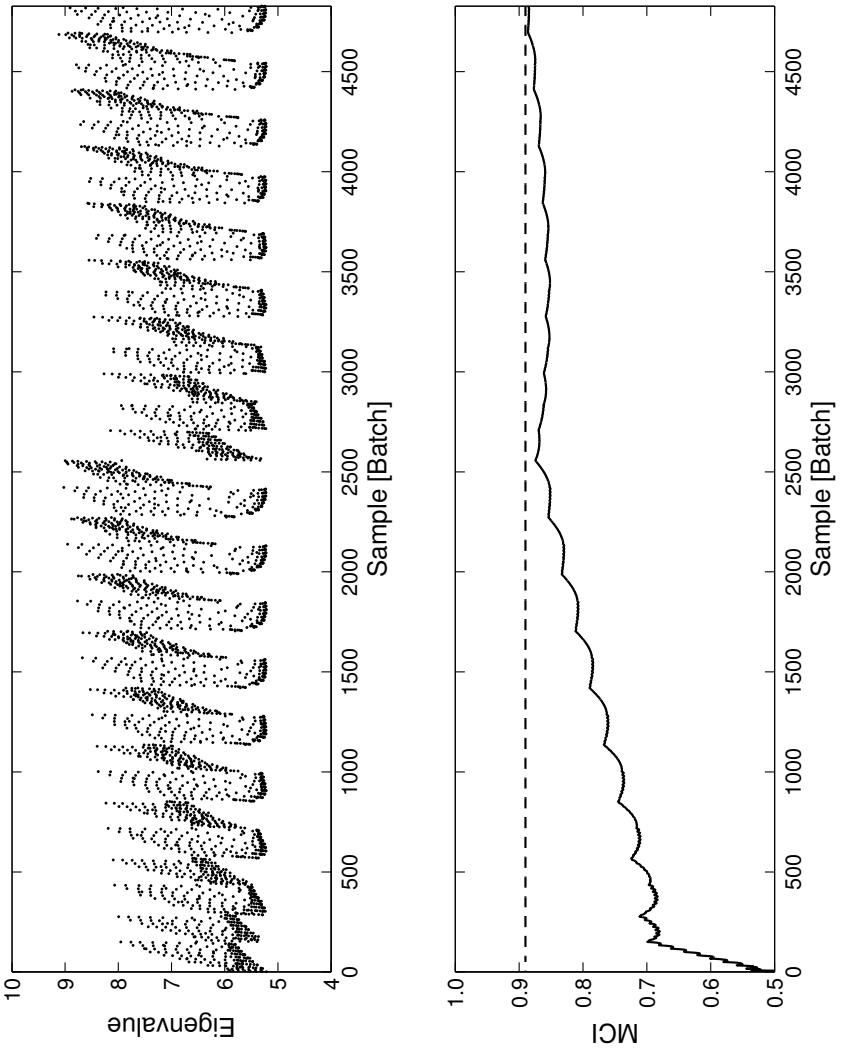


Figure 6.4: MCI calculations for a 4x4 Matrix, Eigenvalue (top), Mean Consistency Index (bottom)

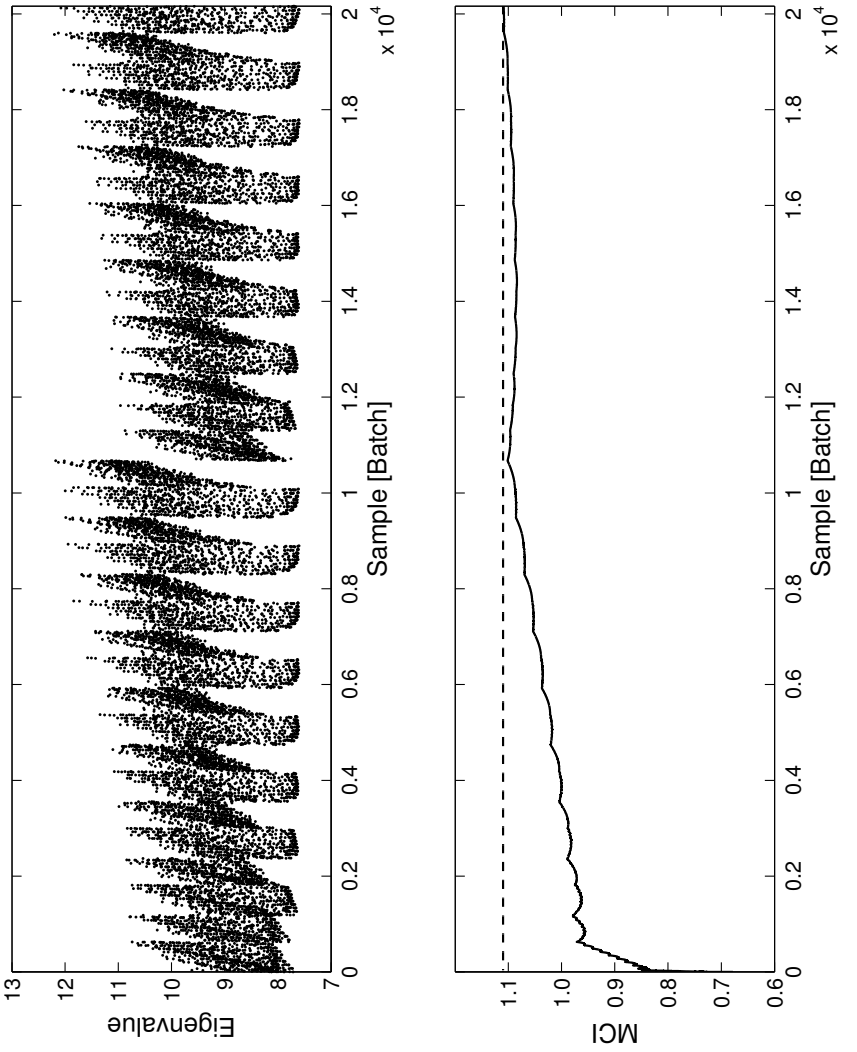


Figure 6.5: MCI calculations for a 5x5 Matrix, Eigenvalue (top), Mean Consistency Index (bottom)

6.4 Metric Value Translations

As pointed out before, the challenge of handling metric values (e.g originally from measurements) to a 9-point scale and a subsequent determination of the value a_{ij} arises.

Let our metric values be denoted as $\mathbb{Q}$ representing a set of numbers in decimal representation by computers. These numbers represent a physical metric value of some sort. The main goal is to translate the metric value into a scale suitable for a MCDM method.

Before the decision model is being used a path must be selected, for which there are four alternatives as shown in Fig. 6.6:

1. Path (a)–(f); the cognitive translation of a value which is directly fed into the AHP, and in this case a scale between 1 (equal importance) and 9 (extreme importance) is used. This step involves no mathematical tools.

2. Path (b)–(e); these metric values are translated with help from *statistics* before being fed into the AHP.

3. Path (b)–(d)–(f); going through statistics and a subsequent translation before entering the AHP. Such a translation can be a simple threshold-based one or based on the Fuzzy Set Theory (FST). In the latter case, the results are called ”fuzzy quantities”.

4. Path (c); the pure user perception and rating is fed into the AHP. This step involves no mathematical tools.

6.4.1 Example of a Simple Translation

Each measured value is checked toward a set of thresholds. Tab. 6.5 shows a simple pseudo-code example in which the value v is chosen based on the interval in which the number of packet losses per observation interval ℓ is found.

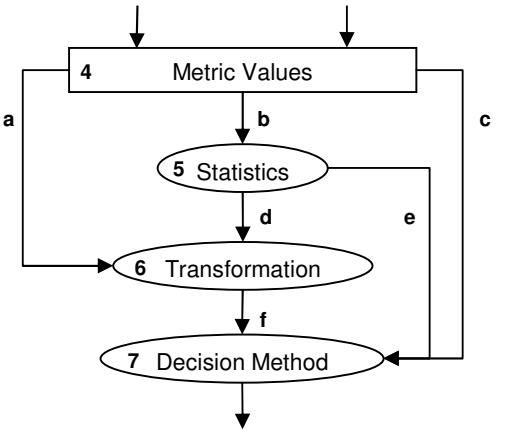


Figure 6.6: Translations paths

Table 6.5: Metric values from packet losses

```
1  if (networkType == Network.WLAN)
   {
3   if (packet_losses > 1)
      v = 3;
5   else if (packet_losses > 3)
      v = 5;
7   else if (packet_losses > 7)
      v = 7;
9   else
      v = 1;}
```

6.4.2 Example of a Fuzzy Translation

Let us again focus on ℓ as introduced in the last subsection. The particular coordinates for the translation based on the membership functions shown in

Table 6.6: A decision matrix with WLAN, UMTS and GPRS

	WLAN	UMTS	GPRS
WLAN	1	a_{12}	a_{13}
UMTS	a_{21}	1	a_{23}
GPRS	a_{31}	a_{32}	1

Fig. 4.4 are given in Equation (6.5). Now, our metric values can be translated with the help of an irregular polygon into a 9-point scale to be used in the AHP decision tool.

$$v = \begin{cases} 1.0 & \text{for} \quad \ell < 0.6 \\ \frac{1.5-1.0}{1.1-0.6} \cdot (\ell - 0.6) + 1.0 & \text{for} \quad 0.6 \leq \ell < 1.1 \\ \frac{3.8-1.5}{1.8-1.1} \cdot (\ell - 1.1) + 1.5 & \text{for} \quad 1.1 \leq \ell < 1.8 \\ \frac{5.2-3.8}{2.3-1.8} \cdot (\ell - 1.8) + 3.8 & \text{for} \quad 1.8 \leq \ell < 2.3 \\ \frac{8.6-5.2}{5.6-2.3} \cdot (\ell - 2.3) + 5.2 & \text{for} \quad 2.3 \leq \ell < 5.6 \\ \frac{9.0-8.6}{6.2-5.6} \cdot (\ell - 5.6) + 8.6 & \text{for} \quad 5.6 \leq \ell < 6.2 \\ 9.0 & \text{for} \quad 6.2 \leq \ell \end{cases} \tag{6.5}$$

6.4.3 Comparison

We now focus on the processing of data coming from the above-described translation step, cf. link (f) in Fig. 6.6. The elements of an attribute matrix, as shown in Tab. 6.6, $\mathbf{A}^{\mathrm{A}kl}$ are calculated as described in Tab. 6.7 based on the following comparisons: (1) WLAN–UMTS ($a_{12}^{\mathrm{A}kl}$) and UMTS–WLAN ($a_{21}^{\mathrm{A}kl}$); (2) WLAN–GPRS ($a_{13}^{\mathrm{A}kl}$) and GPRS–WLAN ($a_{31}^{\mathrm{A}kl}$); (3) UMTS–GPRS ($a_{23}^{\mathrm{A}kl}$) and GPRS–UMTS ($a_{32}^{\mathrm{A}kl}$). In the remainder of this subsection, the indexes $^{\mathrm{A}kl}$ will be omitted.

The comparison between the WLAN and the UMTS is represented by the

Table 6.7: Comparison of translated values.

```
1   a = v1 - v2; // WLAN - UMTS
    if (a >= 0)
3    a12 = a + 1;
    else
5    a12 = 1 / (ABS(a) + 1);
    a21 = 1/a12;
7
    b = v1 - v3; // WLAN - GPRS
9   if (b >= 0)
     a13 = b + 1;
11  else
     a13 = 1 / (ABS(b) + 1);
13  a31 = 1/a13;

15  c = v2 - v3; // UMTS - GPRS
    if (c >= 0) {
17   a23 = c + 1;
    else
19   a23 = 1 / (ABS(c) + 1);
    a32 = 1/a23;
```

local variable a, see Tab. 6.7 line 1. If the value is positive, the global variable a_{12} is set to the calculated value as in line 3. If the value is negative the global variable a_{12} is set to the calculated value as in line 5. The opposite value is translated and saved as shown in line 6. These values are later used in the AHP. This is also done for the combinations WLAN–GPRS and UMTS–GPRS. The next chapter will present tangible examples.

6.5 Summary

This chapter presents a practical decision model to determine the proper network link in consideration of the trade-off between metrics and performance. The method is based on a MCDM, namely the AHP, which is a known decision method. From the outcome of the model it is possible to offer necessary bandwidth and to help users to choose the correct and most efficient decision of the network links available based on a desirable QoS.

The method described in this chapter is normally used for management and business decisions in which the human aspect is involved. However, we have shown that the decision method is useful even for a technical application in the telecommunication area to determine the appropriate connection between different alternatives. This will be illustrated further in the next chapter.

Chapter 7

Case Study

Case study is an ideal methodology when a holistic, in-depth investigation is needed.
Feagin, Orum, & Sjöberg, 1991

This chapter presents a case study of Always Best Connected (ABC) using streaming and messaging services. Two scenarios are described: First, a basic scenario which gives us the fundamental weights between the criteria and technologies, and, second, a scenario in which the WLAN is malfunctioning. For these scenarios the outcomes in terms of reaching the best technology are described. Finally a description of how the algorithm could be implemented into a real code implementation is given.

7.1 Introduction

In this example our criteria, which were defined in Section 3, are added relative comparative linguistic values or scores. To be able to reach the goal of being ABC three groups have been defined: *performance*, *cost*, and *accessibility*. (1) Performance refers to inner criteria related to properties of data transportation as observed from a-priory measurements (static) [30] or from on-line end-to-end monitoring (dynamic) [18]. In this case a decision is made of how to select the best alternative with respect to the necessary and most efficient network link.

7.2 Streaming and Messaging Services

We consider a case study addressing two types of Generic Service (GS), a streaming service and a messaging service. Tab. 7.1 shows the performance criteria settings in the matrix $\mathbf{A}^{\mathrm{C1}}$. As a streaming service needs to behave well while in operation, the importance of the dynamic criteria (throughput, losses, RTT) is in general higher than the importance of the static ones, which is reflected in values $a_{ij}^{\mathrm{C1}} < 1$. Measured throughput and loss statistics are of similar importance ($a_{i4}^{\mathrm{C1}} \equiv a_{i5}^{\mathrm{C1}}$ for $i \leq 3$) and much more relevant than the RTT ($a_{46}^{\mathrm{C1}} = a_{56}^{\mathrm{C1}} = 5$). Regarding cost (matrix $\mathbf{A}^{\mathrm{C2}}$), a volume-based fee is much more critical than a time-based one ($a_{12}^{\mathrm{C2}} = 9$). The relevance of the security overhead is considered to lie in-between that of the other two parameters ($a_{13}^{\mathrm{C2}} = 1/5, a_{23}^{\mathrm{C2}} = 5$). Finally, the interference is considered as important as the coverage area (matrix $\mathbf{A}^{\mathrm{C3}}$ with $a_{12}^{\mathrm{C3}} = 1$).

For a messaging service, things look different, cf. Tab. 7.2. Here, the ID is of high to utmost importance ($a_{1j}^{\mathrm{C1}} > 1$) due to the short-lived nature of the message delivery. The latter also makes a-priori measured static parameters much more relevant than dynamic parameters. For the same reason, capacity and throughput values are less important than losses and RTTs. Regarding cost, the time-based aspect is quite uncritical ($a_{12}^{\mathrm{C2}} = 9, a_{23}^{\mathrm{C2}} = 1/9$), while

Table 7.1: Comparison of performance criteria for streaming service

	ID	LC	DL	Throughput	Losses	RTT	
ID	1	1/5	1/5	1/7	1/7	1/3	0.033
LC	5	1	1	1/5	1/5	1	0.092
DL	5	1	1	1/5	1/5	1	0.092
Throughput	7	5	5	1	1	5	0.352
Losses	7	5	5	1	1	5	0.352
RTT	3	1	1	1/5	1/5	1	0.080
Sum	28.000	13.200	13.200	2.743	2.743	13.333	
$\lambda_{max} = 6.236, \text{CI} = 0.047, \text{CR} = 0.038$							

the security overhead can be of particular importance ($a_{13}^{\text{C2}} = 1/3$). Again, interference is considered as important as the coverage area ($a_{12}^{\text{C3}} = 1$).

Table 7.2: Comparison of performance criteria for messaging service

	ID	LC	DL	Throughput	Losses	RTT	
ID	1	7	3	7	5	3	0.421
LC	1/7	1	1/5	1	1/5	1/7	0.037
DL	1/3	5	1	3	1	1/3	0.130
Throughput	1/7	1	1/3	1	1/5	1/5	0.041
Losses	1/5	5	1	5	1	1	0.154
RTT	1/3	7	3	5	1	1	0.216
Sum	2.152	26.000	8.533	22.000	8.400	5.676	
$\lambda_{max} = 6.293, \text{CI} = 0.059, \text{CR} = 0.047$							

The consistency ratios for both matrices shown in Tab. 7.1 and 7.2 lie well below the critical upper limit of 10 %.

7.2.1 Basic Scenario

We now look at a scenario in which a streaming service has the possibility to use either WLAN, UMTS and GPRS. From the results in [30], we deduce the following static performance-related matrices $\mathbf{A}^{\text{A}kl}$:

$\mathbf{A}^{A11}$ Regarding ID, WLAN is much faster than UMTS ($a_{12}^{A11} = 7$) and notably faster than GPRS ($a_{13}^{A11} = 3$). UMTS can be much slower than GPRS ($a_{23}^{A11} = 1/5$), see Tab. 7.3.

Table 7.3: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of performance (static), Initial Delay with normalized weights

Performance (Static)

Initial Delay	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	7	3	0.643
UMTS	1/7	1	1/5	0.074
GPRS	1/3	5	1	0.283
Sum	1.476	13.000	4.200	

$\lambda_{max} = 3.065, \text{CI} = 0.032, \text{CR} = 0.062$

$\mathbf{A}^{A12}$ Regarding LC, WLAN offers much more bandwidth than UMTS ($a_{12}^{A12} = 5$), which in turn offers much more bandwidth than GPRS ($a_{23}^{A12} = 5, a_{13}^{A12} = 9$), see Tab. 7.4.

$\mathbf{A}^{A13}$ Regarding DL, WLAN is considered better than UMTS ($a_{12}^{A13} = 3$), and both outperform GPRS ($a_{13}^{A13} = 5, a_{23}^{A13} = 3$), see Tab. 7.5.

In the basic scenario, we assume that the monitoring does not display any performance problems. This means:

$\mathbf{A}^{A14}$ No particularities regarding throughput are observed, i.e. all attributes are considered equal ($a_{12}^{A14} = 1$, $a_{13}^{A14} = 1$ and $a_{23}^{A14} = 1$), see Tab. 7.6.

$\mathbf{A}^{A15}$ The same holds for losses, ($a_{12}^{A15} = 1$, $a_{13}^{A15} = 1$ and $a_{23}^{A15} = 1$), see Tab. 7.7.

Table 7.4: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of performance (static), Link Capacity with normalized weights

Performance (Static)

Link Capacity	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	5	9	0.723
UMTS	1/5	1	5	0.216
GPRS	1/9	1/5	1	0.061
Sum	1.311	6.200	15.000	

$\lambda_{max} = 3.117, \text{CI} = 0.059, \text{CR} = 0.113$

Table 7.5: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of performance (static), Directional Loss with normalized weights

Performance (Static)

Directional Loss	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	3	5	0.633
UMTS	1/3	1	3	0.260
GPRS	1/5	1/3	1	0.106
Sum	1.533	4.333	9.000	

$\lambda_{max} = 3.039, \text{CI} = 0.019, \text{CR} = 0.037$

$\mathbf{A}^{\text{A16}}$ RTT differ by nature; WLAN displays shorter RTT values as UMTS ($a_{12}^{\text{A16}} = 5$), which in turn outperforms GPRS ($a_{13}^{\text{A16}} = 9, a_{23}^{\text{A16}} = 5$), see Tab. 7.8.

Table 7.6: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of performance (dynamic), throughput with normalized weights

Performance (Dynamic)

Throughput	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	1	1	0.333
UMTS	1	1	1	0.333
GPRS	1	1	1	0.333
Sum	3.000	3.000	3.000	

$\lambda_{max} = 3.000, \text{CI} = 0.000, \text{CR} = 0.000$

Table 7.7: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of performance (dynamic), losses with normalized weights

Performance (Dynamic)

Losses	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	1	1	0.333
UMTS	1	1	1	0.333
GPRS	1	1	1	0.333
Sum	3.000	3.000	3.000	

$\lambda_{max} = 3.000, \text{CI} = 0.000, \text{CR} = 0.000$

Table 7.8: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of performance (dynamic), round trip time with normalized weights

Performance (Dynamic)

Round Trip Time	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	5	9	0.723
UMTS	1/5	1	5	0.216
GPRS	1/9	1/5	1	0.061
Sum	1.311	6.200	15.000	

$\lambda_{max} = 3.117, \text{CI} = 0.059, \text{CR} = 0.113$

Looking at cost, we can state the following:

$\mathbf{A}^{\text{A21}}$ The TBF for WLAN is usually higher than for UMTS and GPRS ($a_{12}^{\text{A21}} = 1/3, a_{13}^{\text{A21}} = 1/3$), which in turn use to be equally expensive ($a_{23}^{\text{A21}} = 1$), see Tab. 7.9.

$\mathbf{A}^{\text{A22}}$ Modern subscriptions imply flat rates, which is reflected in equal attributes ($a_{12}^{\text{A22}} = 1$, $a_{13}^{\text{A22}} = 1$ and $a_{23}^{\text{A22}} = 1$), see Tab. 7.10.

$\mathbf{A}^{\text{A23}}$ Overhead, introduced by security, has a lower impact for WLAN than for UMTS ($a_{12}^{\text{A23}} = 3$) and especially for GPRS ($a_{13}^{\text{A23}} = 5, a_{23}^{\text{A23}} = 3$), see Tab. 7.11.

Regarding accessibility, we assume:

$\mathbf{A}^{\text{A31}}$ There is no coverage problem which means that all attributes are considered equal ($a_{12}^{\text{A31}} = 1$, $a_{13}^{\text{A31}} = 1$ and $a_{23}^{\text{A31}} = 1$), see Tab. 7.12.

$\mathbf{A}^{\text{A32}}$ There is neither any problem with interference ($a_{12}^{\text{A32}} = 1$, $a_{13}^{\text{A32}} = 1$ and $a_{23}^{\text{A32}} = 1$), see Tab. 7.13.

Table 7.9: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of cost, time-based fee with normalized weights

Cost				
Time-Based Fee	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	1/3	1/3	0.143
UMTS	3	1	1	0.429
GPRS	3	1	1	0.429
Sum	7.000	2.333	2.333	

$\lambda_{max} = 3.000, \text{CI} = 0.000, \text{CR} = 0.000$

Table 7.10: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of cost, volume-based fee with normalized weights

Cost				
Volume-Based Fee	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	1	1	0.333
UMTS	1	1	1	0.333
GPRS	1	1	1	0.333
Sum	3.000	3.000	3.000	

$\lambda_{max} = 3.000, \text{CI} = 0.000, \text{CR} = 0.000$

Table 7.11: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of cost, security with normalized weights

Cost

Security	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	3	5	0.633
UMTS	1/3	1	3	0.260
GPRS	1/5	1/3	1	0.106
Sum	1.533	4.333	9.000	

$\lambda_{max} = 3.039, \text{CI} = 0.019, \text{CR} = 0.037$

Table 7.12: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of accessibility, coverage area with normalized weights

Accessibility

Coverage Area	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	1	1	0.333
UMTS	1	1	1	0.333
GPRS	1	1	1	0.333
Sum	3.000	3.000	3.000	

$\lambda_{max} = 3.000, \text{CI} = 0.000, \text{CR} = 0.000$

Table 7.13: Pair-wise comparison of the alternatives WLAN, UMTS, and GPRS in terms of accessibility, interference with normalized weights

Accessibility

Interference	WLAN	UMTS	GPRS	Normalized Weights
WLAN	1	1	1	0.333
UMTS	1	1	1	0.333
GPRS	1	1	1	0.333
Sum	3.000	3.000	3.000	

$\lambda_{max} = 3.000, \mathrm{CI} = 0.000, \mathrm{CR} = 0.000$

Tab. 7.14 shows the vectors $\mathbf{w}^{\mathrm{D}1}$, $\mathbf{w}^{\mathrm{D}2}$ and $\mathbf{w}^{\mathrm{D}3}$ as well as the average rating $\mathbf{w}^{\mathrm{D}}$ according to Eqn. (6.4). Performance shows the highest value for WLAN (0.438) as compared to UMTS and GPRS due to the outstanding static performance and the low RTT. Costs show the highest value for UMTS (0.349) compared to GPRS and WLAN due to the compromise between TBF and the limited impact of the overhead for security. Accessibility shows the same value (0.333) due to the same conditions for all technologies. Considering the average weights, the priority of choosing networks is (1) WLAN, (2) UMTS and (3) GPRS.

Let us now turn to the messaging service. As messages are short, the difference in link capacities is assumed to have a negligible impact. This implies $a_{12}^{\mathrm{A}12} = 1$, $a_{13}^{\mathrm{A}12} = 1$ and $a_{23}^{\mathrm{A}12} = 1$. The remaining matrices $\mathbf{A}^{\mathrm{A}kl}$ are the same as for the streaming service.

Tab. 7.15 shows the outcomes. Again, WLAN is considered outstanding regarding performance (0.587), and UMTS wins the cost battle (0.363). The average rating prioritizes WLAN before UMTS and GPRS. The latter are ranked quite similarly. The cost advantage for UMTS (smaller impact of the

Table 7.14: Ranking for Streaming Service in Basic Scenario

	WLAN	UMTS	GPRS
Performance	0.438	0.298	0.264
Cost	0.311	0.349	0.340
Accessibility	0.333	0.333	0.333
Preference Ratio	0.361	0.327	0.312

security overhead) is eaten up by worse performance mainly due to long IDs. Accessibility shows the same value (0.333) due to the same conditions for all technologies. Considering the average weights, the priority of choosing networks is (1) WLAN, (2) UMTS and (3) GPRS.

Table 7.15: Ranking for Messaging Service in Basic Scenario

	WLAN	UMTS	GPRS
Performance	0.587	0.189	0.224
Cost	0.320	0.363	0.317
Accessibility	0.333	0.333	0.333
Preference Ratio	0.413	0.295	0.291

7.2.2 Malfunctioning WLAN

Let us now assume that our WLAN access experiences serious performance and accessibility problems due to heavy usage and interference in the 2.4 GHz Industrial Scientific and Medical (ISM)-band. This is reflected in the following settings:

$\mathbf{A}^{\mathrm{A14}}$ Very bad WLAN throughput ($a_{12}^{\mathrm{A14}} = 1/7$, $a_{13}^{\mathrm{A14}} = 1/3$ and $a_{23}^{\mathrm{A14}} = 1$).

$\mathbf{A}^{A15}$ Many losses on the WLAN, which implies $a_{12}^{A15} = 1/9$, $a_{13}^{A15} = 1/9$ and $a_{23}^{A15} = 1$.

$\mathbf{A}^{A16}$ RTT via WLAN in the order of that on UMTS: $a_{12}^{A16} = 1, a_{13}^{A16} = 1/5, a_{23}^{A16} = 5$.

$\mathbf{A}^{A31}$ Problems with WLAN coverage: $a_{12}^{A31} = 1/5, a_{13}^{A31} = 1/5, a_{23}^{A31} = 1$.

$\mathbf{A}^{A32}$ Problems with interference in the 2.4 GHz ISM band: $a_{12}^{A32} = 1/5, a_{13}^{A32} = 1/5, a_{23}^{A32} = 1$.

From Tab. 7.16, we observe that WLAN dropped seriously in performance and that UMTS turned out best in all aspects for the streaming service. For the messaging service, see Tab. 7.17, UMTS and GPRS are almost equal, which again can be related to the better performance of GPRS regarding ID.

Table 7.16: Ranking for Streaming Service, Malfunctioning WLAN

	WLAN	UMTS	GPRS
Performance	0.206	0.445	0.349
Cost	0.319	0.347	0.334
Accessibility	0.091	0.455	0.455
Preference Ratio	0.205	0.416	0.379

Table 7.17: Ranking for Messaging Service, Malfunctioning WLAN

	WLAN	UMTS	GPRS
Performance	0.402	0.309	0.289
Cost	0.320	0.363	0.317
Accessibility	0.091	0.455	0.455
Preference Ratio	0.271	0.376	0.353

7.3 Implementation

Three types of criteria are implemented and connected to the AHP: *throughput* (arrival of packets), *losses* (arrival of packets and ping packets) and the RTT (arrival of packets and ping packets). The throughput criterion could further be refined by using e.g. average and standard deviation, see Section 3.6. Next are the packet losses which are connected to the main stream of packets and message packets, see Section 6.4. Finally, we have the RTT which is also connected to the main stream of packets and message packets. All these criteria are implemented and runnable.

7.4 Summary

In this chapter a case study was performed for both a Streaming Service and Messaging Service. This was derived with the help of a MCDM tool to make a choice based on the following alternatives: WLAN, UMTS, and GPRS. The case study further contained a couple of criteria that were prioritized with respect to the overall goal of Always Best Connected (ABC) and other metrics and which were also weighted against the alternatives. Finally in the case study, the best network link was selected.

For both the Streaming Service (SS) and the Messaging Service (MS) the equilibrium is shown in the basic scenario. In both cases the WLAN is the best alternative followed by the UMTS and the GPRS. In the malfunctioning WLAN scenario the UMTS is the best choice followed by the GPRS.

Chapter 8

Roaming Strategy

You can not control what you can not measure. Measurement is the prerequisite to management control.

Tom DeMarco (1982)

At this point we have a priority list of our choices. The roaming strategy is the ultimate step before executing the final decision regarding which network to choose. The chapter begins with an introduction followed by a description of the roaming strategy. Next, the two decision algorithms are presented; one is a simple decision method and one is a more advanced decision method that includes the Analytic Hierarchy Process (AHP) algorithm. Finally, a description of our implementations and the communication management system is given.

8.1 Introduction

At this point, the AHP has helped us to select a network link. It is time to decide upon a roaming strategy, meaning that we need to define the number of network links, how these links will be managed, and also how to use the previous information in a strategical way before taking any decisions.

The roaming strategy is the process on which the entire seamless connections concept is based. Even if all relevant criteria would be well chosen and the networks would be monitored constantly, the very decision of when and which network link to use is vitally important. Another major advantage regarding the roaming strategy is the ability to exchange the decision method as required. In the thesis two decision methods are presented, one simple and one more advanced. The simple decision method is based on manual ranking of the parameters used and the advanced decision method on the AHP, which was previously described in Chapter 6.

The scale is also part of the roaming strategy. In the case of using a 3-point scale, the color GREEN is equal to *good connectivity* and is related to an *appropriate* network link; the color YELLOW is equal to *connectivity with potential problems or shortcomings regarding performance* and is related to a *limited appropriate* network link; and the color RED is equal to *insufficient connectivity* and is related to be a *not appropriate* network link. This rather simple decision system is mainly aimed at human perception and demonstrations [107].

8.2 The Structure

The three main building blocks of the structure shown in Fig. 8.1 are as follows: the *application box*, the *virtual network driver* called TAP, see Chapter 9, and the *Network Selection Box (NSB)*.

The application comprises Generic Service, the QoS needs and the data, see Fig. 8.1 (top). QoS needs are directly connected to the NSB and are

currently dependent on three different types of GSs: *streaming*, *messaging* and *interactive* services. The application box is the interface between the end-user and the NSB. The end-user is also bidirectionally connected to the NSB through the application box. The big arrow directed downwards between the end-user and the NSB is used for direct interactions affecting the final decision. The big arrow directed upwards between the end-user and the NSB is used for feedback information. The application can of course do without a roaming strategy. However, its type (GS) and its needs are extremely important to arrive to the right decision regarding manual ranking. Application in our context refers to the functions and information that interact with the network selection. Finally, the small arrow directed upwards between the end-user and the NSB is the data itself.

The application box is divided into two parts: the data itself and the QoS needs. In the case of streaming video service the distortion could be high and the reason for that could be e.g. jitter, packet loss, and insufficient buffer size. In this situation the end-user perceives the outcome of a decision but does not necessarily see the reason for the behavior. In this model, these types of problems will be handled by the AHP. Still, the end-user will be informed about the problem and able to decide whether to take over control.

Between the application box and the NSB, the TAP driver is located. The TAP driver is the enabler of seamless communications, as it hides the socket connection from the upper layer, in this case the application box. More information on its implementation and application can be found in Chapter 9.

The NSB alone is responsible for both handling the data and taking the decision when to switch between different connections. The NSB is located between the application box and the network links, see Fig. 8.1 (right-side), and is responsible for choosing the adequate network for the service used by the end-user. It consists of five parts: the *roaming policy*, the *link parameters* data base, the *link monitor* data base, the *Switch Control Unit* and the *Network Selection Algorithm*. The roaming policy is based on already stated priorities

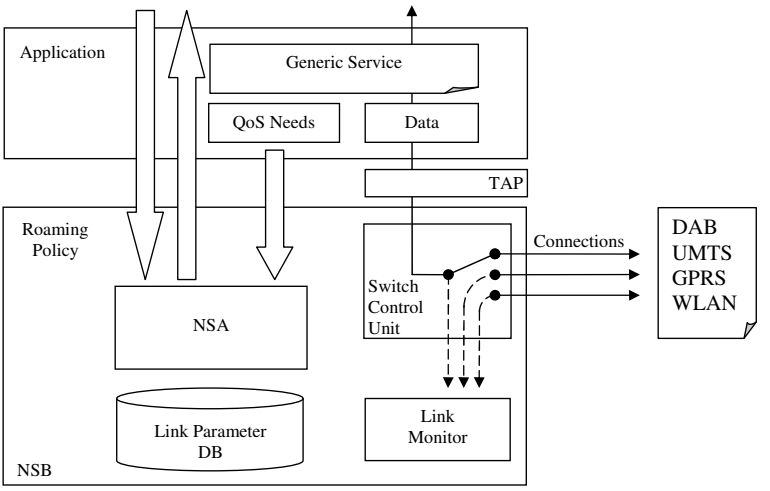


Figure 8.1: The main blocks of the roaming strategy

reflecting experienced performance from initial measurements [4, 29, 30, 62]. The *link parameter DB* stores related static information while the *link monitor* stores all the dynamic values. The Switch Control Unit (SCU) is the place of the actual switching between the network links.

8.3 The Manual Ranking

First, a simple method is presented, which is the manual ranking decision method. The basic idea is to have a manual and static ranking based on different GSs like *streaming*, *messaging* and *interactivity* readily defined, see Section 2.4. The structure of the roaming strategy is based on three horizontal layers and two vertical groups, see Fig. 8.2.

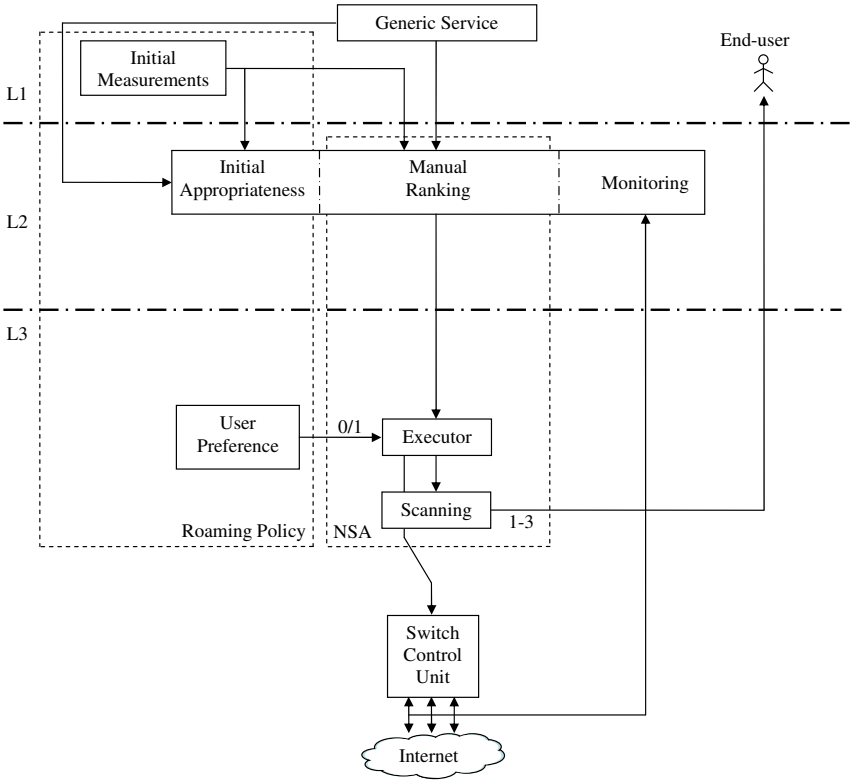


Figure 8.2: Roaming strategy using manual ranking

8.3.1 The Roaming Strategy

The roaming strategy is divided into two vertical groups; the *roaming policy* and the *Network Selection Algorithm (NSA)*. The roaming policy defines the predefined setting for our initial measurements, user preference and the initial appropriateness box. The NSA consists of the decision algorithm, the executor and the scanning box. Inside the NSA they constitute the core of all decisions inside the NSB. The decision method is interchangeable.

The roaming strategy is also divided into three horizontal layers as follows:
Layer 1 consists of external factors and players such as:

- the GS with its communication characteristics and principal communication needs;
- the initial measurements;
- the end-user who is interested in the outcome of the selection process and who has the possibility to make the final decision of a network link.

Layer 2 consists of the very ranking method:

- manual ranking, a rather simple method, which takes the needs of the GS and the corresponding experiences of the initial measurements into account; this manual ranking is assisted by
  - the evaluation of initial appropriateness and
  - the monitoring of properties of the network traffic that are relevant to the ABC decisions;

In **Layer 3** we find functions related to the execution of the network switch:

- the end-user is able to interact with the final decision through the user preference box;
- the executor uses the outcome of the manual ranking based on the evaluation of the appropriateness in combination with monitoring;
- the scanning box uses the outcome from the executor to send back information to the end-user in a 3-point scale, in this case GREEN, YELLOW or RED for each network link;
- the Switch Control Unit (SCU) has the responsibility to support the decision once it is taken, more information on how this is realized is found in Chapter 9.

8.3.2 Initial Appropriateness

Without a service specified together with a mobility scenario, it is hard to make an optimal decision [48], see Section 2.4. First we have to give each network link a color which is defined in the initial appropriateness box. Moreover, we have to consider the throughput time budget for each technology. The selected colors on the GS are GREEN, YELLOW or RED as described before.

Initialization

First we have to initialize the current status with the proper color, see Tab. 8.1. The definition of the current status is saved in the `_Status` vector (line 1). A second vector `best[i]` stores the outcome of the evaluation of the initial appropriateness for each network, coded by the index `i`. Third comes the predefined priorities `prio[i]` (line 16), based on experience from the initial measurements. The structure handles parameters related to the key parameters (lines 4–11) obtained from initial measurements as well as from monitoring. These parameters are `R_min`, `Delta_T`, `ID`, `monStatus_client`, `monStatus_server` and `Status`. Each technology is evaluated in advance, and simple estimations of these parameters are listed as follows:

- `R_min` is the parameter for the boundary of the minimum throughput in bps during `Delta_T` for each technology. These are approximate values from our initial measurements;
- the `Delta_T` parameter uses 1 s for WLAN and UMTS, as well as 2 s for GPRS. The latter choice is based on the observation that even though data had been sent continuously, there were many empty intervals of duration 1 s at the receiver, which would imply `R_min` = 0;
- Initial Delay (ID) uses 1 s for WLAN, 2 s for GPRS, 7 s for UMTS [30];
- the `monStatus_client` handles the monitored values from the client side;

- the `monStatus_server` handles the monitored values from the server side;
- the `Status` parameter for both the client and server indicates the color as described before.

Table 8.1: Initialization

```
enum _Status {GREEN, YELLOW, RED};
enum _Status best[i];

struct{
 double R_min;
 double Delta_T;
 double ID;
 enum _Status monStatus_client;
 enum _Status monStatus_server;
 enum _Status Status;
} NetwData;

struct NetwData* GPRS = new struct NetwData;
struct NetwData* UMTS = new struct NetwData;
struct NetwData* WLAN = new struct NetwData;
struct NetwData* prio[i];

GPRS->R_min = 2000;  // bps
GPRS->Delta_T = 2;   // s
GPRS->ID = 2;        // s
UMTS->R_min = 20000; // bps
UMTS->Delta_T = 1;   // s
UMTS->ID = 7;        // s
WLAN->R_min = 200000;// bps
WLAN->Delta_T = 1;   // s
WLAN->ID = 1;        // s
```

Interactive Service

For *interactive* services, we denote the response time budget, i.e. the maximal response time allowed for a service, by T_{Resp}. The delay experienced by the service consists of the following components:

- T_{P1} = time for processing the request at the client;
- T_{N1} = time for transmitting the request via the network to the server;
- T_{P2} = time for processing the request at the server and generating the response;
- T_{N2} = time for transmitting the response to the client;
- T_{P3} = time for processing the response at the client.

For the network time budget, this implies the following condition:

$$T_{N1} + T_{N2} \leq \frac{1}{\gamma} \left(T_{Resp} - \sum_{i=1}^{3} T_{Pi} \right) \tag{8.1}$$

where γ represents a safety factor. Obviously, a longer transmission time in one direction can to a certain extent be compensated by a shorter transmission time in the other one.

The interactive service depends on data packets within a specific volume within a specific time frame. Tab. 8.2 provides a code example for how to define the best network. The default technology is WLAN (line 2).

Regarding UMTS and GPRS we have to consider the relationship between throughput and initial delay for both technologies, which is illustrated in Fig. 8.3 applying the values shown in Tab. 8.1. After 2 s at latest, GPRS is assumed to start transmitting at least at 2 kbps. After 7 s at latest, UMTS is assumed to start transmitting at least at 20 kbps. This means that GPRS will most probably deliver the first 1250 B faster than UMTS. The boundary is defined as the point of intersection which is the estimated volume of sent

Table 8.2: Initial Appropriate Interactive Service

```
1  else if (service == INTERACTIVE){
     prio[1] = WLAN;
3    if (volumeSent + volumeReceived < 1250){
       prio[2] = GPRS; prio[3] = UMTS;}
5    else{
       prio[2] = UMTS; prio[3] = GPRS;}
7
   for (i = 1; i <= 3; i++){
9    t_Netw = max(prio[i]->delta_T,
     8*volumeSent / prio[i]->R_min) + max(prio[i]->delta_T,
11   8*volumeRcvd / prio[i]->R_min);
     if (t_Netw + prio[i]->ID <= timeBudget)
13     best[i] = GREEN;
     else
15     best[i] = YELLOW;
```

data, see Fig. 8.3. The ID is the starting value at the x-axis and the volume defines the slope of the line. If the volume is lower than this boundary, GPRS is given precedence over UMTS (line 3) and vice versa (line 6).

In line 9–11, the transmission-related part of network time is estimated for both directions individually. In order to yield a conservative estimation, the minimal throughput `R_min` is used. Moreover, the size of the averaging interval `delta_T` has to be taken as a lower bound per direction, as our throughput estimations relate to this value. This transmission-related part needs to be increased by the initial delay before comparing it to the time budget (line 12). If the time budget is met the parameter `best[i]` is given the color GREEN (line 13), otherwise YELLOW is indicated (line 15).

The outcome from these first steps could be as follows: `prio[1]` = `UMTS` is given the color `best[1]` = GREEN; `prio[2]` = `WLAN` is given the color `best[2]` = GREEN; and `prio[3]` = `GPRS` is given the color `best[3]` = YELLOW, meaning that it fits the later examples.

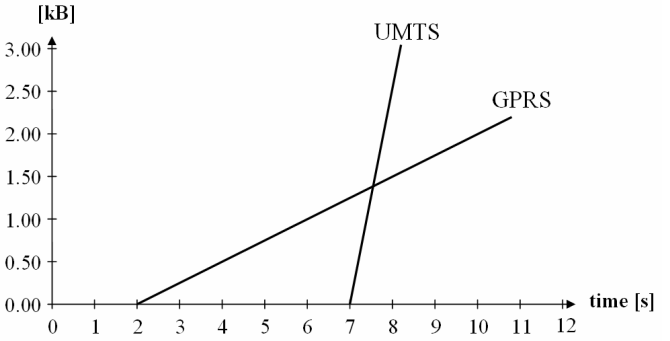


Figure 8.3: Elapsed time vs. throughput between UMTS and GPRS

In order to meet the requirements, the sum of the measured times has to fit into the time budget. In an example similar to the one presented in Fiedler *et al.* [3], see Fig. 8.4, the response time T_{Resp}, see Equation (8.1), is set to 8 s and the request in uplink directions consists of 3000 B, the answer of 4500 B. Processing times sum up to $\sum_{i=1}^{3} T_{Pi} = 2\,\text{s}$, so that the time budget becomes 6 s, divided by the safety factor γ. The application-perceived uplink speed is given by r_{A1} and the application-perceived downlink speed that is *required* to meet the time budget as c_{A2}. The capacity of GPRS using one slot per direction à 9.6 kbps does not even match the basic condition, which means that there is practically no chance of meeting the desired response time. Being able to use four time slots (38.4 kbps) in the downstream direction improves the situation, yielding $\gamma = 1.7$. The latter hints at the fact that a certain time buffer is available.

Messaging Service

A messaging service can be seen as a simplified version of the interacting service employing only one direction. Timely delivery of the message is unimportant. The delivery time budget is denoted by T_{Deliv} and it consists of the

following components:

- T_{P1} = time for processing data at the sender;
- T_N = time for transmitting data via the network;
- T_{P2} = time for processing data at the receiver.

For the application-perceived latency, this implies the following condition:

$$T_N \leq \frac{1}{\gamma}\left(T_{Deliv} - \sum_{i=1}^{2} T_{Pi}\right) \tag{8.2}$$

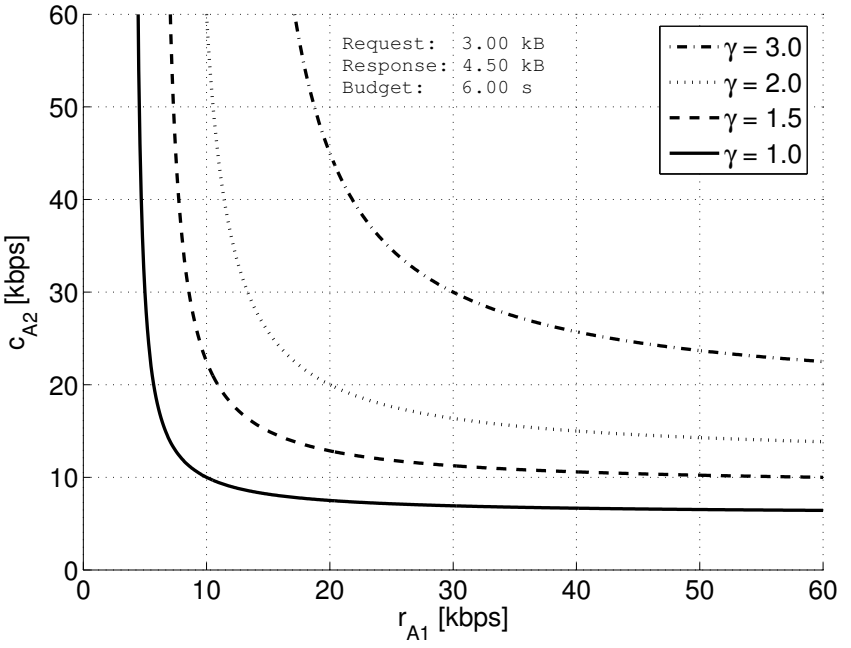


Figure 8.4: Required downlink speeds as function of uplink speeds for different safety factors γ

Table 8.3: Initial Appropriate Messaging Service

```
1  if (service == MESSAGING){
     prio[1] = WLAN;prio[2] = GPRS;prio[3] = UMTS;
3    for (i = 1; i <= 3; i++){
       t_Netw = max(prio[i]->delta_T,8*volumeSent /
5        prio[i]->R_min);

7      if (t_Netw + prio[i]->ID <= timeBudget)
         best[i] = GREEN;
9      else
         best[i] = YELLOW;}
```

The messaging service depends on small data packets within a specific time frame, see Tab. 8.3. The default order is, because of the ID, as follows: WLAN, GPRS and UMTS (lines 1–3). The estimation of the network time (lines 4–5) is done in the same way as for the interactive service, with the only difference being that one direction only is taken into account. If the calculated time is within the time budget (line 7), the color is indicated GREEN (line 8), else the color is indicated YELLOW (line 10).

Streaming Service

Streaming depends on a continuous stream of data packets. For that reason the throughput is more important than anything else, like e.g. initial delay. So, the default priority is as follows: UMTS, WLAN and GPRS (line 2), see Tab. 8.4. The required throughput has to be checked a priori against `R_min` (lines 5, 9, and 13). If the minimal observed throughput during ΔT is not sufficient, the color indicated is YELLOW (lines 8, 12, and 16) instead of GREEN (lines 6, 10, and 14).

If the desired throughput is larger than the capacity (which is not shown explicitly in Tab. 8.5) the network is not selected and will be classified as

Table 8.4: Initial Appropriate Streaming Service

```
1  if (service == STREAMING){
     prio[1] = UMTS;prio[2] = WLAN;prio[3] = GPRS;}
3  for (i = 1; i <= 3; i++){
     best[i] = YELLOW;
5    if (throughput <= UMTS->NetwData.R_min)
       best[1] = GREEN;
7    else
       best[1] = YELLOW;
9    if (throughput <= WLAN->NetwData.R_min)
       best[2] = GREEN;
11   else
       best[2] = YELLOW;
13   if (throughput <= GPRS->NetwData.R_min)
       best[3] = GREEN;
15   else
       best[3] = YELLOW;}
```

non-appropriate, i.e. RED.

8.3.3 Monitoring

The service level of the perceived quality must be maintained by monitoring the flow of data packets. If other connections are monitored as well, the quality of the perceived service could also be reinforced by switching over to another accepted and monitored connection. Each monitored connection is ranked by a color, see Tab. 8.5. Lines 1–2 and 6–7 check the difference between the amount of sent and received packets. If the relative amount of packet loss exceeds a specific threshold the status is indicated as GREEN (line 4). If the amount of received packets as compared to the amount of sent packets exceeds a specific threshold the status is indicated as YELLOW (line 9), otherwise it is RED (line 13).

Table 8.5: Monitoring

```
1  if (number_of_received_packets_within_last_Delta_W/
    number_of_sent_packets_within_last_Delta_W > 0.9)
3  {
    prio[i]->monStatus = GREEN;
5  }
   else if (number_of_received_packets_within_last_Delta_W/
7   number_of_sent_packets_within_last_Delta_W > 0.75)
   {
9   prio[i]->monStatus = YELLOW;
   }
11 else
   {
13  prio[i]->monStatus = RED;}
```

Tab. 8.7 shows the way the monitoring status affects the rating based on the initial evaluation of appropriateness. In principle, the final status cannot be better than the lowest ranked indicated color, see Tab. 8.6. For example, if the parameter `monStatus` were GREEN and the parameter `best` were YELLOW, the outcome would be YELLOW. Assume now that link 1, which originally was ranked the most feasible, gets RED from the monitoring. In this case, the status of link 1 was reduced to RED, and link 2 being the highest-ranked one with GREEN rating would be chosen by the executer. If now also link 2 got RED from the monitoring, link 3, being the only one with YELLOW, would be chosen.

The corresponding code is found in Tab. 8.7. If the monitoring showed best condition (lines 3–6), the former status (best) can be replicated. Otherwise a YELLOW rating can be reduced to RED, while a RED coding is maintained.

Let us assume the following example: network links 1 and 2 are given the color GREEN and network link 3 is given the color YELLOW.

Table 8.6: Status matrix

monStatus	best	Status
GREEN	GREEN	GREEN
GREEN	YELLOW	YELLOW
GREEN	RED	RED
YELLOW	GREEN	YELLOW
YELLOW	YELLOW	YELLOW
YELLOW	RED	RED
RED	GREEN	RED
RED	YELLOW	RED
RED	RED	RED

Table 8.7: Status as a result of investigating initial appropriateness and monitoring

```
1   for (i = 1; i <= 3; i++)
    {
3    if (prio[i]->monStatus == GREEN)
      prio[i]->Status = best[i];
5    else if (prio[i]->monStatus == YELLOW)
     {
7    if (best[i] == RED)
      prio[i]->Status = RED;
9    else
      prio[i]->Status = YELLOW;
11   }
     else
13    prio[i]->Status = RED;
    }
```

8.3.4 User Preference

In some cases the end-user wants to override a decision. In this situation an on/off switch is required which is indicated as 0/1. Before the actual

choice of the network to be used is made, the outcome of the user preference is concatenated with the `status`. If the user decides not to allow a certain network, the corresponding `status` is set to RED, which prevents the executor from choosing this network link.

8.3.5 Executor

Based on the color of each network i found in `prio[i]->status`, the executor selects the network as illustrated in Tab. 8.8. The corresponding pseudo-code is given in Tab. 8.9. The executor tries to find the best GREEN network according to the priorities given in the beginning (lines 1–9). If no such network was found, which is signaled by a value `selected` < 0, the best YELLOW network is looked for (lines 11–17). If also this search was unsuccessful (`selected` < 0), all networks are RED, which means that the executor has to issue a problem report stating that no network connectivity could be chosen (lines 19–20). This implies that a continuous scan for new networks is necessary.

8.3.6 Scanning

The possibility of simultaneous connections is an important aspect in the concept of seamless communications which gives us the possibility of having a fast switch between the network links. The limit or desired number of simultaneous connections could be one, two or three depending on the demands stated by the end-user. We need to look for new networks if the number of connections with a specific quality is not sufficient.

Scanning with no distinction of rank is appropriate if the predefined number of appropriate quality network links with the color GREEN or limited appropriate networks with the color YELLOW is satisfied, see Fig. 8.5. This type of scanning handles only two levels; GREEN and YELLOW are at the same level, and then there is the RED level. If only one network was available, the basic idea is to start *scan* in state π_0 to look for another network.

Table 8.8: Choice matrix for the executer

prio[1]->Status	prio[2]->Status	prio[3]->Status	Choice
GREEN	GREEN	GREEN	1 (GREEN)
GREEN	GREEN	YELLOW	1 (GREEN)
GREEN	GREEN	RED	1 (GREEN)
GREEN	YELLOW	GREEN	1 (GREEN)
GREEN	YELLOW	YELLOW	1 (GREEN)
GREEN	YELLOW	RED	1 (GREEN)
GREEN	RED	GREEN	1 (GREEN)
GREEN	RED	YELLOW	1 (GREEN)
GREEN	RED	RED	1 (GREEN)
YELLOW	GREEN	GREEN	2 (GREEN)
YELLOW	GREEN	YELLOW	2 (GREEN)
YELLOW	GREEN	RED	2 (GREEN)
YELLOW	YELLOW	GREEN	3 (GREEN)
YELLOW	YELLOW	YELLOW	1 (YELLOW)
YELLOW	YELLOW	RED	1 (YELLOW)
YELLOW	RED	GREEN	3 (GREEN)
YELLOW	RED	YELLOW	1 (YELLOW)
YELLOW	RED	RED	1 (YELLOW)
RED	GREEN	GREEN	2 (GREEN)
RED	GREEN	YELLOW	2 (GREEN)
RED	GREEN	RED	2 (GREEN)
RED	YELLOW	GREEN	3 (GREEN)
RED	YELLOW	YELLOW	2 (YELLOW)
RED	YELLOW	RED	2 (YELLOW)
RED	RED	GREEN	3 (GREEN)
RED	RED	YELLOW	3 (YELLOW)
RED	RED	RED	- (RED)

If a network *appears* and a connection is established, this should be kept and runnable until a disconnection is requested or a connection *disappears*. In the case of several available networks an upper limit of the number of simultaneous networks has to be determined in advance. In this case a limit of two is

Table 8.9: Check for appropriate network

```
1   selected = -1;
    for (i = 1; i <= 3; i++){
3
     if (prio[i]->Status == GREEN)
5     {
       selected = i;
7      exit;
      {
9   }

11  if (selected < 0)
     for (i = 1; i <= 3; i++)
13    if (prio[i]->Status == YELLOW)
      {
15     selected = i;
       exit;
17    }

19  if (selected < 0)
     report_problem();
```

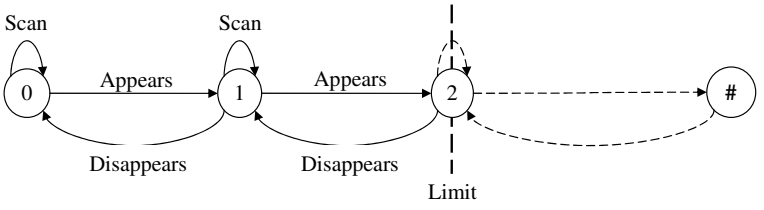


Figure 8.5: Scanning with no distinction of rank

set at state π_2. If two connections are established we are satisfied. Now the process stops. The limit could be changed to a lower or to a higher value. This is decided by the end-user and forms part of the roaming policy. The

upper limit π_{limit} is determined by the number of networks selected. Even if there were more network links available $\pi_{\#}$, we have ended the search for more network links.

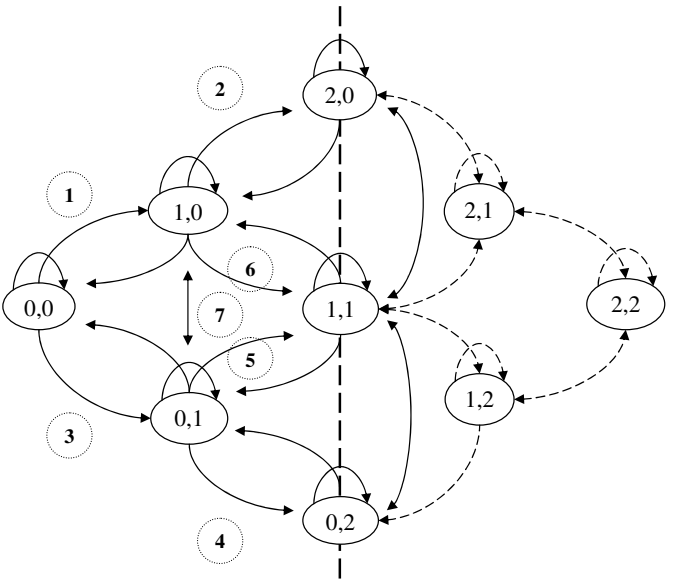


Figure 8.6: Scanning with distinction of rank

In the case of a different rank of network links a state matrix is needed, see Fig. 8.6. The x in $\pi_{x,y}$ indicates the appropriate networks with the color GREEN and the y in $\pi_{x,y}$ indicates the number of limited appropriate networks with the color YELLOW in state $\pi_{x,y}$. A distinction in rank, meaning the difference between GREEN and YELLOW, means that we have a network that is preferable to another network. A state transition between $\pi_{1,0}$ and $\pi_{0,1}$ means a change between an appropriate network and a limited appropriate network. At the limit there are three possible states: state $\pi_{2,0}$ which consists of two appropriate networks, state $\pi_{1,1}$ which consists of one appropriate net-

work and one limited appropriate network, and state $\pi_{0,2}$ which consists of two limited appropriate networks, see Fig. 8.6. The transitions between two states are described as:

1. One new appropriate network found;
2. Another appropriate network found;
3. One new limited appropriate network found;
4. Another limited appropriate network found;
5. A new appropriate network found;
6. A new limited appropriate network found;
7. An appropriate or limited appropriate network is changed to the opposite.

8.4 The AHP Ranking

The advanced roaming strategy, see Fig. 8.7, is based on a 9-point scale, see Chapter 6. Compared to the manual ranking, see Section 8.3, some changes have taken place. Still, layer 1 is the same. The major changes have occurred at layer 2 with some minor changes in layer 3.

Two new boxes needed by the AHP are introduced. A new static criteria box is now the closest box to the left-side of the AHP box. The static criteria box collects information from the GS (1a) and the initial measurements box (2a). This information is later fed into the AHP box (4). A new dynamic criteria box is now the closest box to the right-side of the AHP box. The dynamic criteria box collects information from the GS (1c) and the monitoring box (5a). This information is later fed into the AHP box (3a).

8.4.1 Initial Appropriateness

The initial appropriateness box is now separated from the AHP box, which differs from the manual ranking solution. As opposed to the manual ranking, the initial appropriateness box acts as some kind of ”emergency brake” in case the strategic ranking made by the AHP does not prevent critical choices. The initial appropriateness box is fed by the GS box (1b) and the initial measurements box (2b). The initial appropriateness box delivers two types of scales. The first is fed into the executor box with values, ia[i] = {0 in case of RED, 1 in case of YELLOW and GREEN} (8a). In this situation an on/off situation is given which is indicated as 0/1. RED or 0 are indicated in case of insufficient throughput or if the ID is higher than the time budget, cf. Section 8.3.2. The second scale is fed into the scanning box with values such as RED, YELLOW, or GREEN (8b).

8.4.2 Monitoring

The monitoring box is now also separated from the AHP box as in the manual ranking solution. The monitoring box feeds the executor box (5b) with monitoring information indicating abnormal behavior that might prevent the AHP from skipping the corresponding link. This information is coded as pl[i] = {0 in case of too many sequential packet losses, 1 else}. The dynamic criteria box is now the new receiver from the GS (1c) and the monitoring box (5a) which also feeds the scales into the scanning box (3b) with values such as RED, YELLOW, or GREEN.

8.4.3 User Preference

In some cases the end-user needs to override a decision. In this situation an on/off situation is required which is indicated as 0/1. The user preference box could deliver two types of values, up[i] = {0 in case of user deselection, 1 in case of user selection} (7).

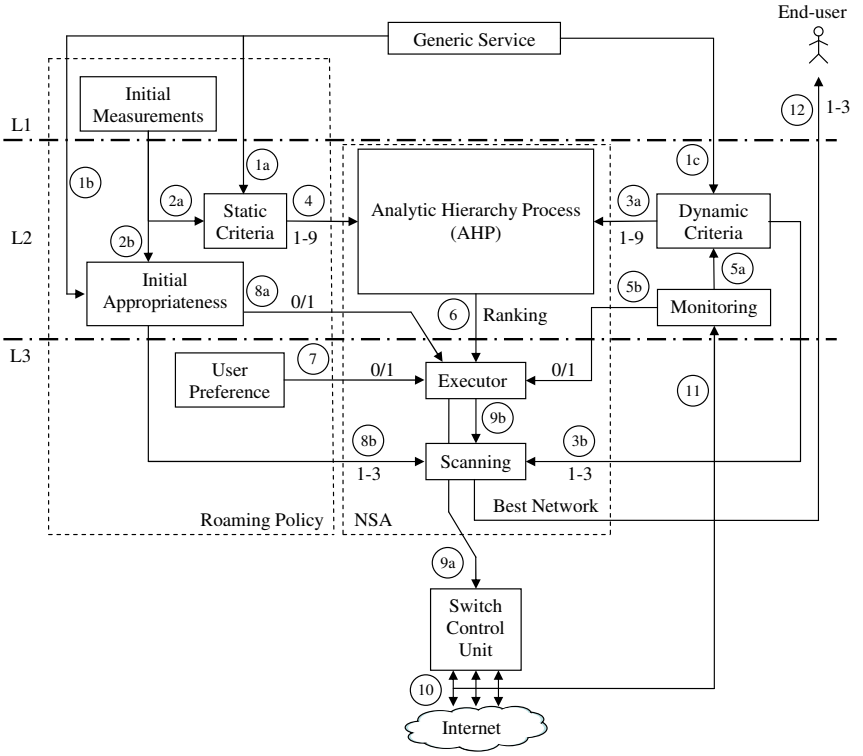


Figure 8.7: Roaming strategy for the AHP

8.4.4 Executor

The network parameter `Network[i]` summarizes the performance, cost and accessibility results from the AHP which will be sorted and selected by the highest score. The parameter `up[i]` (User Preference), `ia[i]` (Initial Appropriateness) and the `pl[i]` (Packet Loss) are the final enablers for selecting a network link. If the parameters `up[i]` or `ia[i]` or `pl[i]` are set to zero the network parameter `Network[i]` is set to zero for that specific network and, thus, it would not be selected. The specific network is now the last one in the sorted

weighted list of all networks and consequently not selected. If the parameters `up[i]`, `ia[i]` and `pl[i]` are set to one the network is one of the candidates, see Tab. 8.10.

Table 8.10: Network selector, the advance decision method

1	`Network[1] = (perf[1]+cost[1]+acce[1]) * up[1] * ia[1] * pl[1];`
	`Network[2] = (perf[2]+cost[2]+acce[2]) * up[2] * ia[2] * pl[2];`
3	`Network[3] = (perf[3]+cost[3]+acce[3]) * up[3] * ia[3] * pl[3];`

The outcome from the executor box is fed into the SCU (9a) which does the switch between the network links (10). The network links are monitored constantly (11). The same information is also fed into the scanning box (9b). Finally, the scanning box presents the behavior of the network links based on information from the initial appropriateness box (8b), the dynamic criteria box (3b) and the executor box (9b).

So far, the AHP together with the 9-point scale have made all the decisions hidden from the end-user. So, the obvious questions is: *how should the results be presented to the end-user?* The end-user needs a scale suitable for the human capacity, see Miller [19]. For that reason the results from the executor (9b) are fed into the scanning box. To be able to handle the different situation of networks, ranking, see Fig. 8.5, and non-ranking, see Fig. 8.6, our networks are defined. To extend the understanding of the information a color system is added, i.e. GREEN, YELLOW, RED. Each color is initially defined in the initial appropriateness box which is fed into the scanning box (8b). The color GREEN is defined as an *appropriate* network. The YELLOW color is defined as a *limited appropriate* network. Finally, the RED color is defined as *unusable*. Also, the dynamic criteria are scaled down to a 3-point scale which is fed into the scanning box (3b). The end-user (12) is presented with the chosen network together with a color status. These are given by the scanning box.

Table 8.11: NSB control messages

Message	Direction	Interface	Explanation
`REGISTER`	Client – Server	NSB – NSB	Register with server and get a virtual IP
`ACKREGISTER`	Server – Client	NSB – NSB	Response to register request
`ADDNET`	Client – Server	NSB – NSB	A new network is available
`REMOVENET`	Client – Server	NSB – NSB	A network was lost
`IAMALIVE`	Client – Server	NSB – NSB	Client is alive and wants to keep his virtual IP
`BYE`	Client – Server	NSB – NSB	Client logging of, release virtual IP
`NETSTAT`	Both ways	NSB – NSB	Network statistics
`ACKNETSTAT`	Both ways	NSB – NSB	Response to `NETSTAT` message
`APPPREF`	App.	App. – NSB	For controlling NSB settings and QoS feedback

8.4.5 Implementation and Communication Management

Both the NSB client and the server were implemented on desktop computers, running the popular Microsoft Windows XP. C# .NET was used as the programming language, see Waltersson [112] and Chevul *et al.* [18].

To assure that packets are sent on the intended interface, a route is created in the routing table for each added network, with the same metric value as the other networks. In this way, Windows will not route packets in an undesirable way. Prior to sending packets, the NSB server refers to the tables in the Controller and the `evaluateSend()` method in the Network Selector to find the best network to use. The NSB client uses a similar table and the `evaluateSend()` method. In this way, the NSB can be seen as a multiplexer.

The NSB uses control messages for communication management between NSB client and server. Furthermore, the control messages are used to monitor network performance. All control messages use the same User Datagram Protocol (UDP) sockets as the data traffic with the exception of the `APPPREF` message, which uses a separate port. Tab. 8.11 lists the control messages.

The two control messages REGISTER and ACKREGISTER are used for address allocation. The client sends a REGISTER request together with information about his first network. The server answers with an ACKREGISTER message containing the virtual Internet Protocol (IP). In this sense the server operates much like a Dynamic Host Configuration Protocol (DHCP) server. The client will keep this address until it disconnects with the control message BYE.

ADDNET and REMOVENET are sent by the client when a new network is connected or when a connection is lost. ADDNET contains the virtual IP of the client, and information about the new network. The REMOVENET message is not that critical, as the server's monitor will discover a network loss anyway within time. It is sent to speed up the server's adoption to the new situation.

IAMALIVE is used by the client to hold on to a virtual IP-address. The server expects all clients to send this message periodically, otherwise it assumes that the client has crashed without notification and releases the client's virtual IP so that others can use it. When the client NSB shuts down normally, it sends a BYE message to tell the server that it does not need its virtual IP anymore.

Applications have the possibility to control the NSB by using the APPPREF control message. The message contains information about the requirements of the application in terms of e.g. performance and cost. This information is used by the Network Selector to find the most suitable network. Applications do not need to control the NSB as the NSB implements automatic network selection. APPPREF are also used by the application in order to inquire the QoS status of the network connection used at the moment.

Through control messages NETSTAT (issued by the sender and including a time stamp) and ACKNETSTAT (issued by the receiver upon reception of a NETSTAT message) the application-level RTT is measured. If no ACKNETSTAT message has been received for a predefined period of time, the packet is considered lost. A specific network is classified as unavailable when a predefined number of ACKNETSTAT is lost. According to our experience, this predefined

number is set to five. However, the value might be further tuned for special network and application scenarios.

In addition, the `NETSTAT` and `ACKNETSTAT` packets contain information about how many packets were sent by the sender and received at the receiver side in the last time period. In this way, packet loss can be measured.

8.5 Summary

As discussed in this section, several important components have to work together to finally reach the goal of ABC. The criteria alone are not sufficient. Correspondingly, the roaming strategy was defined. Its layered structure allows for exchanging the decision algorithm, two of which were discussed in detail. The basic one was a so-called manual ranking algorithm and the advanced one was the AHP. Next, a description of some important parameters used in the initial appropriateness box was given together with the implementation of communication management.

Chapter 9

Switch Control Unit

Science is not merely a collection of empirical facts but the knowledge of how they are causally connected. Knowledge of facts is knowledge of 'things past' but science is knowledge of 'the dependence of one fact upon another' and enables us to predict the future.

Thomas Hobbes (1588 - 1679)

In this chapter the Switch Control Unit (SCU) is described. First, the state of the art is presented to give the background of some of the problems related to mobility issues and the IP-address translation. Finally, a discussion on the IP-address issues and how these are related to the thesis is undertaken.

9.1 Introduction

Finally, almost all pieces are in place. GSs, different wireless technologies and their behaviors have been described, and criteria for network selection have been developed. Different mathematical tools like the FST and the MCDM were used. The final problem now is how the actual switch between the network links should be handled.

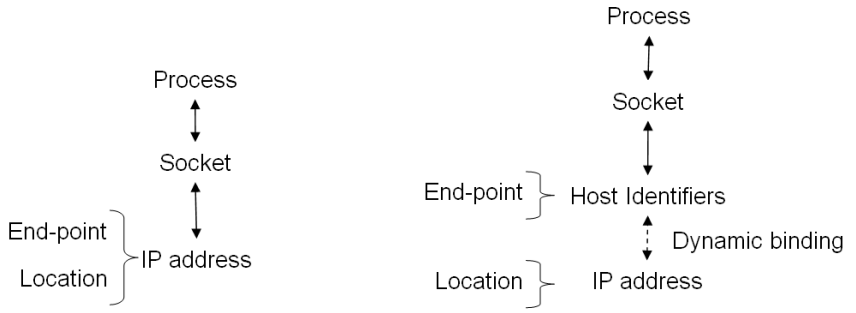
The implementation of seamless communications, in the thesis, requires that two implementation issues be solved: (1) the IP-address issue, and (2) the use of simultaneous connections. The addressing scheme used today is not built for mobility. The Internet is a static network and mobility and changes of the IP address were not considered when the first version of the Internet came out. The current Internet address scheme consists of an identity (the host) and an address (the local net). The key issue is how to divide these. The main problem with the IP-address is that it does not support mobility except in the case of using the same subnet which takes care of the problem in layer 2 of the Open System Interconnection (OSI) model. So, every time the end-user moves to a new location the IP-address changes and the current connection has to be reconnected at layer 3 of the OSI model. The reason is that the transport layer is not able to handle this type of situation while using the current IP implementation.

9.2 State of the Art

Nikander *et al.* [113–115] describe five problems regarding the current Internet system. First, the end-point identifiers, at the host, are heavily connected to the current IP address. Second, home-agent solutions used by Mobile IP can not be fully optimized. Third, it is preferable to allow access control based on cryptography instead of using only an IP-address. Fourth, many security protocols are not able to stop denial-of-service attacks. Finally, the limitation of being anonymous in terms of (location) is not possible if the IP-address

is known. Nikander also describes a new solution called the Host Identity Payload (HIP) as a way of dealing with the IP-address syndrome for mobility. This separates the end-point identifier (the host) and the topological locater which are both based on the IP-address. The new host identity is based on a cryptographic key called a Host Identity Tag (HIT). This tag could be a 128-bit key (SHA-1) or a 32-bit key called the Local Scope Identity (LSI). The HIP protocol is located between the transport layer and the Internet working layer. All incoming and outgoing packets are mapped between an HIP-address and an IP-address.

In the transport layer a 4-tuple socket is created to communicate with the destination; source HI, source port, destination HI, and destination port. This is changed by the network layer to source IP, source port, destination HI, and destination port. For mobility this is important. Now the IP-address could be changed, and still, continuous sending and receiving of packets between the same nodes without disconnection can take place.



(a) Current architecture

(b) New architecture HIP

Figure 9.1: IP address bindings

The current IP-address binding looks as shown in Fig. 9.1 (a). The IP-address combined two things, identity (end-point) and location. The new architecture has divided the meaning of the IP-address into two parts, see

Fig. 9.1 (b). The IP-address is the location. Between the IP-address and the host identifiers there is a dynamic binding. The host identifier is the final end-point to the host.

Comparisons of different implementations of mobility and multi-homing have been made in different papers by e.g. Andersson *et al.* [116]. There are several reasons why end-users would like to have more than one connection. According to Gundu [117] such reasons are e.g. load sharing, service provider selection and enhanced mobility support.

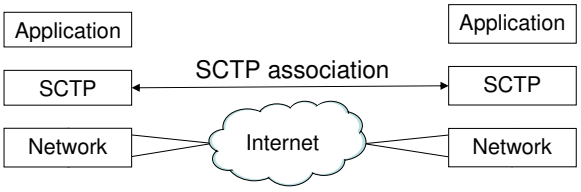


Figure 9.2: SCTP architecture

The Stream Control Transmission Protocol (SCTP), RFC 2960 [118] and RFC 3309 [119], is a new protocol next to the Transmission Control Protocol (TCP) and the UDP, offering more features. Two very important features included are the ability to do multi-streaming and multi-homing. The security is also considered especially regarding flooding and masquerade attacks. One other important feature compared to the TCP is that a connection could have many streams of messages simultaneously within the same connection, which is known as *associations*, see Fig. 9.2. One other feature is the ability to detect path failure. Each session is controlled by a function called *heartbeat*. A description of features available for the SCTP are provided by Ratola [120] and Stewart *et al.* [121]:

- The multi-streaming data transfer has to be controlled to be, like the TCP, a strict order delivery or, like the UDP, a non-strict order of the delivery of messages.

- The multi-homing feature offers mobility for a host. A host with many network layer addresses is called multi-homed. This means that no more router agents in the network are necessary. For the host to be considered mobile it has to change its endpoint, in this case the network layer address, and by doing this it keeps the end-to-end connection. To achieve this change of addresses the Dynamic IP Address Reconfiguration (DIPAR) [122] has to be used. During an active connection between two or several hosts an IP-address could be changed, deleted, or added. An SCTP with the additional DIPAR extension is called mobile SCTP (mSCTP) [123–125]. This extension provides the ability to perform a seamless handover and roaming.

- The SCTP uses a more secure connection scheme against DOS attacks, which employs a four-way handshake. This eliminates the TCP SYN flooding attacks, which is possible if a three-way handshake is used. Each node acts as a *client* and a *server*. The client starts by sending an INIT chunk. The server responds with an INIT-ACK message with a *cookie* of information, which is a secure hash based on RFC 2104 [126]. The client responds with a COOKIE-ECHO back to the server, which enables the server to verify the client. The server verifies the association with a COOKIE-ACK response message. Now the two nodes have an association (connection) between each other.

- The SCTP uses already established techniques like slow-start, congestions control, and fast retransmission.

- A heartbeat mechanism is implemented that controls if an association is up and working or down and not working.

- An SCTP association could be based on one or many *IP-addresses* together with only one *port*. In the TCP connection, one IP-address and one port are paired together, which is called a *socket* connection.

Many SCTP implementations for different platforms are available for downloading:

- OpenSS7 Project, Linux Native SCTP Prerelease, February 2-19, 2004 [127].
- Linux Kernel SCTP Project, 4-beta [128].
- NS-2 SCTP module [129], for simulation purposes.

A performance analysis has been done by Jungmaier *et al.* [130] between a TCP connection and a SCTP association through a WAN emulator. The behavior and the influences on each other were evaluated. Jungmaier *et al.* concluded that the SCTP traffic behavior has the same characteristics as the TCP and the shared resources were equally shared. Several future features like selective acknowledgment, fast retransmission and out-of-order delivery were not tested.

So, one solution to the IP-address problem is to address the issue as in Fig. 9.1 (b). One has to give the *location* and the *end-point* different identities and still have a connection in-between like a dynamic binding. Still the ordinary paradigm of using an IP-address is used. This in mind, the solution of using OpenVPN[1] seems to be a choice which solves a couple of our problems as decribed by Waltersson [112]. In this case a TAP drive was used. Each packet was added an additional header information to make the packet transparent to the network, see Fig. 9.3.

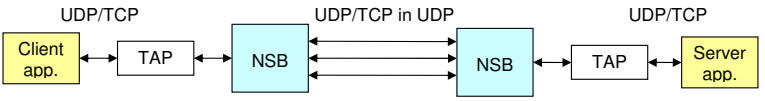


Figure 9.3: Virtual Network Interface in the NSB

[1] http://openvpn.net/ .

9.3 Performance Overhead Issues

Finally, a seamless communication between different network links can be realized. Still, some cryptography algorithms may cause performance degradations, e.g. processing overhead in protocols/algorithms. This is not an issue in the Data Encryption Standard (DES), Blowfish or RC5 [131] to mention a few of them. In this case the size of the information which is to be encrypted does not change in size. Another issue is the complexity, which could be measured in different ways. One way is to compare the speed of block cipher per byte encrypted. According to Stallings [131], between the three algorithms of Blowfish, RC5 and DES, there is a significant difference in speed. If Blowfish speed is the reference speed, RC5 needs 27 % more clock cycles per encrypted byte, and DES needs 150 % more clock cycles per encrypted byte. So, the issue of performance overhead and complexity remains.

In our solution of the seamless communication concept we introduce a virtual TAP drive which means that four combinations of the two protocol TCP and UDP could occur. TCP-TCP is dangerous due to the double timeouts and packet overhead etc., TCP-UDP and UDP-TCP may provide reliable service except for real-time applications and UDP-UDP minimizes the total packet overhead. In the thesis only the UDP-UDP is used. The main reason is to minimize the overhead which is introduced by the TAP driver. Still, in the future when new types of transport protocols emerge, other types of combinations could be looked at.

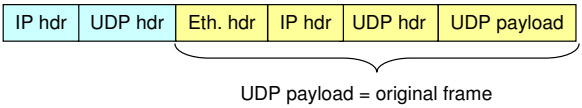


Figure 9.4: Encapsulated packet for tunneling

The frame size is also important. For UDP = 8 B, IP = 20 B and Ethernet = 14 B respectively, see Fig. 9.4, the total overhead introduced is 42 B. In

Fig. 9.5, the ratio between header and payload is plotted. If we use large packets the efficiency is higher than if we use small packets. If we use a packet size of more than 450 bytes the efficiency is between 90 % and 97 %.

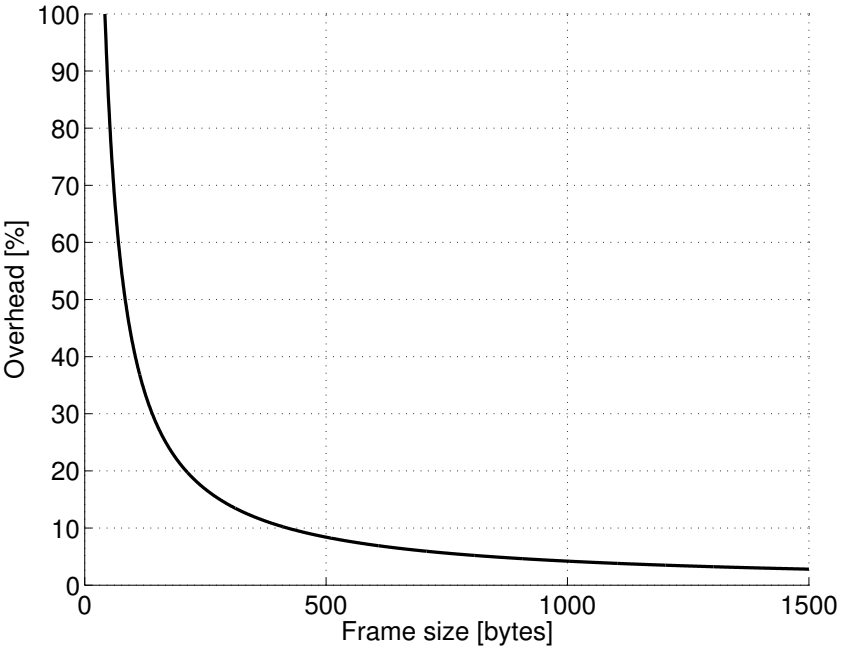


Figure 9.5: Overhead vs. packet size ratio

Many mobility solutions use the "tunneling" technique like the Mobile IP which is heavily tied to the UDP protocol. The approach shown in the thesis is not an exception from this rule. Still, the new seamless communication concept presented is not stuck with the UDP protocol compared to the Mobile IP (MIP). This makes the new concept more flexible compared to the MIP solution.

Chapter 10

Conclusions

History is not events, but people. And it is not just people remembering, it is people acting and living their past in the present. History is the pilot's instant act of decision, which crystallises all the knowledge, all the science, all that has been learned since man began.

J. Bronowski, The Ascent of Man

In this chapter a final summary of our seamless communication concept is given. Finally, contributions and future perspectives are presented.

10.1 Summary

1. First a background and the motivation for having seamless communication was given. The methodology used was presented. One of the first components in the seamless communication concept was the introduc-

tion of Generic Services (GSs) and how these could be used in different scenarios.

2. Next there was a presentation of the performance issues and behavior of network links. A detailed research of the performance issues was conducted, but only the most relevant parts of the results in the context of this thesis were presented. The results from this research formed the foundation for some of the decision criteria in the thesis.

3. Another issue of concern was the effect different criteria could have on the final choice. The arrival of new technologies may cause interference in current access points. A new affordable wireless technology makes it possible to better make, in real time, a decision based on new criteria. The metric values and how these are measured together with different types of statistics was accounted for.

4. The next step was to find a tool which was able to make multi-criteria decisions. The choice fell on the Analytic Hierarchy Process (AHP). This tool is able to handle several criteria and attributes with a specific goal in mind and at the same time provide a sorted list of all our alternatives. The Multi-Criteria Decision Making (MCDM) and the AHP are typically used for management and business decisions in which the human aspect is involved to determine the importance between different criteria and alternatives. However, we have shown that the decision method is useful even for a technical application, namely to choose the appropriate connection between the three alternatives WLAN, UMTS and GPRS in the context of seamless communications.

5. The decision tool was not able to use any type of input values except a linguistic point-scale. One way would then be to do the calculation by hand and translate every value into an appropriate linguistic level. Still, this does not work if many decisions must be made. A more refined method or tool must be used. The tool selected was the FST which was

able to transform all types of metric values into well chosen and limited linguistic levels suitable for the decision tool.

6. Furthermore, there was a need to form a roaming strategy for seamless integration of the WLAN and cellular networks. This roaming policy is based on monitoring, scanning and priority of a network link. The roaming strategy is based on two components, the AHP and a 3-point scale. The fine-tuned decision comes from the AHP decision tool. The 3-point color scale, which is used in the roaming policy, could also be used by itself.

7. Next, the enabler, which was the Switch Control Unit (SCU), was presented. The SCU is responsible of sending and receiving data packets. It handles all types of control messages, e.g. "ping" and is handled at the application layer. It also performs the switch between the network links when instructed.

8. Finally, different parts in the seamless communication concept are implemented. Some of the criteria and statistical methods were implemented as were different types of optimized algorithms. Altogether, the seamless communication concept was implemented and proven to work.

10.2 Contributions

1. The first contribution is the *seamless communication concept*. The concept is defined with several criteria and these are connected to a specific GS. Each criterion is described and motivated. Depending on type, the criteria are grouped to fit into a MCDM tool.

2. The second main contribution is the cognitive perspective of the "human capacity". The implementation is based on the end-user capacity and perception. This view, based on the end-user perceptions, is implemented in our seamless communication concept.

3. The implementation of Fuzzy Sets (FS) constitutes another contribution. By introducing knowledge into the membership functions and into FS rules, a transformation of different scales could be made. Classifications of different wireless technologies are also possible thanks to this tool.

4. The MCDM model called the AHP was implemented. The model requires a linguistic 9-point scale. To transform each metric value into a scale suitable for the AHP the FST was used. All data is now more easily transformed linearly or not linearly into this 9-point scale which is demanded by the decision model. The decision model is very helpful for making judgments and for comparisons between two different criteria. We have seen that different criteria for different GS and conditions can make a difference regarding the decision based on performance, cost and accessibility ratings. As the calculations are neither numerous nor complicated, a use for real time link selection is possible. The proposed hierarchy can easily be adapted to needs and preferences. It can also be expanded by additional criteria and attributes.

5. The Fuzzy Set Theory (FST) is used to classify and detect other types of interfering technologies. This new method of detecting and classifying other wireless technologies in the 2.4 GHz ISM band is presented. Eventually a more accurate decision is now possible to make with the objective of being ABC.

6. The definition of the roaming strategy was given. Different parts of the NSB together with the GS are the enablers which decide when to switch between different network links. The more refined decision is based entirely on the AHP. A simpler 3-point scale separated from the AHP could also be used.

10.3 Future Perspectives

In the thesis the MCDM has been used together with the AHP for the decision making. The method of decision making could be improved by using the Fuzzy Relational Inference Language (FRIL). Its strength lies in the ability to make a decision with vague information, uncertain information or in some cases no information at all. It also has the ability to include all three areas of *fuzzy sets*, *probability* and *neural net* theories according to Baldwin [132]. Today this is highly motivated as the amount of available information is bigger than some of the decision models can deal with. At the same time, it is difficult to rate different alternatives due to complex interrelations between different factors. So, an optimized solution may not be what we are looking for but, simply, a ”good enough” solution.

Now, the seamless communication concept is defined and partly implemented. The remaining issues are as follows:

- Further implementation of different types of decision models needs to be made. According to Hall [87] there are many decision models which could be used depending on the process-modeling techniques.
- Other types of criteria have to be evaluated. In the thesis, the amount of criteria and the selected ones are not optimized. A more elaborated and extended work is required selecting the criteria needed in different scenarios together with GSs.
- The weights between criteria need to be further evaluated. In some cases some criteria weights are static compared to other types of criteria. This has not been considered to its full extent and needs to be considered in the future.
- Performance measurements of handover situations need to be evaluated. The current IP paradigm requires a connection to be disconnected before a new connection with a different network link can take place. The

thesis presents a different case. In our solution all network links are accessible all the time, allowing immediate switches between the networks. Therefore, new measurements benchmarks are required.

- The safety factor, with GSs, need to be further investigated. The size of the safety factor and how it relates to the time budget also needs further investigations in connection to a specific GS.

- Future work includes a refined roaming strategy that will take advanced performance monitoring into account and faster handover by optimizing the corresponding parameter settings. Also, additional measurements of one-way delays and TCP "goodput" need to be considered.

- Incorporation of more monitoring algorithms and results into the seamless communication concept is required. The type of monitoring results and how these are extracted also needs more investigation as does different types of algorithms and how these should be related to the monitored data.

- Future work also includes refinements of the concept such as introducing another decision level, yielding additional weights between performance, cost and accessibility. The concept will also be connected to operational end-to-end monitoring and tested in real seamless communication scenarios.

The thesis has introduced the seamless communication concept. Many issues have been dealt with and new ones have been discovered. More research is, thus, required in the field of seamless communications.

Appendix A

Abbreviations and Acronyms

ABC	Always Best Connected
AFH	Adapted Frequency Hopping
AHP	Analytic Hierarchy Process
AODV	Ad Hoc OnDemand Distance Vector
AP	Access Point
BET	Bandwidth Estimation Techniques
BS	Base Station
BSS	Backwards Streaming Service
BTH	Blekinge Institute of Technology

CA	Coverage Area
CDMA	Code Division Multiplexing Access
CI	Consistency Index
CM	Channel Map
CP	Compromise Programming
CR	Consistency Ratio
CS	Coding Scheme
CTA	Criteria Trade-off Analysis
DAB	Digital Audio Broadcast
DCF	Distributed Coordination Function
DES	Data Encryption Standard
DHCP	Dynamic Host Configuration Protocol
DIPAR	Dynamic IP Address Reconfiguration
DL	Directional Loss
DMRG	Decision Making based on Relationships between Goals
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
DSS	Decision Support System
DSSS	Direct Sequence Spread Spectrum
E2E	End-to-End
ELECTRE	Elimination and Choice Translating Reality
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission

FDM	Frequency Division Multiplexing
FHSS	Frequency Hopping Spread Spectrum
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Control
FMOP	Fuzzy Multiple Objective Programming
FRIL	Fuzzy Relational Inference Language
FS	Fuzzy Sets
FST	Fuzzy Set Theory
FTP	File Transport Protocol
GA	Generic Algorithm
GPRS	General Packet Radio Service
GRA	Grey Relational Analysis
GS	Generic Service
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HIP	Host Identity Payload
HIT	Host Identity Tag
ID	Initial Delay
IEEE	Institute of Electrical and Electronics Engineers
IMS	Individual Messaging Service
IP	Internet Protocol
IPD	Inter Packet Delay
IPER	IP Packet Error Ratio

IPLR	IP Packet Loss Ratio
IS	Interactive Service
ISM	Industrial Scientific and Medical
ITS	Intelligent Transport Systems and services
ITU-T	ITU-Telecommunication Standardization Sector
JPEG	Joint Photographic Experts Group
LC	Link Capacity
LSI	Local Scope Identity
MADM	Multi-Attributive Decision Making
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MCI	Mean Consistency Index
MCR	MATLAB Component Runtime
MIP	Mobile IP
MISO	Multiple-Input Single-Output
M-MIP	Multihomed Mobile IP
MODM	Multi-Objective Decision Making
MRCI	Mean Random Consistency Index
MS	Messaging Service
NSA	Network Selection Algorithm
NSB	Network Selection Box
OS	Operating System
OSI	Open System Interconnection

PDA	Personal Digital Assistant
PDMS	Patient Data Management System
PDS	Personal Download Service
PFLA	Programmable Fuzzy Logic Array
PIITSA	Personal Information for Intelligent Transport Systems through Seamless Communications and Autonomous Decisions
PIS	Personal Interactive Service
PPTD	Packet Pair Train Dispersion
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PSS	Public Streaming Service
QoS	Quality of Service
RTT	Round Trip Time
SCTP	Stream Control Transmission Protocol
SCU	Switch Control Unit
SF	Spreading Factor
SIPR	Spurious IP Packet Rate
SLoPS	Self-Loading Periodic Streams
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SS	Streaming Service
SSS	Selective Streaming Service
TBF	Temporary Block Flow

TBF	Time-Based Fee
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TOPP	Trains of Packet Pairs
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
UDP	User Datagram Protocol
UI	User Interface
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
VBF	Volume-Based Fee
VPS	Variable Packet Size
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WPM	Weighted Product Method
WSM	Weighted Sum Method
WUSB	Wireless Universal Serial Bus

Appendix B

Lightweight ABC for WPAN

Figures and tables that were not presented in the chapters are found in this appendix on lightweight ABC for Wireless Personal Area Network (WPAN). For additional information see Chapter 4.

Table B.1: File: WLAN.fis (System)

```
[System]
Name='WLAN'
Type='sugeno'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=9
AndMethod='min'
OrMethod='max'
ImpMethod='prod'
AggMethod='sum'
DefuzzMethod='wtaver'
```

Table B.2: File: WLAN.fis (Input1)

```
[Input1]
Name='Std.'
Range=[0 3]
NumMFs=3
MF1='middle':'trapmf',[0.1778 0.2778 0.3873 0.4873]
MF2='low':'trapmf',[-0.2 -0.1 0.17778 0.2778]
MF3='high':'trapmf',[0.3873 0.4873 3.1 3.2]
```

Table B.3: File: WLAN.fis (Input2)

```
[Input2]
Name='Power'
Range=[-100 20]
NumMFs=3
MF1='middle':'trapmf',[-69 -67 -55 -53]
MF2='low':'trapmf',[-115 -105 -69 -67]
MF3='high':'trapmf',[-55 -53 22 25]
```

Table B.4: File: WLAN.fis (Output1)

```
[Output1]
Name='Level'
Range=[-30 30]
NumMFs=3
MF1='low':'constant',[0]
MF2='middle':'constant',[4]
MF3='high':'constant',[8]
```

Table B.5: File: WLAN.fis (Rules)

1	[Rules]
	1 1, 3 (1) : 1
3	2 2, 1 (1) : 1
	2 3, 1 (1) : 1
5	3 2, 1 (1) : 1
	3 3, 1 (1) : 1
7	1 2, 1 (1) : 1
	1 3, 1 (1) : 1
9	2 1, 1 (1) : 1
	3 1, 1 (1) : 1

Table B.6: Rules

1	If (Std. is A) and
	(Power level is B) then (Level is C)
3	If (Std. is not A) and
	(Power level is not B) then (Level is not C)

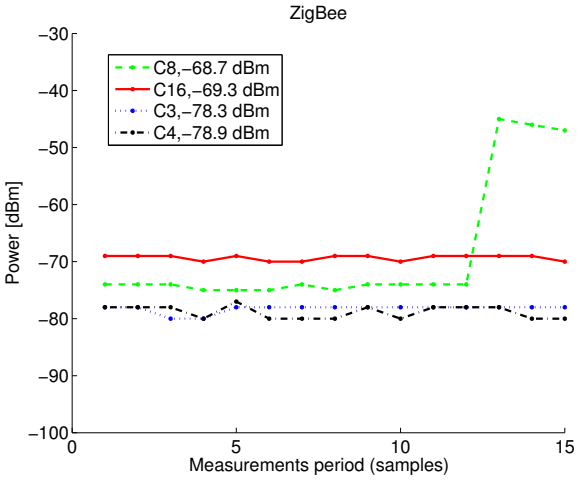


Figure B.1: ZigBee channels sorted in descending order, first four channels shown, samples 1 to 15

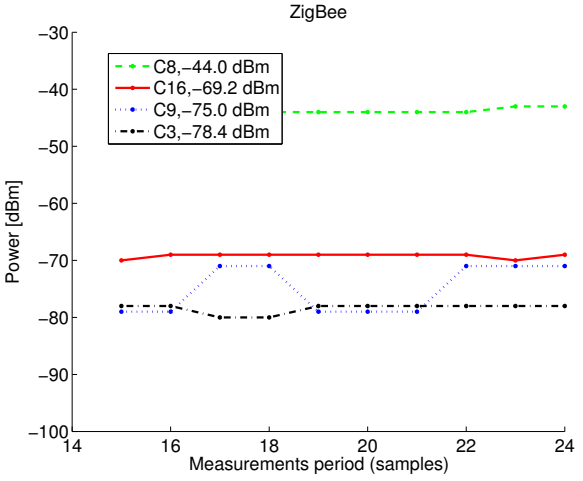


Figure B.2: ZigBee channels sorted in descending order, first four channels shown, samples 1 to 15

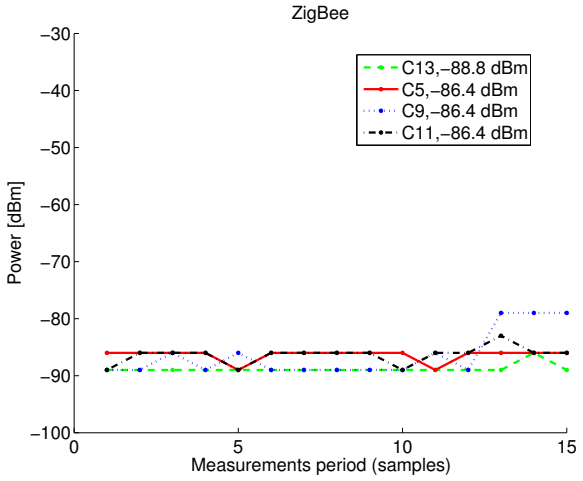


Figure B.3: ZigBee channels sorted in ascending order, first four channels shown, samples 1 to 15

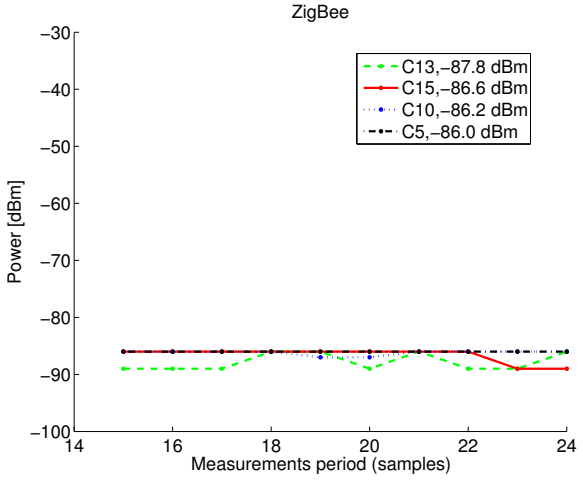


Figure B.4: ZigBee channels sorted in ascending order, first four channels shown, samples 15 to 24

Appendix C

WPAN Classification

Figures that were not presented in the chapters are found in this Appendix on the FST. For additional information see Chapter 4.

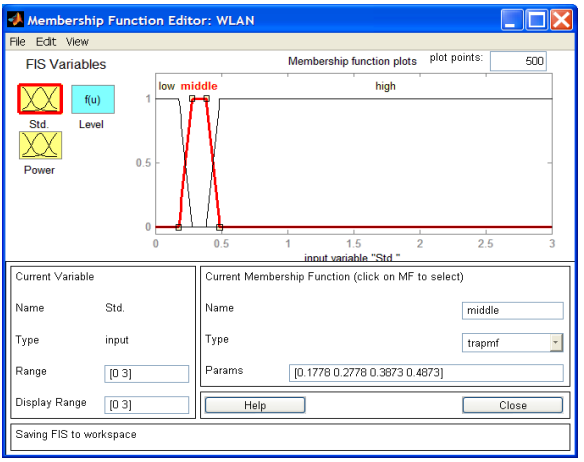


Figure C.1: Membership function of the standard deviation for WLAN

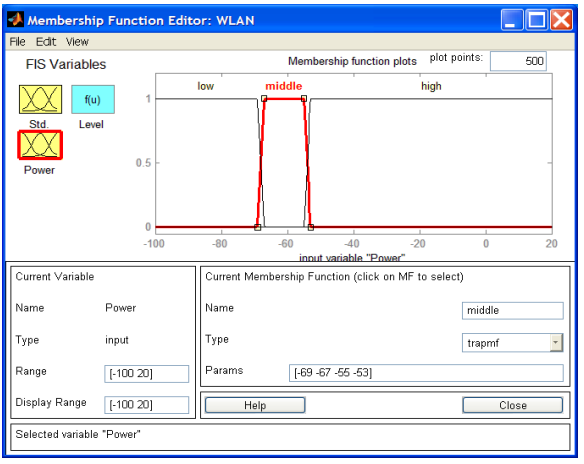


Figure C.2: Membership function of the power level for WLAN

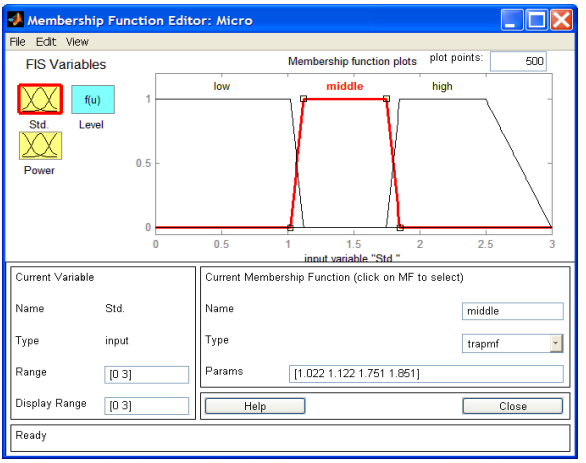


Figure C.3: Membership function of the standard deviation for microwave oven

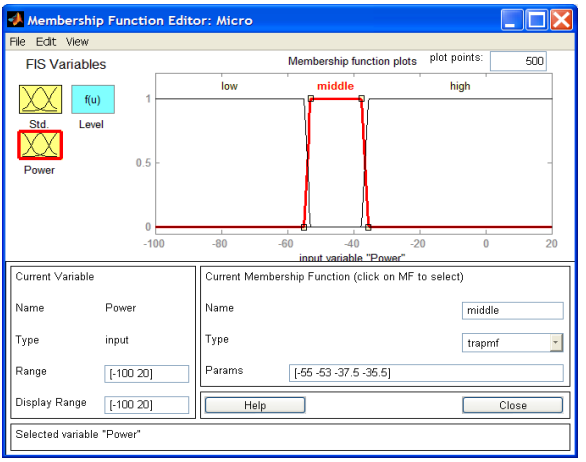


Figure C.4: Membership function of the power level for microwave oven

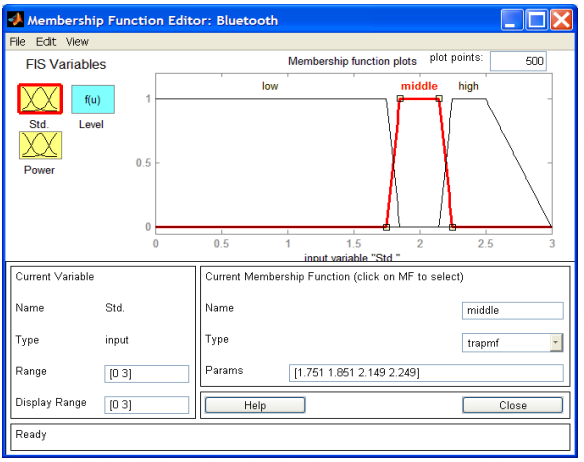


Figure C.5: Membership function of the standard deviation for Bluetooth

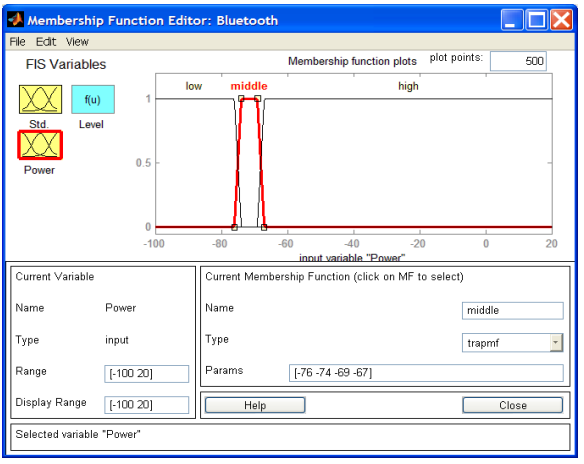


Figure C.6: Membership function of the power level for Bluetooth

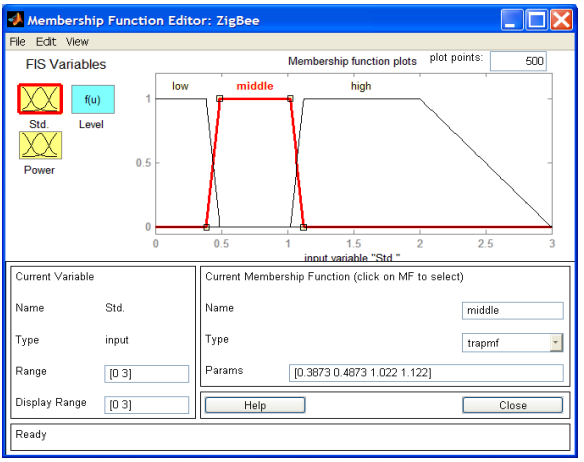


Figure C.7: Membership function of the standard deviation for ZigBee

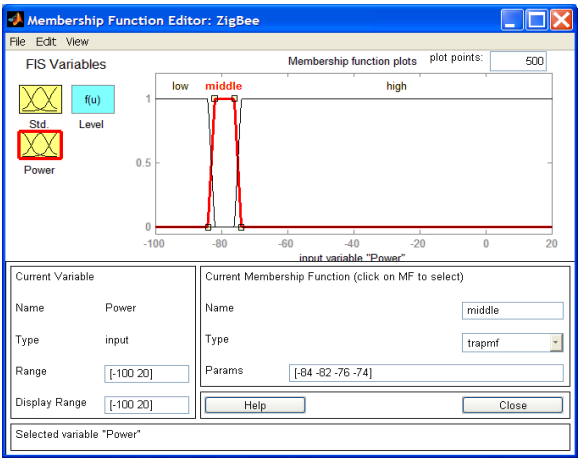


Figure C.8: Membership function of the power level for ZigBee

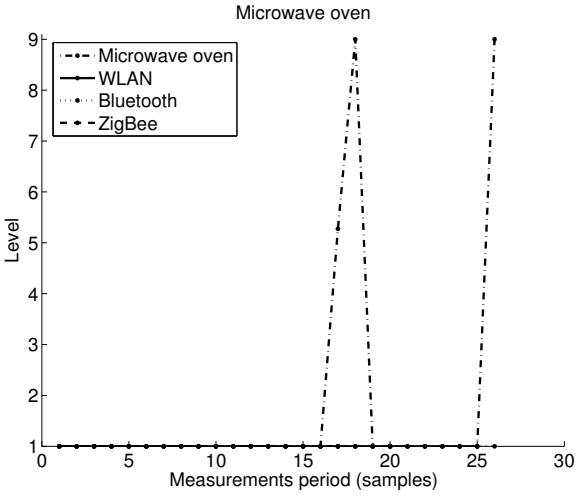


Figure C.9: WPAN classification for microwave oven

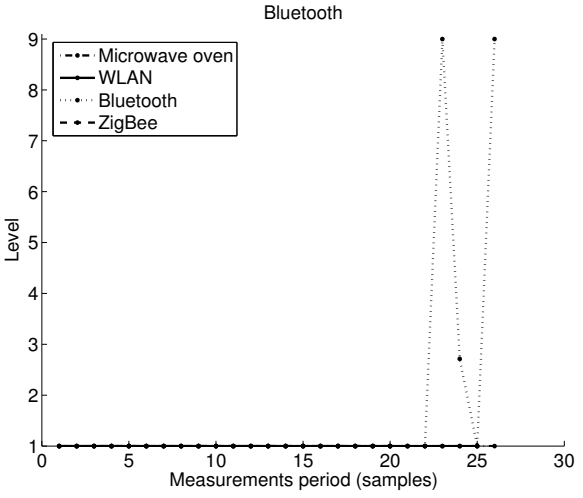


Figure C.10: WPAN classification for Bluetooth

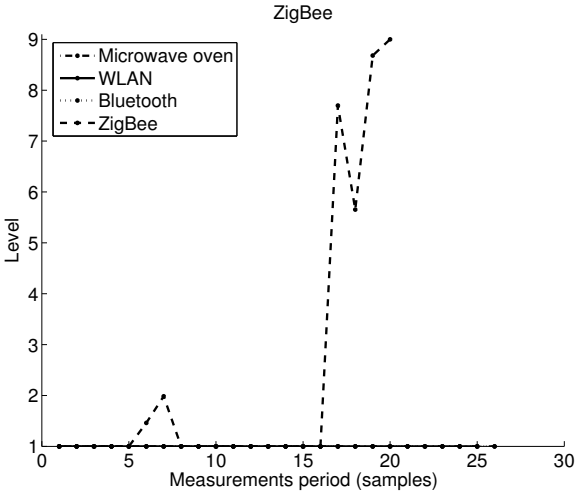


Figure C.11: WPAN classification for ZigBee

Appendix D

Real- and Pseudo-Code Examples

Real- and pseudo-code implementations that were not presented in the chapters are found in this Appendix.

Table D.1: Mean Consistency Index Script, 3x3 Matrix

```
close all;
clear all;
clc;

H = [1 2 3 4 5 6 7 8 9 1/2 1/3 1/4 1/5 1/6 1/7 1/8 1/9];
Hs = size(H,2);
N = 3;
VN = ((N * N) - N) / 2;
s = Hs^VN;
K = 0;
V = 0;
W = eye(N,N);

for i = 0:s - 1
  for j = 1:VN
    data(j) = H(mod((fix(i / Hs^(VN - j))),Hs) + 1);
  end

  count = 0;
  for r = 1:N - 1
    for c = r + 1:N
      count = count + 1;
      W(r,c) = 1 / data(count);
      W(c,r) = data(count);
    end
  end

  [V,D] = max(real(eig(W,'nobalance')));
  K = K + V;
end
MRCI = (mean(K / s) - N) / (N-1)
```

Table D.2: Bluetooth AFH in hex code excluding WLAN channels

Channels	Bluetooth
Default (79)	0x7FFFFFFFFFFFFFFFFFF
$P_{W(C1)}$	0x000080FFFFFFFFFFFFF
$P_{W(C2)}$	0x0F0000F0FFFFFFFFFFF
$P_{W(C3)}$	0x7F030000FEFFFFFFFFF
$P_{W(C4)}$	0x7F7F0000C0FFFFFFFFF
$P_{W(C5)}$	0x7FFF0F0000F8FFFFFFF
$P_{W(C6)}$	0x7FFFFF010000FFFFFFF
$P_{W(C7)}$	0x7FFFFF3F0000E0FFFFF
$P_{W(C8)}$	0x7FFFFFF070000FCFFF
$P_{W(C9)}$	0x7FFFFFFFF000080FFF
$P_{W(C10)}$	0x7FFFFFFFF1F0000F0F
$P_{W(C11)}$	0x7FFFFFFFFFF030000FE
$P_{W(C12)}$	0x7FFFFFFFFFF7F0000C0
$P_{W(C13)}$	0x7FFFFFFFFFFFF0F0000

Table D.3: Bluetooth AFH in hex code excluding ZigBee channels

Channels	ZigBee
Default (79)	0x7FFFFFFFFFFFFFFFFFFF
$P_{Z(C1)}$	0x63FFFFFFFFFFFFFFFFFF
$P_{Z(C2)}$	0x7FF8FFFFFFFFFFFFFFFF
$P_{Z(C3)}$	0x7F1FFFFFFFFFFFFFFFFF
$P_{Z(C4)}$	0x7FFFE3FFFFFFFFFFFFFF
$P_{Z(C5)}$	0x7FFF7FFCFFFFFFFFFFFF
$P_{Z(C6)}$	0x7FFFFF8FFFFFFFFFFFFF
$P_{Z(C7)}$	0x7FFFFFFFF1FFFFFFFFFF
$P_{Z(C8)}$	0x7FFFFFF3FFEFFFFFFFF
$P_{Z(C9)}$	0x7FFFFFFFFC7FFFFFFFF
$P_{Z(C10)}$	0x7FFFFFFFFFFF8FFFFFF
$P_{Z(C11)}$	0x7FFFFFFFFFF1FFFFFFF
$P_{Z(C12)}$	0x7FFFFFFFFFFFFE3FFFF
$P_{Z(C13)}$	0x7FFFFFFFFFFFF7FFCFF
$P_{Z(C14)}$	0x7FFFFFFFFFFFFFF8FFF
$P_{Z(C15)}$	0x7FFFFFFFFFFFFFFFFF1
$P_{Z(C16)}$	0x7FFFFFFFFFFFFFFFFF3F

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ABSTRACT

The evolution of today's wireless technologies and small hand-held devices has enabled the handling of the trade-off between mobility and performance. Things have, however, become more complex. Users demand high performance when using small and resource-efficient devices. Users also demand high-performance connectivity anywhere and anytime without having to care about transitions between different access networks. As of today, the absence of Mobile IP (MIP) support in most networks implies the need for a reconnection of the service as soon as the access network changes. That is why a new seamless communication concept is required. In the thesis, a new seamless communication concept is proposed. The goal is to be Always Best Connected (ABC) even if the conditions change. Initially, a network link has to be selected and a connection has to be established. The service used should be maintained as long as the conditions are fulfilled. First, a set of Generic Services (GSs), each related to a specific communication task, is defined. Furthermore, a deep performance investigation of some of the wireless technologies available is summarized and used. Based on the combination of a GS and a wireless technology selected criteria are used. The data extracted from our measurements have the option of later being fed into statistical algorithms. The translation of the extracted information through the statistical methods could be non-linear and for that reason the Fuzzy Set Theory (FST) is used. The FST provides us with the tool needed for the next step, the decision aiming at ABC. To be able to handle the large amount of data, the Multi-Criteria Decision Making (MCDM) is used. This decision model requires a linguistic 9-point scale which suits the FST tool perfectly. A judgment between different criteria can then be made. Moreover, the thesis describes a couple of important issues regarding the Internet protocol address problem. Each problem is discussed and solutions are presented in the context of having seamless communication without today's constraints. The result is a seamless communication concept that is more flexible than other solutions. Both the FST and the MCDM tools have been successfully implemented into a running prototype.

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