TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY
Julkaisu 777 • Publication 777

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Design of a Performance Management Model for Wireless Local Area Networks

Tampere 2008

Tampereen teknillinen yliopisto. Julkaisu 777
Tampere University of Technology. Publication 777

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Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Tietotalo Building, Auditorium TB109, at Tampere University of Technology, on the 5th of December 2008, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2008

ISBN 978-952-15-2075-4 (printed)
ISBN 978-952-15-2140-9 (PDF)
ISSN 1459-2045

ABSTRACT

The amount of Wireless Local Area Network (WLAN) deployments has increased rapidly in recent years. High throughput Internet access and operation without wires enables new innovative applications for communication, information retrieval, and entertainment. Increasingly, these applications set strict requirements for Quality of Service (QoS).

Interference, a constantly changing environment, multipath signal propagation, and the movement of networking terminals are characteristic of wireless communication. Such characteristics cause varying bit rates and frequent packet retransmissions and consequently problems for applications requiring high throughput or low delay.

Network management has a significant role in managing QoS by providing information from the network and controlling the network operation. Managing QoS would not be possible without information on the network performance. Performance parameters cannot be measured when the network is being planned or only partially deployed, and for cost reasons performance estimates may also be preferred when the network is operational.

This thesis presents the development of a performance model that can be utilized in WLAN management tools. The output of the model is a set of metrics that are estimates of the network performance parameters. The model provides feedback on the network performance and allows the network administrator to control network management algorithms. Thus, the performance model facilitates high quality network planning and operational network management based on the preferences of the network administrator.

The performance model developed here supports both traditional WLANs and Wireless Mesh Networks (WMN). It is designed specifically for supporting mechanisms utilized in the IEEE 802.11 standard. These include the distributed medium access mechanism, contention between devices, WLAN multirate operation, multi-interface and multi-radio devices, as well as advanced antennas.

The performance model has been integrated into a designed planning process. The planning process is a conceptual framework that describes how planning algorithms can use the performance model. The feasibility of both the planning process and the performance model is demonstrated by designing example algorithms for WMN performance optimization that utilize the performance model. Algorithms are collected into two prototype tools, one for WLAN planning and the other for WLAN management.

The performance model has been developed on the basis of an analysis of IEEE 802.11 technology operation, existing research results, WLAN throughput measurements and network capacity simulations. The simulation results presented in this thesis provide a significant insight into WMN operation. According to the results, multirate operation, interference aware routing, and the use of multiple evaluation criteria are crucial in WMN deployment planning.

The accuracy of the performance model has been validated with simulations, which show that the performance model provides reasonably accurate estimates of the network capacity, even with dense network deployments. The simulation results also show that the performance model can be successfully controlled by the network administrator to achieve the desired planning results. As a result, the performance model is of benefit to the network administrator both in network planning and operational management.

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LIST OF PUBLICATIONS

This thesis consists of an introductory section and seven publications [P1] - [P7]. Supplementary publications [P8] - [P13] are not included but are closely related to its contents and therefore separated from the list of references.

[P1] T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Evaluation of Throughput Estimation Models and Algorithms for WLAN Frequency Planning", Elsevier Journal of Computer Networks, vol. 51, no. 11, pp. 3110–3124, 2007.

[P2] T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Performance Model for IEEE 802.11s Wireless Mesh Network Deployment Design", Elsevier Journal on Parallel and Distributed Computing, vol. 68, no. 3, 291–305, 2008.

[P3] T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Optimization of Mesh WLAN Channel Assignment with a Configurable Genetic Algorithm", in *Proceedings of the First International Workshop on "Wireless mesh: moving towards applications" (WiMeshNets'06)*, Waterloo, Canada, August 10, 2006.

[P4] T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Genetic Algorithm to Optimize Node Placement and Configuration for WLAN Planning", in *Proceedings of the 4th IEEE International Symposium on Wireless Communication Systems (ISWCS'07)*, Trondheim, Norway, October 17–19, 2007.

[P5] T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Multihop IEEE 802.11b WLAN performance for VoIP", in *Proceedings of the 16th IEEE International Symposium on Personal, Indoor & Mobile Radio Communications (PIMRC'05)*, Berlin, Germany, September 11–14, 2005.

[P6] T. Vanhatupa, A. Koivisto, J. Sikiö, M. Hännikäinen, T. D. Hämäläinen, "Design of a Manageable WLAN Access Point", in *Proceedings of the 11th Internal Conference on Telecommunications (ICT'04)*, Fortaleza, Brazil, August 1–6, 2004, pp. 1163–1172.

[P7] T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Frequency Management Tool for Multi-Cell WLAN Performance Optimization", in *Proceedings of the 14th IEEE Workshop on Local and Metropolitan Area Networks (LANMAN'05)*, Chania, Greece, September 18–21, 2005.

Supplementary publications

Publications [P8] and [P9] describe and analyze the operation of IEEE 1588 Precision Time Protocol with several prototypes. Accurate time synchronization is important for WLAN management, especially with delay sensitive applications. Publication [P10] contains background information on the design of Wireless Access Management System (WAMS) described in Section 5.4. Publications [P11], [P12], and [P13] describe a development of software for WLAN cell management implemented by the author.

[P8] J. Kannisto, T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Precision Time Protocol Prototype on Wireless LAN", in *Proceedings of the 11th International Conference on Telecommunications (ICT'04)*, Fortaleza, Brazil, August 1–6, 2004, pp. 1236–1245.

[P9] J. Kannisto, T. Vanhatupa, M. Hännikäinen, T. D. Hämäläinen, "Software and Hardware Prototypes of the IEEE 1588 Precision Time Protocol on Wireless LAN", in *Proceedings of the 14th IEEE Workshop on Local and Metropolitan Area Networks (LANMAN'05)*, Chania, Greece, September 18–21, 2005.

[P10] T. Rantanen, J. Sikiö, T. Vanhatupa, M. Hännikäinen, O. Karasti, T. D. Hämäläinen, "Design of a Management System for Wireless Home Area Networking", in *Proceedings of the 9th International Conference on Parallel and Distributed Computing (Euro-Par'03)*, Klagenfurt, Austria, August 26–29, 2003, pp. 1141–1147.

[P11] M. Hännikäinen, T. Vanhatupa, J. Lemiläinen, T. D. Hämäläinen, J. Saarinen, "Architecture for a Windows NT Wireless LAN Multimedia Terminal", in *Proceedings of the IEEE International Workshop on Multimedia Signal Processing (MMSP'99)*, Copenhagen, Denmark, September 13–15, 1999, pp. 535–540.

[P12] M. Hännikäinen, T. Vanhatupa, J. Lemiläinen, T. D. Hämäläinen, J. Saarinen, "Windows NT Software Design and Implementation for a Wireless LAN

Base Station", in *Proceedings of the ACM International Workshop on Wireless Mobile Multimedia (WoWMoM'99)*, Seattle, USA, August 20, 1999, pp. 2–9.

[P13] M. Hännikäinen, T. Vanhatupa, J. Lemiläinen, T. D. Hämäläinen, J. Saarinen, "Design and Implementation of a Wireless LAN Interface Card Driver in Windows NT", in *Proceedings of the International Conference on Telecommunications (ICT'99)*, Cheju, Korea, June 15–18, 1999, pp. 347–351.

LIST OF ABBREVIATIONS

ACK	Acknowledge
AP	Access Point
BSS	Basic Service Set
CAPWAP	Control And Provisioning of Wireless Access Points
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CCK	Complementary Code Keying
CTS	Clear to Send
DCF	Distributed Coordination Function
DiffServ	Differentiated Services
DSSS	Direct-Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
ESS	Extended Service Set
ETT	Expected Transmission Time
ETSI	European Telecommunications Standards Institute
FHSS	Frequency-Hopping Spread Spectrum
GA	Genetic Algorithm
HC	Hybrid Coordinator
HCCA	Hybrid Coordination Function Controlled Channel Access
HCF	Hybrid Coordination Function
HWMP	Hybrid Wireless Mesh Protocol
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force

IFS	InterFrame Space
ILP	Integer Linear Program
IntServ	Integrated Services
ISM	Industrial, Scientific, and Medical
ISO	International Organization for Standardization
IP	Internet Protocol
ITU-T	International Telecommunication Union Telecommunication standardization sector
JVM	Java Virtual Machine
LAN	Local Area Network
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MOS	Mean Opinion Score
OFDM	Orthogonal Frequency Division Multiplexing
P2P	Peer to Peer
PCF	Point Coordination Function
PM1	Performance Model 1 [P3]
PM2	Performance Model 2 [P1]
QoS	Quality of Service
RADIUS	Remote Authentication Dial In User Service
RCP	Rich Client Platform
RFC	Request for Comment
RTS	Request to Send
SLA	Service Level Agreement
SLS	Service Level Specification
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio
SSID	Service Set Identifier
TCL	Tool Control Language
TMN	Telecommunications Management Network

UI	User Interface
UNII	Unlicensed National Information Infrastructure
VLAN	Virtual Local Area Network
VoD	Video on Demand
VoIP	Voice over Internet Protocol
WAMS	Wireless Access Management System
WISP	Wireless Internet Service Provider
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
WPA	WiFi Protected Access
WTP	Wireless Termination Point
XML	eXtensible Markup Language

1. INTRODUCTION

Wireless communication technologies have several advantages over traditional wired networking. These include freedom of movement, as well as easier and less expensive installation. Operation without wires enables new innovative applications for communication, information retrieval, and entertainment that support the natural behavior of people in different situations and surroundings.

Wireless Local Area Network (WLAN) technologies are in a key position for providing high throughput wireless Internet access. The fast and widespread acceptance of WLAN has caused the technology to develop rapidly. Moreover, the price of equipment has decreased to a level that promotes extensive WLAN deployments. Currently many forward-thinking cities are building municipal WLANs and wireless networks are now included in the development plans of many new residential areas [112].

In this context, WLAN is designed, deployed, owned, and managed by a Wireless Internet Service Provider (WISP). A managed WLAN may comprise only a couple of Access Points (AP) or it may be a city-wide deployment with hundreds of APs. WLAN users may have to pay a fee, or the network access can be free. Nevertheless, the WISP has made an investment in the WLAN infrastructure and wishes to profit from the investment.

A WISP may provide various types of services for the user. In this thesis, the focus is on Internet Protocol (IP) communication service. As described in Figure 1, IP communication service enables data flow between applications within the WISP network and also to applications in the Internet. Examples of these applications are web surfing, voice over IP (VoIP) [28], file transfer, email, and video on demand (VoD) [133]. Each application has a set of requirements for the communication service. For example, VoIP requires both low delay and a small packet loss rate to achieve high voice quality [28, 63]. VoD, on the other hand requires higher throughput but tolerates higher delays [147].

The properties of the communication service are commonly referred to as Quality of Service (QoS). In [29], three aspects of QoS are defined. These are intrinsic, per-

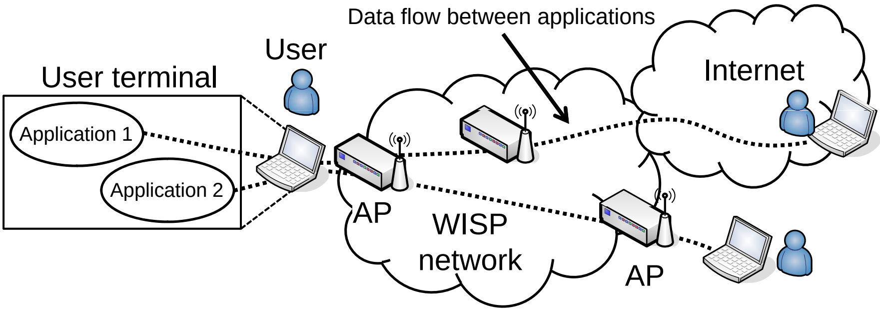


Fig. 1. *Providing wireless IP communication service for user applications.*

ceived, and assessed QoS. Intrinsic QoS measures the network performance and can be expressed using performance parameters collected from the network. Examples of these parameters are bit rate, delay, delay variance, and packet loss rate. Perceived and assessed QoS reflect different sides of the user experience. Perceived QoS describes the subjective user experience and is affected by user expectations. Assessed QoS describes the value of the service for the customer by determining whether or not the user continues using the service. User experience depends on intrinsic QoS but is also affected by the experiences and expectations of the user [29]. Thus, the focus in this thesis is on intrinsic QoS and the term QoS is later used to refer intrinsic QoS.

Wireless communication has properties that differ from those of traditional fixed network communication and make the provision of a controlled communication service more challenging [125]. The properties of a wireless communication channel are under constant change due to interference, changing environment, multipath signal propagation, and the movement of networking terminals. This causes varying bit rates and frequent packet retransmissions, and consequently problems for applications requiring high throughput or low delay. Nevertheless, controlling QoS allows WISP to provide communication services that support a variety of applications.

Provisioning QoS in the Internet has been studied extensively. A significant part of the results have been taken into daily use by combining them into Internet standards and recommended practices developed by the Internet Engineering Task Force (IETF). IETF is a large, open international community responsible for overseeing the Internet architecture evolution. IETF has developed Differentiated Services (DiffServ) [11] and Integrated Services (IntServ) [13] architectures for providing QoS. Due to the special characteristics of wireless transmission, traditional QoS control mechanisms do not meet the requirements of wireless networking. Basic assumptions that the transmission channel is reliable and that the loss of packets is an indication of congestion are no longer valid for wireless networks [129].

Applications with high QoS requirements have also recently moved from technology trials to mainstream daily usage. According to Forrester Research, about 20% of small and medium size businesses were already adopting or piloting VoIP with WLAN in 2007 [128].

Network management is a tool for WISP to manage all aspects of the network. Examples of management tasks are controlling QoS and security of the user services, and collecting information about network performance for enabling network maintenance and optimization. Network management comprises the management of both wired and wireless networks. Thus, later we employ the term WLAN management, which delimits management to the WLAN. A detailed definition of WLAN management is the topic of Chapter 3.

WLAN management is needed in each phase of the network life-cycle, which is generalized in Figure 2. The life-cycle starts with network planning, which includes service planning, and network deployment planning. Once the network has been planned, it is installed and made operational. When the network is operational, the maintenance phase begins. This process is usually continuous and new APs are added to the operational network when needed. Thus, network planning continues throughout the network life-cycle.

A WISP has multiple requirements when planning a network or optimizing an existing one. Predictable QoS for the user should be a key requirement, but the deployment cost, service area, number of users, and resource utilization must also be considered [29]. Thus, an operational network is always a compromise between the various requirements that a WISP has. Requirements can be seen as the target values for the performance parameters of the network [145]. For example, WISP may set a requirement that the effective coverage must be 95% of a specified area.

Fulfilling the requirements that a WISP may have is not possible without information about the network performance. Performance data can be measured if the network already exists. In the planning phase, the network does not exist, at least not completely, and performance data must be estimated. The main users of the performance

Fig. 2. *WLAN life-cycle.*

data are management algorithms for planning and network optimization, access control for provisioning capacity for the users, network planning tools for visualizing the network operation, and the network administrator for obtaining feedback from the network. During network planning, performance estimation provides instant feedback to the network designer. Performance estimation also decreases the need for expensive site measurements that otherwise must be carried out constantly to provide reliable information from the network.

Examples of parameters collected from the network are maximum network capacity, coverage area, deployment cost, and the amount of interference in the network. The parameters are often mutually conflicting. For example, a network with high capacity or large coverage area is bound to be more expensive than a small network with just few APs. Similarly, deploying a high capacity network to a small geographic area causes the APs to interfere with each other more than in a sparsely deployed network.

Simultaneous optimization of multiple and conflicting objectives make optimization difficult for WISP, and it also complicates the development of the optimization algorithms. Without special control, optimization algorithms cannot differentiate the significance of each objective to the WISP and the results may not be useful. To enable automatic network management based on estimated performance parameters, the data must be further refined on the basis of the preferences of WISP. This gives more weighting to selected parameters and enables the network management algorithms to improve the network operation in a direction closer to the requirements of the WISP.

Recent advances, such as Wireless Mesh Networking (WMN), and usage of advanced antennas have raised new issues for WLAN management that existing network management approaches do not address [14, 87, 127, 131, 144]. In WMN, devices other than terminals are static and network management methods developed for ad-hoc networks do not fit WMNs due to low device mobility [83].

The capacity of a WMN is difficult to estimate because each traffic flow is transmitted via multiple network devices that cause interference to each other. One of the original design objectives of WMN technology was to enable automatic configuration of the network devices when new devices are added [14]. This removes the need to individually configure each device but makes the network more dynamic. The WISP should be aware of these configuration changes in order to estimate the network capacity and optimize network performance [115].

Popular applications that benefit from WMN accelerate the acceptance of the technology. VoIP has been regarded as one of the most important applications in WMNs

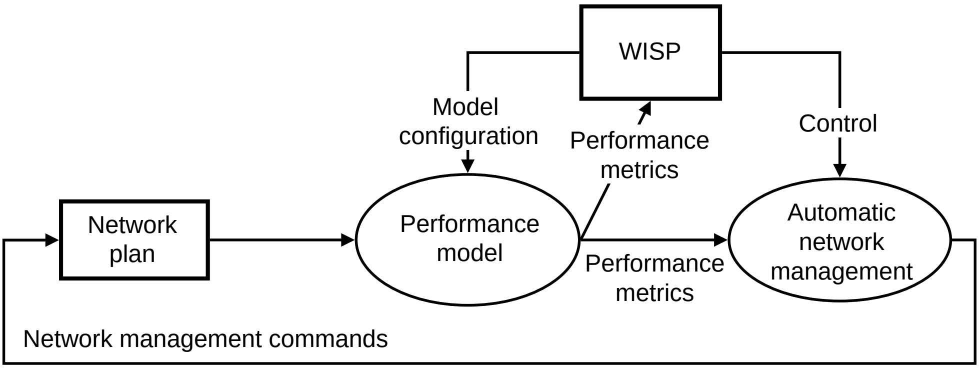


Fig. 3. *Performance estimation and usage for network management presented as a data flow diagram.*

[142]. However, VoIP is sensitive to transmission losses and delay variation, which makes VoIP difficult for WMNs [142]. Due to a small packet size and high Medium Access Control (MAC) layer overhead, VoIP also requires a considerable amount of capacity [97].

Performance enhancements in IEEE 802.11n [52] are mostly achieved by means of advanced antennas. Despite their undoubted benefits, the estimation of network coverage and capacity in IEEE 802.11n is more difficult because of the complicated propagation of the wireless signal.

Recent WMN management research has concentrated on developing methods for optimizing the network resource usage. Comprehensive methods to estimate WMN performance do not exist. A common disadvantage in proposed optimization algorithms is that they solve only a strictly defined problem without giving possibilities for the WISP to control the results [127].

1.1 Objective and Scope of Research

The objective of this research is to design a *performance model* that can be utilized in WLAN management tools. Usage of the performance model enables high quality network planning and optimization according to the preferences of the network designer.

Figure 3 presents the use of the performance model. The input of the performance model is a *network plan*, which specifies either an existing network or the network that will be installed. The output of the model is a set of *metrics* that are estimates of the network performance parameters. The model provides information of the network performance for the WISP. The model also provides refined performance metrics that are created on the basis of preferences set by the WISP. Refined metrics are used by the optimization algorithms in automatic network management. This allows the WISP to define the relative importance of each metric during optimization. The network can also be managed manually based on the feedback provided by the performance model. Both automatic and manual network management commands affect the existing network plan.

The performance model is designed to support performance estimation of both traditional WLANs and WMNs. It is designed especially for supporting mechanisms utilized in IEEE 802.11 technology. These include distributed medium access mechanism, contention between devices, WLAN multirate operation, multi-interface and multi-radio devices, as well as advanced antennas. Selected routes have a significant affect on capacity in WMN networks. Thus, the performance model is designed so as to allow usage of arbitrary routing methods.

The methodology used in the research is the following. The performance model is developed on the basis of the analysis of the operation of IEEE 802.11 technology, existing research results, conducted WLAN throughput measurements and network capacity simulations. The feasibility of the developed performance model is demonstrated by designing example algorithms for WMN performance optimization that utilize the performance model. Algorithms are collected into two prototype tools, one for WMN planning and one for WLAN management.

1.2 Main Contributions

The following represents the main contributions of this thesis:

- A performance model for estimating WMN performance parameters. The performance model can be used both in network planning and operational management to provide performance data from the network.

- Planning and management algorithms that use the performance model. The publications included in this thesis propose one algorithm for finding locations for WLAN APs and channel assignment algorithms for both traditional WLANs and WMNs. In addition, a pruning algorithm for WMN topology and a channel assignment algorithm for operational WLAN are proposed.

- A planning process that uses the performance model. The planning process is a conceptual framework describing how planning algorithms can use the performance model.
- Prototype tools that contain the developed performance model and algorithms. Prototypes have been utilized to demonstrate the feasibility of the proposed methods.
- Simulation results of the WMN operation. The results give significant insight into WMN operation with VoIP application and they have been applied to the development of the performance model.

1.3 Outline of the Thesis

This thesis consists of an introductory section and seven publications [P1-P7]. The introductory section presents the technical background to WLAN technology and management. It also describes the research problem and related proposals to motivate the work. The main results are presented in the publications. The rest of the introductory section is organized as follows:

Chapter 2 provides background information of IEEE 802.11 based WLAN standards that form the basis of current mainstream WLAN technology. The Chapter starts with an overview of IEEE 802.11 technology. The operation of IEEE 802.11 technology is described at a level that is essential to the development of a performance model.

Chapter 3 provides an introduction to WLAN management. The chapter concentrates on a definition of WLAN management and the requirements it places on the WISP. The chapter describes the technical challenges of WLAN management and presents related proposals.

Chapter 4 presents the issues and typical methods for estimating WLAN performance. The Chapter introduces the key performance metrics for WLAN, namely, interference, capacity, coverage, and fairness. The Chapter also describes how a performance model can be utilized in WLAN planning and optimization.

Chapter 5 presents a summary of the research results described in detail in publications [P1-P7]. The Chapter starts with a description of the performance model developed for IEEE 802.11 WMNs. Next, the Chapter describes the developed planning process and proposed algorithms. There is then a description of management algorithms and the proposed architecture developed for WLAN operational management. Finally, the Chapter presents the prototypes that were developed.

Chapter 6 summarizes the publications contained in the thesis. Chapter 7 concludes the thesis.

2. IEEE 802.11 WLAN TECHNOLOGY

Standardization plays an important role in wireless communication [111, 121]. Two main reasons are interoperability and legislation. The interoperability of the equipment, even from different vendors, allows the creation of large service areas with a single technology. It creates new markets and competition reducing costs as a result of the higher volume of manufactured devices. Cost savings and competition mean lower prices for end users, thus accelerating market acceptance.

The development of standards in the wireless communication industry is indicative of the state of the technology. The fact that a large group of companies have agreed and created a standard shows that the technology is mature and ready for real product development.

WLAN technology was originally designed for extending the coverage of wired Local Area Networks (LAN). The technology has further developed into wireless broadband access in hotspot areas and citywide networks. Current mainstream WLAN technology is based on an 802.11 standards group developed by the Institute of Electrical and Electronics Engineers (IEEE) [53].

The present chapter summarizes the technical background necessary to understand the challenges posed by IEEE 802.11 WLAN technology for WLAN management as well as the technical solutions in the developed performance model and algorithms.

Despite its success, the IEEE 802.11 is not the only WLAN technology. HiperLAN/2 is a European WLAN standard, developed by European Telecommunications Standards Institute (ETSI). HiperLAN/2 operates at 5.2 GHz and allows a nominal data rate up to 54 Mbit/s. The same frequencies are used by devices implementing the IEEE 802.11a standard. It has been a competitor of IEEE 802.11a, which has conquered the 5 GHz WLAN markets in Europe. HiperLAN/2 is based on Orthogonal Frequency-Division Multiplexing (OFDM) and has connection oriented MAC protocol, which enables advanced QoS support [21, 37, 141]. HiperLAN/2 standard has been considered sufficiently sophisticated for selected parts of this technology to be adopted in IEEE standards. Nevertheless, the global success of IEEE 802.11

technology has meant that nowadays HiperLAN has become marginal technology. Consequently, there is no further discussion of HiperLAN in this thesis.

2.1 Overview of IEEE 802.11 Technology Development

The IEEE 802.11 standard [42] is the original WLAN standard that IEEE began to develop in 1990. It defines the MAC protocol and three physical layers: two radios and infrared. The physical layers of the standard are no longer in use as such, but the standard is the groundwork for the current and future WLAN standards developed by IEEE.

Since then, the technology has been further developed to provide new functionality. New developments are incorporated in the standard as amendments. Amendments are specified by task groups set up by the IEEE whenever new functionality is needed.

New physical layers IEEE 802.11a [43], 802.11b [44], 802.11g [46], and 802.11n [52] have been developed to improve the transmission rate. The task group 802.11e [49] has modified the MAC protocol to add QoS support. Task groups 802.11i [47], and 802.11w [50] have made modifications to provide enhanced security. Functionality supporting WLAN management has been defined by task groups 802.11v [58], and 802.11k [55]. Task group 802.11s [56] has developed mesh networking functionality for the MAC protocol. Improvements to the standard have also been developed by several other task groups [45, 51, 54]. A summary of the standard amendments is presented in Table 1.

2.2 IEEE 802.11 Topologies

IEEE 802.11 standard defines two network topologies: ad-hoc and infrastructure. The ad-hoc topology is called Independent Basic Service Set (IBSS), and it simply connects two or more stations together in ad-hoc manner. In IEEE terminology, a *station* is simply a device containing IEEE 802.11 MAC protocol and a physical layer to connect a wireless medium [42]. IBSS is termed independent, because no connection to the external networks is defined.

The basic component in the infrastructure topology is a Basic Service Set (BSS). By definition, BSS consists of a set of stations controlled by a single coordination function. In practice, it consists of AP, which may be connected to a wired network, and a set of user terminals. In BSS, the stations may communicate with each other or

Table 1. *Summary of selected IEEE 802.11 standard amendments.*

Name	**Description**
IEEE 802.11a-1999	Physical layer for 5 GHz band, nominal bit rate 54 Mbit/s
IEEE 802.11b-1999	Physical layer for 2.4 GHz band, nominal bit rate 11 Mbit/s
IEEE 802.11g-2003	Enhanced physical layer for 2.4 GHz band, nominal bit rate 54 Mbit/s
IEEE 802.11n	High throughput physical layer, nominal bit rate up to 600 Mbit/s
IEEE 802.11s	Modifications for the MAC protocol to support mesh networking operation
IEEE 802.11e-2005	Modification for the MAC protocol to provide QoS enhancements
IEEE 802.11i-2004	Improved security mechanisms for the MAC protocol
IEEE 802.11w	Security enhancements for improving the security of management frames
IEEE 802.11v	Framework and common methods for WLAN management
IEEE 802.11k	Radio resource measurement enhancements for collecting information from the network

to the wired network. All traffic in BSS is conveyed via AP. Multiple BSSs form an Extended Service Set (ESS). From the user point of view, ESS is the wireless network that the user selects. ESS is identified with a Service Set Identifier (SSID), which is the name of the network.

Topology becomes important when analyzing how the user data is transmitted between the sender and the receiver, and how much infrastructure (network equipment) is required for deploying the network. Topology has direct consequences on the network operation and capacity.

In an infrastructure topology, only the last hop of the connection is wireless. Connections outside the transmission range of the AP require the supporting wired infrastructure. This enables relatively simple user devices because the network infrastructure can take care of the network operation and management tasks. On the other hand, it requires an expensive network infrastructure.

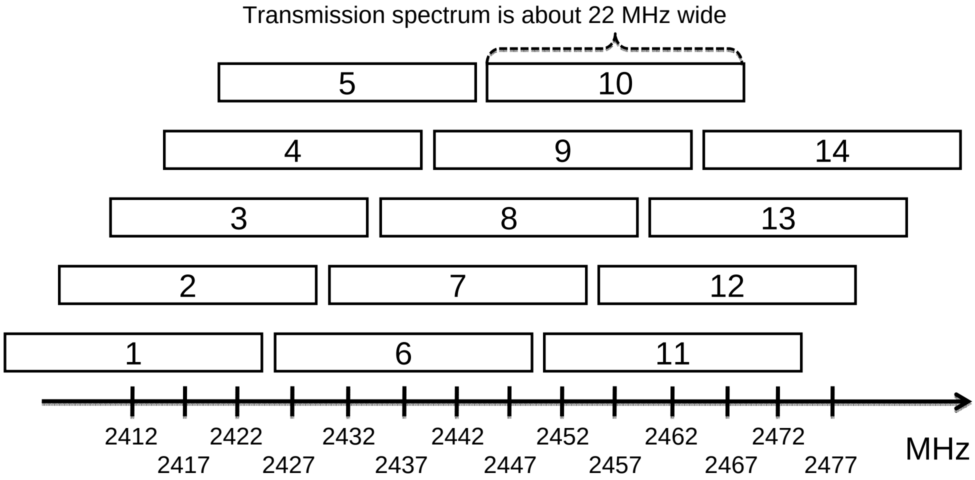


Fig. 4. *Channels in the 2.4 GHz frequency band [99].*

In the ad-hoc topology, the devices communicate only with their neighbor devices. Ad-hoc network is multihopping if communication to distant devices can be done using other devices as relays. This requires implementing routing functionality to the devices. Ad-hoc topology is suitable when no infrastructure is available and independent devices need to momentarily form a wireless network. Deployment of the network is faster and becomes cheaper than building an infrastructure. This is done by transferring the responsibilities of the infrastructure network to the end user devices that are often not designed for the purpose.

2.3 IEEE 802.11 Frequency Bands

IEEE 802.11 operates on two frequency bands that are the 2.4 GHz Industrial, Scientific, and Medical (ISM) and the 5 GHz Unlicensed National Information Infrastructure (UNII) [61]. Both frequency bands are license free.

The 2.4 GHz frequency band contains 14 frequency channels as shown in Figure 4. Channels 1-11 are available in the USA and Canada, and 1-13 in Europe. The channels are spaced at 5 MHz intervals and are about 22 MHz wide. Thus, channels are overlapping and an interference free channel configuration can be selected for only three APs in the same area. Selected channels can be, e.g., 1, 6, and 11 [99]. Frequency overlap causes stations in adjacent channels to interfere with each other, which decreases the available capacity.

The 5 GHz band is divided into 4 sub bands. These are 5.15 - 5.25, 5.25 - 5.35, 5.49 - 5.71, and 5.725 - 5.825 GHz. Channels in 5 GHz band are about 20 MHz wide and spaced at an interval of 20 MHz. Most of the IEEE 802.11a channels are non overlapping. Depending on the regulatory domain, the 5 GHz band contains up to 19 channels [45].

2.4 IEEE 802.11 Medium Access Control Protocol

The MAC protocol operation is crucial for the performance of the network. The 802.11 MAC protocol can operate in two modes: Distributed Coordination Function (DCF), and Point Coordination Function (PCF) mode. PCF uses AP as a centralized coordinator in the network, whereas DCF is designed to operate without centralized control in the network. However, PCF is an optional mode and it has not been widely implemented [148] [38].

For controlling access to the medium, the protocol uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method. Figure 5 presents an illustration of the medium access operation. The basic principle in medium access is that before sending, each station must listen to the medium and send only when the medium is sensed free. Detection of collisions is difficult in a wireless environment and the following method is used to avoid collisions. When the medium is sensed free, the station waits for the duration of an InterFrame Space (IFS) more. The time between the IFS and the next transmitted frame is called a contention window, which is divided into transmission slots. After the IFS period has passed, the station starts a backoff counter. The initial value for this counter is selected randomly between zero and contention window minus one slots. When the counter reaches zero and the medium is still idle, the station starts transmitting. If another station starts to transmit before, the counter is stopped and the counting continues when the medium has been idle again for more than IFS. Each transmitted packet is acknowledge with ACK

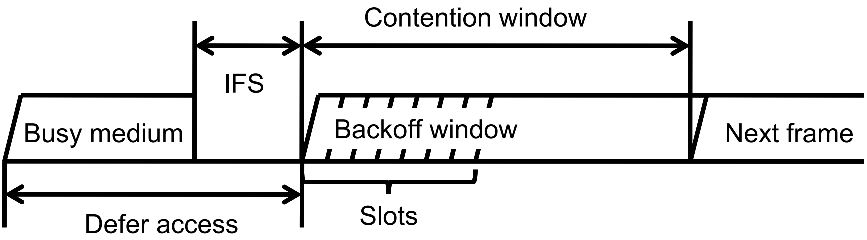


Fig. 5. IEEE 802.11 access cycle, simplified illustration [42].

packet and retransmitted if no ACK packet is received. Several additional methods are used to avoid collisions. These are dynamically changing contention window, as well as Request to Send (RTS), Clear to Send (CTS) packets [142] [41].

The medium access method described above enables controlled usage of the transmission medium simultaneously by a several stations. However, it also requires a considerable overhead before each sent frame and this causes problems, especially with high loads and small packet sizes. There are also other consequences arising from the use of CSMA/CA. Stations compete on the shared radio channel before each transmission. All competing stations have an equal chance to win (including AP). Thus, two equally sending stations will get equal shares of the throughput. Since all nodes are equal, no QoS differentiation is supported. Thus, the 802.11 poses problems for applications requiring low delay or constant throughput.

2.5 Quality of Service in IEEE 802.11 Medium Access Control

In practice, the original 802.11 MAC protocol does not support QoS. It implements two priority values for wireless stations. These are contention, implemented with DCF and CSMA/CA, and contention free, implemented with PCF. With PCF, there exists a contention free period where the access point polls stations and asks if they have data to send. PCF is designed to support time-sensitive traffic flows. Neither DCF nor PCF differentiates between traffic types or sources.

The IEEE 802.11e standard [49] has been designed to add QoS support for 802.11 WLANs. IEEE 802.11e defines a new medium access mechanism called Hybrid Coordination Function (HCF). It supports DCF and PCF for backwards compatibility but combines them with enhanced QoS-specific mechanisms.

HCF has two access mechanisms: contention-based Enhanced Distributed Channel Access (EDCA), and HCF Controlled Channel Access (HCCA) based on controlled channel access. EDCA is an enhancement for 802.11 DCF. It supports 8 priority values (traffic classes). The priority values (0 to 7) are identical to the priorities defined in IEEE 802.1D [48] standard. Traffic priorization is done with two methods. First, four different IFS lengths are used depending on the selected traffic priority. Second, a station transmits high priority traffic before low priority traffic. Thus, EDCA provides priorization of traffic but does not guarantee that low priority frames will always wait until all higher priority frames are transmitted. Thus, it provides statistical traffic class differentiation [78]. HCCA uses a QoS-aware centralized coordinator called a Hybrid Coordinator (HC). It has higher priority than EDCA. HC polls stations and provides negotiated connections between an access point and stations, and specifically assigned transmit times for every frame. This enables close to strict QoS guarantees and support of low delay applications, such as VoIP. IEEE 802.11e is currently supported by the majority of WLAN vendors.

2.6 Physical Layers of the Standard

IEEE 802.11a specified a new physical layer for 5 GHz that provides nominal throughput up to 54 Mbit/s. This was a significant improvement but there were two downsides. The physical layer is not compatible with devices implementing the original 802.11 standard. Earlier, it was not allowed in Europe due to regulatory requirements in 5 GHz band. In 2003, IEEE published an amendment 802.11h [45] that provides the required mechanisms for dynamic frequency selection and transmission power control.

IEEE 802.11b established a global market for the adoption of WLAN technology. It provides a nominal data rate up to 11 Mbit/s and utilizes 2.4 GHz frequency band. By providing a higher data rate than the original IEEE 802.11 standard, 802.11b technology enabled wireless connectivity in local environments such as offices. The IEEE 802.11b standard provides full backward compatibility with the 802.11 Direct Sequence Spread Spectrum (DSSS) mode. It defines two new transmission rates, 5.5 and 11 Mbit/s, that are implemented with Complementary Code Keying (CCK) modulation. IEEE selected DSSS as a spread spectrum method over Frequency Hopping Spread Spectrum (FHSS) because it is more efficient in radio channel usage.

IEEE 802.11g [46] is a higher data rate physical layer for 802.11. It was published in 2003 and has further accelerated the adoption of 802.11 based WLAN technologies. It is designed to be fully compatible with 802.11b. This was a clear requirement of IEEE in order to guarantee seamless adoption and interoperability between 802.11b and 802.11g products. By developing the 802.11g standard, IEEE wanted to retain the advantages of OFDM technology used in 802.11a and bring them on top of 802.11b DSSS. This was accomplished and the standard provides a higher nominal data rate up to 54 Mbit/s.

IEEE 802.11n specifies yet another physical layer providing higher data rate. It also contains various modifications to the MAC protocol. IEEE 802.11n differs from other physical layers by operating in both the 2.4 GHz and 5 GHz frequency bands. IEEE started the task group N in late 2003 to develop 802.11 physical layer that provides at least 100 Mbit/s effective user data rate. According to the IEEE official timeline [59], the IEEE 802.11n standard amendment will be published in June 2009.

Multipath signal propagation has always been a significant problem for wireless systems. It means that transmitted signal is reflected by walls and other physical obstacles and multiple instances of the signal are received by the receiving station [3]. This creates various impairments to the received signal and decreases QoS. IEEE 802.11n uses Multiple Input Multiple Output (MIMO) antenna technology to exploit multipath signal propagation and increase throughput via spatial multiplexing. MIMO technology also allows increased transmission range.

2.7 Mesh Networking

When implementing city-wide WLANs, the network deployment costs are increased due to the number of WLAN APs needed to provide coverage. WMN is one of the latest WLAN technologies designed to provide large network coverage at low deployment cost, as well as to increase network flexibility and robustness [14, 112].

WMN is formed by devices called mesh points that contain WMN functionality [35] [34]. WMN architecture is presented in Figure 6. Mesh points can be mesh portals, mesh APs or mesh portal APs. A mesh point may also lack both AP and portal functionality. Mesh portals have wired connections to a core network, while other mesh points rely on wireless connections when forwarding packets to their destinations. Logically, WMN consists of two layers that are the access network providing connectivity for user terminals, and the wireless backbone network, which forwards packets between WMN portals and APs [115]. Extending coverage without wired connections to each AP keeps deployment costs low.

Mesh networking changes the fundamental operation of infrastructure WLAN. Thus, several assumptions made by traditional WLAN management solutions no longer ap-

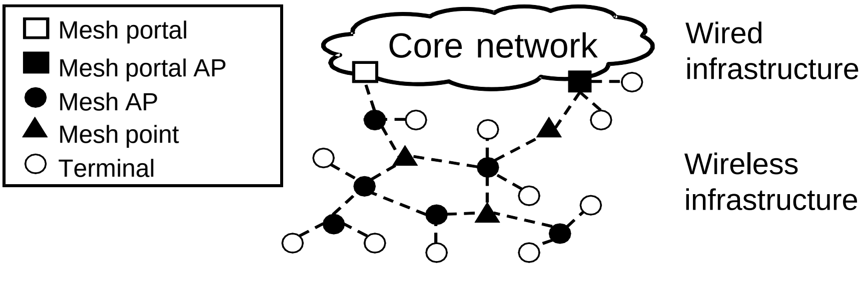


Fig. 6. WMN Architecture.

ply. Mesh networking introduces routing in the wireless network, which dramatically affects the network capacity and management.

The routing method proposed for IEEE 802.11s is the Hybrid Wireless Mesh Protocol (HWMP) [8]. HWMP uses radio aware routing attributes and either reactive or proactive routing, depending on the usage scenario. IEEE 802.11s uses layer 2 routing, which means that routing is done on the MAC protocol and is not visible for the network layer routing protocols. In IEEE 802.11s, the preferred term for routing is *path selection*. HWMP contains an extensibility framework supporting implementation of optional path selection mechanisms and route metrics in addition to the default ones [8].

Mesh networking increases the self-management functionality of the network devices, which means that devices are able to automatically adapt to the changes in the environment. Examples of the changes are automatic change of the frequency channel when AP is interfered by a foreign AP, and modification of the wireless backbone network topology to recover from a device failure. Adding self-management functionality to network devices basically means that network management functionality and responsibility are transferred from network management tools and a network administrator to the device. This is advantageous when two conditions are fulfilled. First, the current network state should be visible for the network administrator [2]. Second, the network administrator must be able to override the automatic configuration when necessary.

2.8 WLAN Management Standards

The broad usage of WLAN technology has increased the requirements to manage these networks. Standardization bodies have also noticed this need and introduced new functionality into existing standards in order to enable management. This Section describes the standardization work related to introducing management functionality into WLAN devices. The methods utilized for WLAN management form the topic of Chapter 3 and are not considered here.

In IETF, a specification for control and provisioning of wireless APs is under development by the Control And Provisioning of Wireless Access Points (CAPWAP) group [60]. CAPWAP is a protocol that allows a device called an access controller to manage a collection of Wireless Termination Points (WTPs). WTP is a reduced version of a traditional AP containing antenna and wireless physical layer to transmit and receive traffic. CAPWAP moves some MAC functions from AP to the access con-

Table 2. *Summary of IEEE 802.11k measurement reports.*

Report	**Description**
Beacon report	Information about received beacon, probe response and measurement pilot frames. Received signal strength (dBm), SNR, and the antenna used for reception.
Frame report	Similar to beacon report. Information about all received frames.
Channel load report	Measured time share when the medium was found busy
Noise histogram report	Histogram describing how the noise level (dBm) was distributed over time
Location report	Methods to exchange location information between stations (latitude, longitude)
QoS report	QoS information about traffic streams and traffic categories
Neighbor report	Stations report the list of detected neighbor APs

troller [120]. Thus, such devices are referred to as *split MAC WTPs* by the CAPWAP specification. CAPWAP specifies the required services, functions and resources in order to enable interoperable implementations of WTPs and access controllers. [60]

Simultaneously, IEEE is developing management related extensions to the IEEE 802.11 standard in several task groups. These include the work done for wireless network management in 802.11v [58], as well as for radio resource measurements in 802.11k [55]. IEEE is also developing a recommended practice IEEE 802.11.2 for evaluation of 802.11 wireless performance in a task group T [57].

IEEE 802.11v defines a framework and common methods for wireless network management. As is common with IEEE standards, the focus is on defining the necessary information for management and interactions between network management tools and network devices. However, management algorithms are not specified. The goals of this amendment include defining an upper layer interface for managing 802.11 devices in wireless networks [58]. The interface should enable the management of attached stations in a centralized or in a distributed fashion. Examples of the functionality included are QoS aware load balancing, power control, and interference detection and reporting. IEEE 802.11v is estimated to be completed in September 2009 [59].

IEEE 802.11k defines methods for AP to measure radio environment. It aims to provide radio and network measurement mechanisms for higher layers. The proposal includes various types of measurements that can be requested from other 802.11 stations to measure network operation and environment [91]. Table 2 summarizes the most important reports relevant to this thesis [18, 91, 92, 137].

IEEE task group T develops performance metrics, measurement methodologies, and test conditions to enable measuring and predicting the performance of 802.11 WLAN devices and networks at the component and application level [57]. The purpose is to enable the testing, comparison, and deployment planning of 802.11 WLAN devices based on a common and accepted set of performance metrics, measurement methodologies and test conditions.

In standardization, the aim is to provide common frameworks for implementing interoperable products. This includes agreed interfaces between devices to collect information from the network as well as to control the network devices. Thus, the standards described do not define methods for estimating WLAN performance or optimizing the network configuration. This allows vendors to innovate and gain competitive advantage with their products. In the context of this thesis, the WLAN management standards are not competing solutions but they are used as a reference in the design of proposed methods.

3. WLAN MANAGEMENT

This chapter concentrates on describing what is meant by WLAN management and identifying the requirements that it places on WISP and on the WLAN management methods. Network management is a broad area that covers issues from planning a single configuration parameter for a network device to defining contracts between organizations.

Figure 7 contains the classification of WLAN management used in this thesis. WLAN management is divided into planning, installation and operational management, based on the phases of the network life-cycle. The planning involves defining the requirements for the network, service planning, and network deployment planning. The installation is a transitional phase, which starts when the network planning is completed. It consists of deploying the network devices into the planned installation sites. The operational management consists of managing and maintaining the network when it is operational. During the network operation, the network planning continues and new APs are installed into an existing network where needed.

The operational management is further divided into sub classes based on the managed functionality. A comprehensive definition has been developed by International

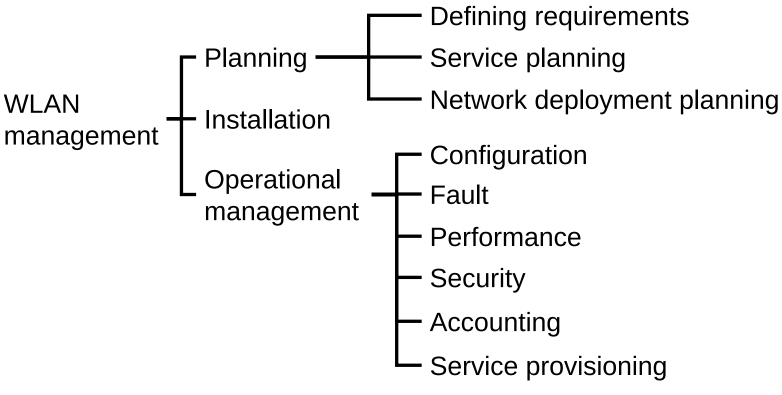


Fig. 7. *Classification of WLAN management in this thesis.*

Organization for Standardization (ISO) [64], which has specified five network management applications for the network operational management [132]. These applications specify the functionality that management concentrates on. The applications are configuration, fault, performance, security and accounting management.

A parallel definition for operational management has been specified by International Telecommunication Union Telecommunication standardization section (ITU-T) [65]. It is called the Telecommunications Management Network (TMN) protocol model and has been developed for telecommunication networks.

As Figure 8 shows, TMN divides management into four layers that concentrate on the management of different aspects of the system. The layers are element management, network management, service management, and business management. Business management includes, e.g., the management of agreements between operators. Defining, selling, selecting, and controlling the services used is referred to as service management. Correspondingly, network management includes configuring, controlling, and monitoring the managed network. Element management involves functionality for directly controlling individual network devices.

The difference between TMN and ISO models is that they approach the problem from different points of view [100]. TMN considers network management from a telecommunications network perspective, and ISO considers it from a data communication network perspective. WLAN is a data communication network and usually handled using the ISO approach. This is because it has been considered questionable whether the separation of management functionality into layers, as with TMN, is feasible for IP based systems [24]. Instead, the preferred approach is to consider management

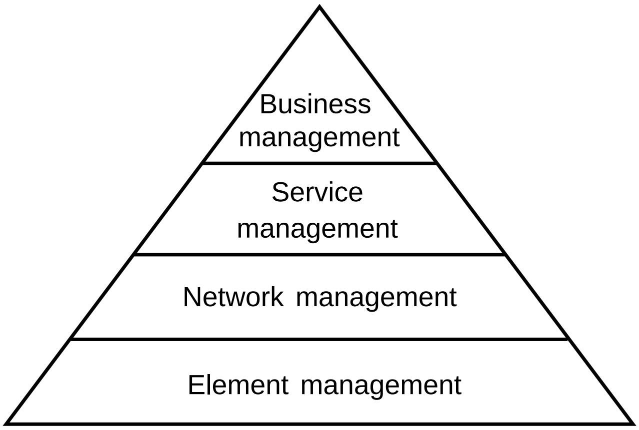


Fig. 8. *Telecommunications Management Network (TMN) layer model.*

layers in terms of their functionalities and not necessarily as being separate entities. Thus, the current trend is to implement management solutions that integrate functionality from all layers and provide service and user oriented management [88] [86].

3.1 WLAN Planning

This section defines the tasks involved in WLAN planning. The requirements for WLAN planning tools are further deduced from these tasks in Section 3.4.

3.1.1 Defining Requirements for the Network

The requirements that WISP makes for the network have been set out in [143]. The key requirements are summarized in Table 3.

Business requirements include defining a budget and timetable for the network deployment. Network planning is always a compromise between budget, the size of the network deployment, and the number of users that the network can support. A greater number of network devices, or higher quality devices, cost more but allow more users.

The expected customer base, customer applications, service area and traffic profiles should be specified. Traffic profile defines the type and amount of user traffic. The applications are important in determining the requirements for services. Each application has a distinct traffic profile and places a set of requirements on a service that can support it. The geographical area, where the service is provided for the users, is called the service area. Geographical areas in the network are not equal in terms of the number of users or required capacity. For example, a conference room often requires much higher transmission capacity than a hallway or other part of the service

Table 3. *WISP requirements for the network [143].*

Requirement	**Description**
Business requirements	Deployment budget, time frame for completion
Customer base	Expected amount and type of users. Their applications and estimated traffic profiles.
Technical requirements	Management system requirements, preferred technologies or vendors

area. Users have different requirements for the service. Thus, the customer base can be divided into groups, each of which has its own set of services and service areas.

Figure 9 shows an example how WISP may divide the network into a number of logical networks each having distinct services. This example demonstrates the complexities that exist in defining the requirements for the users. The example WISP has a network, which is divided into two logical networks, one intended for campus users and one for office users. These networks have different security requirements because the campus network must support users without authentication. The office network is restricted to the use of WiFi Protected Access (WPA). A medium quality video service provided in the campus network is shown as an example. It can be used only with WPA security level and only in the geographical area where campus network is provided. Providing access to different logical networks and different service levels using the same APs is possible by defining multiple virtual networks for APs and using Virtual Local Area Network (VLAN) technology to separate the traffic of each network in APs.

Technical requirements comprise all the requirements that WISP has for the technology. These are selection of implementation technology, preferred AP vendors and specific AP device types, as well as the utilized frequency usage policy. WISP may prefer IEEE 802.11b,g technology for implementing the network because of a large existing device base that users have. On the other hand, WISP may prefer IEEE 802.11a technology to maximize available capacity. IEEE 802.11a has a higher

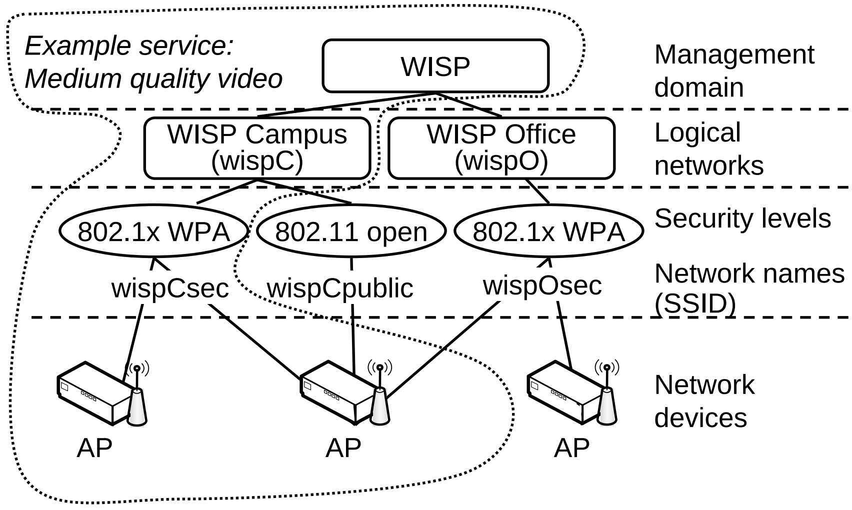


Fig. 9. *Example of dividing WISP network into logical networks and providing different services in each logical network.*

number of interference free frequency channels but few users currently have IEEE 802.11a client devices.

Frequency usage policy determines how WISP utilizes the frequency resources. The policy defines the frequency bands used as well as the channels that can be selected in the AP configuration. For example, WISP may decide to use only channels 1, 6, and 11 in the 2.4 GHz band to minimize adjacent channel interference.

Introduction of the IEEE 802.11n technology increased the need for frequency policy. Previously, the selection of the technology also determined the frequency band. However, as presented in Section 2.6, IEEE 802.11n can operate on both 2.4 GHz and 5 GHz bands. This depends on the selected AP device because not all AP types support both bands. Selection of the frequency band determines the set of clients that are supported. The 5 GHz band enables 802.11n to obtain highest performance with channel bonding due to a higher number of free channels. However, this prevents usage by IEEE 802.11b, and g clients [20].

3.1.2 Service Planning

The purpose of the network is to provide services to users. The defined services are the input for service provisioning, which ensures that defined QoS is provided for users. The content of the service being offered is defined using a Service Level Agreement (SLA) between the user and WISP [94]. In practice, SLA and its technical part, Service Level Specification (SLS), are used to define the QoS.

Table 4 summarizes the QoS parameters that SLS commonly defines for the user service [93]. QoS parameters include transmission rate, delay, traffic class, packet dropping policy, and security level. Traffic class defines how packets in this service

Table 4. *Key QoS parameters specified by SLS.*

Parameter	**Description**
Rate	Transmission rate
Delay	Expected delay of transmitted packets
Traffic class	Traffic class of the transmitted traffic. Affects the priority of data packets in devices.
Policy	Policy for packets exceeding the defined traffic profile
Security level	Required or allowed security configurations

are handled in the network compared to the packets of other services. Policy defines how packets exceeding the traffic profile are handled and it enforces the data flow to comply with the specified traffic profile. Traffic exceeding the amount specified in SLS can, for example, be shaped by delaying selected packets. Another method is to drop packets instead of delaying them. Shaping is not beneficial for applications that require low delay, such as VoIP. Security level defines the security configurations allowed for the service.

3.1.3 Network Deployment Planning

Deployment planning is made on the basis of both the requirements and the designed services described above. The planning requires the selection of actual network devices, antennas, installation locations, and the creation of a detailed configuration for each device. The vendor and type of device are selected mainly on the basis of the technical requirements described in Section 3.1.1, but the earlier experience of the network designer is also relevant.

The next step is to select the number of APs and their installation locations, radio interfaces as well as antenna directions. The environment limits the set of candidate deployment locations, which usually cannot be selected freely. In practice, each location has different costs depending on the required equipment space, wired network connection, and in outdoor deployments, the building, or tower height. A limited set of possible deployment locations complicates development of planning algorithms. However, the limited set of possibilities is beneficial for algorithms that explore the search space. This is because the search space is smaller.

The node placement problem is different in non-mesh WLANs and WMNs. In WMNs, it actually involves three different problems. The first problem is to find installation locations for WMN portals. Each portal location should have a wired Internet access but the locations should be distributed equally over the required coverage area. The second problem is the selection of mesh AP locations. Mesh APs must provide coverage with adequate signal strength for all user terminals. The third problem is the selection of locations for additional mesh points that improve the capacity of the mesh backbone.

WMN topology is closely linked to fairness, which means how equally the available capacity is divided among APs. Without special attention, fairness becomes problematic as several research articles testify [14, 115, 127, 130]. The reason is that the IEEE 802.11 MAC protocol aims to give an equal number of transmission opportunities to all APs and user terminals. Unless APs actively limit the amount of traffic user terminals are allowed to transmit, more capacity is effectively available to terminals that are closer to a portal. IEEE 802.11e [49] can be utilized to control mesh point capacity reservations and this improves MAC protocol fairness, as shown by Duffy *et al.* in [23]. However, fairness must also be taken into account in WMN deployment planning to ensure sufficient capacity for WMN APs in the network boundary areas [130].

Network devices have a large set of configurable parameters. Of these, the parameters that affect the network capacity and coverage are transmission power, frequency channel and routing method. Since the network may be divided into several logical networks each having a distinct service area and set of users, SSIDs and security settings are also important. Selection of frequency channels is made on the basis of the defined frequency usage policy. Each selection described above affects another and makes the planning process extremely complex. Selection of devices, installation locations and configuration are often made separately. However, it is preferable to take these dependencies into account in the planning.

Feedback on the network performance during planning is useful for the network designer. Early feedback saves costs by enabling the network designer to experiment with various setups without installing the network devices. Since the network plan specifies the network that is installed, it dictates the number of users and services the network is able to support. It defines the service areas and the capacity provided in each area. Thus, the developed network plan should be as good as possible to maximize the gains in relation to the cost of the network. The last phase of the network planning is the documentation of the plan for the installation.

3.2 WLAN Installation

Network installation is done on the basis of the network plan. It consists of deploying and configuring the network, and fully documenting the installed network. Documentation includes the locations of the devices, the equipment and configuration used. The deployed network should be tested by measuring its coverage and signal levels. Capacity tests can also be done to gain at least some information about the network performance.

3.3 WLAN Operational Management

Management applications defined by ISO specify the major areas of operational network management [132]. Operators have large networks with thousands of network devices. Thus, from the standpoint of the operator, configuration management is one of the key challenges for WLAN management [123].

The configuration management maintains a device inventory containing detailed information of the technology utilized in the network. This includes network devices, radio interfaces, antennas, and device configuration. As in the planning, device configuration may involve hundreds of settings, of which the most important are device type, radio interfaces, transmission power, antenna direction, frequency channel, security settings, and SSIDs.

Fault management is responsible for reacting to defects in the network. Maximizing the network uptime is critical for WISP, since each fault creates dissatisfied customers [132]. Fault management should locate the defects as early as possible and automatically restore the network operation. Usually, fault management contains a trouble ticketing system [99] that can be used for following up the defects.

Performance management monitors the performance of the network and provides methods to optimize the network configuration and supervise the execution of the new configuration. Performance management supervises the network capacity, environment, interference level, coverage, as well as service capacity and user QoS level in different areas of the network. Environment monitoring provides information about APs from external networks that may cause interference. Information about the network traffic is refined into traffic trends. This information is provided to network maintenance and planning, and it enables the addition of new devices to the network when necessary. Methods to optimize network configuration are needed for improving network performance. Key optimization targets include decreasing interference in the network, and improving coverage, capacity, and reliability. Consequently, the purpose of the performance management is to provide a reliable and stable network for users and deliver the promised QoS.

Due to usage of a wireless communication medium, security is an important aspect of wireless network management. Security management defines the security configuration for APs, including the authentication and encryption protocols used. The area where communication is possible is very difficult to control. Security management involves preventing unauthorized access, eavesdropping, and message tampering, as well as verifying user identity. However, the network access should be made easy for authorized users.

Security management is closely linked with accounting management, which handles the information on customers. User authorization and accounting is often implemented using a Remote Authentication Dial In User Service (RADIUS) [113]. Identification information about authorized users is stored in a RADIUS server and utilized by WLAN APs. In this architecture, WLAN APs act as gatekeepers, identifying users and authorizing access to the network. Accounting management is also responsible for collecting billing data from the network. This is done by monitoring user traffic, and recording the volume of traffic and connection time [99].

3.3.1 Service Provisioning

Service provisioning is not thoroughly addressed in the management applications defined by ISO. The purpose of service provisioning is to offer a controlled network connectivity and transmission service for the user. Service provisioning has been seen as one of the key competitive differentiators between WISPs [126]. Detailed discussion of the requirements for WISP in the area of service provisioning can be found in [9,24,72,93,123].

The following are key requirements:

- fast network access supporting also roaming users
- user control of the utilized services
- controlled and predictable QoS level of the user service
- easy service selection for the user
- simple configuration process for the user terminal
- adequate security level for the user
- a method to define the QoS level of the services
- separation of different user groups
- allow different security levels and services for each user group.

Defining the provided service is part of the planning phase as described in Section 3.1.2. The parties of the service provisioning and interfaces between the parties are presented in Figure 10. These parties are the user, WISP, and all service providers that WISP management domain is connected to.

The implementation of service provisioning requires a service selection mechanism for the user and a method to enforce and monitor the agreed QoS level. Service selection can be either static SLA defined between the user and WISP or a mechanism to change the properties of the service dynamically. For providing controlled end-to-end service for the user connections, QoS control is needed in various locations. First, QoS is controlled at the interfaces of the network devices. Second, strict QoS guarantees for supporting applications requiring low delay, such as VoIP, cannot be implemented without the support of link layer QoS control. Third, enforcing the QoS level of the service when crossing management domains requires agreements between WISP and other service providers.

3.4 Requirements for WLAN Planning Tools

A set of requirements for a WLAN planning process and planning environment can be deduced from the tasks that the network designer has to perform. A summary of the requirements relevant to the present thesis is presented in Table 5. Requirements can also be set for the quality of the planning result. The main issue concerning service provisioning is how much capacity can be guaranteed for the user [127]. The

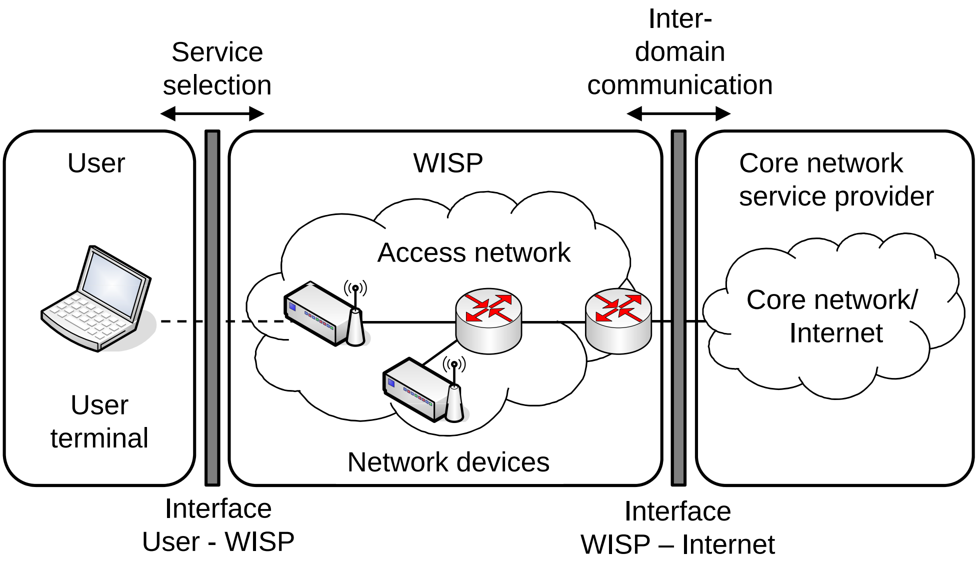


Fig. 10. *Parties and interfaces related to service provisioning.*

performance of the designed network must be estimated before the capacity can be provisioned for the users. The reliability and stability of the network influence how accurate such estimates are. Thus, predictability is one of the key requirements for the deployed network. For example, route instability causes changes in the capacity given to the user [106].

Table 5. *Summary of the requirements for WLAN Planning Process.*

Class	**Requirement**	**Description**
Planning requirements	Equipment selection	Network designer selects the types of WLAN equipment, antennas, cables. Technology selection: IEEE 802.11a,b,g,n.
	Mesh point locations	Deployment locations for WMN mesh points, APs, and portals
	Radio interface selection	Radio interfaces added to each WMN mesh point
	Mesh point configuration	Transmission powers, frequency channels, antenna directions
Quality requirements	Planning control	Network designer has the control of the planning process
	Support for continuous planning	System allows extending an existing network. Performance estimation must support a combination of real and proposed devices.
	Quality of the created network plan	Optimized network performance. Network should be reliable and stable.
Feedback	Performance estimation	Information on the network performance is provided to the network designer. The amount of capacity available for the user. E.g. how many VoIP calls can be supported?
	Network visualization	System provides visual feedback of the network and its performance for the designer

Feedback should be provided as early as possible to decrease planning time and improve the planning result. Visualization of the planned network in terms of network architecture, radio signals, interference, and performance, helps the network designer to gain a deeper understanding of the network operation.

The support for continuous network planning differs from generating a complete network plan. A planning tool should provide a proposal for adding a new AP into an existing network. This includes location and type, interfaces, radios, and configuration for an added AP. Performance estimation should also support continuous network planning.

3.5 Related Proposals

WLAN management research has its origins in the research of wired network management. Cellular and ad-hoc networks have also affected WLAN management research. The key differences between these networks lie in their physical layer and MAC layer as well as in the characteristic operation of the network nodes.

Compared to wired networks the main difference is the wireless operation, which introduces several additional challenges as described in Chapter 1. The design of physical and MAC layers differs significantly from the ones utilized in cellular networks. Thus, the management methods developed for cellular networks are not applicable for WLANs as such [85]. In ad-hoc networks, the nodes are mobile by definition, which differs from the basic WLAN operation. In WLANs and WMNs, the infrastructure nodes are mostly immobile.

Earlier published research on WLAN management relating to this thesis concentrates on methods for node placement, WMN topology and channel assignment optimization. Node placement is part of the WLAN planning, whereas WMN topology and channel assignment optimization can be done either during WLAN planning or at the operational management phase.

Changing the MAC protocol operation is also one promising method to increase WMN performance using, e.g., smart or directional antennas [131], or the simultaneous use of multiple channels [82]. However, the need for WMN deployment planning still remains and this thesis does not concentrate on MAC modification proposals.

3.5.1 Node Placement Optimization

Three heuristic algorithms for optimizing the placement of mesh portals based on Integer Linear Program (ILP) have been proposed by Chandra *et al.* in [16]. The approaches require prior knowledge of the traffic flows and aim to strategically place a minimum number of mesh portals to satisfy the capacity demand.

A greedy algorithm for AP placement have been proposed by Max *et al.* in [95]. After the user has selected node equipment, antennas, and node configuration, the proposed algorithm selects locations for the nodes. The algorithm concentrates on maximizing the signal strength with a minimal number of APs.

Kouhbor *et al.* propose a mathematical model to select the minimum number of APs to serve a given set of terminals in [79, 80]. The proposed model is solved by means of a developed discrete gradient optimization algorithm. The algorithm starts with a small number of APs and increases it until the constraints are satisfied. Minimized optimization criterion is the path loss between APs and terminals.

In [15], Chan *et al.* have proposed a Genetic Algorithm (GA) [69] to select optimal locations for APs in a factory environment. Their optimization target is to maximize signal strength and minimize the number of APs required.

In [117], Rodrigues *et al.* propose a method for the optimal placement of APs in an indoor environment. Their method maximizes signal strength and the coverage area. The problem is formulated as ILP and solved with a commercial optimization software.

In [101], Prommak *et al.* propose a WLAN design approach that focuses on assuring network capacity. The approach is formulated as a constraint satisfaction problem. The solution provides access point locations, frequency channels, and power levels to meet user demands. The problem is solved using a brute force mechanism.

The main drawback of the proposals described above is that they fail to consider the characteristics of WLAN operation, such as medium access mechanism, contention between network devices, and interference. As a result, their applicability is questionable for WLANs using the IEEE 802.11 MAC protocol.

A method for optimizing WLAN capacity with joint optimization of AP placement and channel assignment has been proposed by Lee *et al.* in [84]. The objective is to minimize the maximum channel utilization in the network. The problem is modeled as ILP and solved with a commercial optimization software.

Recently, Bosio *et al.* have proposed several ILP formulations for AP placement and channel assignment. They start with a simple ILP minimizing the number of APs when the required coverage has been specified. The next model aims to minimize the coverage overlap between APs, which is desirable since this achieves minimal interference between terminals and neighbor APs. The third model maximizes the network efficiency by considering how the capacity is divided between network devices. For this, the method defines a balanced share of the capacity provided for a terminal. Balanced share is calculated by dividing the total capacity by the number of interfering terminals. The balanced share concept has similarities to the throughput estimate presented in this thesis [P1], [135]. However, the balanced share concept does not take overlapping channels into account.

The following proposals aim to select the locations of gateways in WMNs. ILP and a polynomial time near-optimal algorithm for selecting a set of APs to act as portals in WMN have been proposed by Aoun *et al.* in [7]. This approach requires prior knowledge of the traffic flows and it attempts to select the minimum number of mesh points to act as portals to satisfy the capacity demand.

A method to select mesh portals from a predefined set and create routes between mesh points to form a backbone topology for WMN has been proposed by Hsu *et al.* in [40]. Their method utilizes GA to find a feasible network topology by selecting portals and routes for the network. The method does not consider mesh point frequency channels and assumes only a single radio in each mesh point. Neither of these latter two proposals considers interference between mesh points or the WLAN medium access mechanism.

The major difference between our work and the proposals cited above is that in the latter the set of optimization criteria is fixed by the algorithm designer and cannot be adjusted. This is a significant limitation because the same optimization criterion is not generally suitable for all planning situations. As described in Chapter 1, the planning requirements, such as coverage, cost, and capacity, are mutually conflicting and WISP may place a different emphasis on each requirement depending on the situation. The performance model presented in this thesis is designed to be flexible and be configured by the network designer.

Another common limitation in the abovementioned proposals is a failure to take WLAN capacity into account. Overlapping channels, distributed medium access, and multirate operation are key WLAN characteristics, which make traditional network planning methods unsuitable for WLANs. This is particularly unacceptable in WMNs where inadequate performance can easily render the entire network unusable.

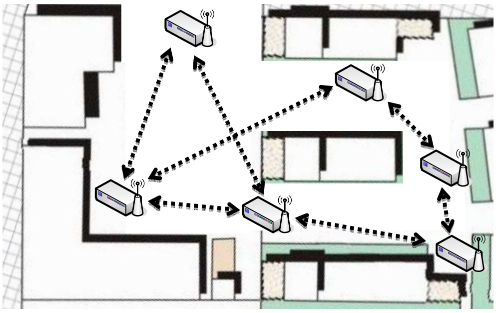


Fig. 11. *Interference graph between 6 network devices.*

3.5.2 Channel Assignment Optimization

The traditional method for modeling the WLAN channel assignment problem is to create an *interference graph* of the network. An example of an interference graph is presented in Figure 11. Network devices are nodes in the graph. An interference graph contains a link between two nodes if the corresponding network devices interfere with each other. Interference is usually represented as bidirectional. As the figure shows, one benefit of the interference graph is that it can take the operating environment into account. An obstacle may prevent two nodes from interfering with each other, even though they are actually close enough to interfere in terms of the carrier sense range.

With an interference graph, an interference free channel setup can be created using a graph coloring method. Graph coloring means that a graph is colored in a way that each node connected with a link has a different color. The color space is selected to model non-interfering frequency channels. This way, a graph coloring method results in an interference free network. It has been demonstrated that the graph coloring problem is NP complete [114]. The problem has been well studied and several effective heuristics exist for solving the problem.

However, there remain problems with the graph coloring method. First, there are often no interference channel setups available, which means that the graph coloring method does not find an interference free setup. Another problem is that graph coloring cannot be applied to WMNs, where backbone network connections must also be taken into account during channel assignment.

Heuristics for minimizing the interference by channel assignment have been proposed by Tang *et al.* in [66] and Ramachadran *et al.* in [105]. Both of these approaches use an interference graph and a centralized algorithm that minimize the interference according to the graph. Das *et al.* have proposed two ILPs for the same purpose in [19].

Further, in [30], Greve *et al.* have proposed ILP formulation for the purpose. Greve *et al.* have developed algorithms for distributing the neighbor nodes over wireless interfaces and for distributed channel assignment in order to minimize the interference.

Optimization of WMN channel assignment using load balancing-based approaches has been presented by Jingyi *et al.* in [73], and Raniwala *et al.* in [107, 109]. Both use long time traffic trends to estimate capacity need in different parts of the network. A heuristic is then used to equally divide the load between APs in the area. In [108], Raniwala *et al.* have also developed a distributed algorithm for load-aware channel assignment. Load-aware channel assignment enables the concentration of resources where they are actually needed. However, load-aware algorithms often have problems with stability, especially in small scale networks such as WMNs [30].

Alicherry *et al.* have proposed a linear programming model for joint channel assignment and routing in [4]. Their approach optimizes the overall network throughput subject to fairness constraints. Using a tight dependence between routing and channel assignment, the otherwise elegant proposal limits itself to its defined routing method.

A method for distributed channel assignment has been proposed by Villegas in [27, 136, 140]. In this method, APs communicate and adjust their frequency channel to adapt to the changes in the environment. The method implements a greedy heuristic for graph coloring. Frequency channels are assigned to one AP at a time using a specified order. The order is defined using two criteria. The first of these is to select APs, which have a higher number of neighbors already having an assigned channel. The second criterion is to select APs, which have a higher amount of interference or number of neighbors. As a result, while the utilized algorithm is fast, it is not guaranteed to provide optimal channel assignment.

Design employing multiple design criteria for WMNs has been proposed by Kodialam *et al.* in [77]. They propose two link channel assignment schemes based on ILP formulation that is solved using a fast primal-dual algorithm. Their proposal is able to optimize a single objective function at a time but it does not provide a generic method for dealing with the multiple design objectives. A method for node configuration optimization has been proposed by Sen *et al.* in [124]. The proposal divides the node configuration problem into four parts, each of which is solved separately. The proposal contains methods for WMN topology search, WMN AP tower height optimization, antenna, and transmission power selection.

Several algorithms have been proposed for channel assignment. However, there is still need for a more comprehensive solution for the entire planning process and also for backbone network planning. The algorithm should select mesh point locations, assign backbone network interfaces for APs, select equipment and configuration. The planning should also be done according to designer preferences. The planning process and the performance model described in this thesis aim to provide a more comprehensive solution for WLAN management.

4. MODELING IEEE 802.11 WLAN PERFORMANCE

In this thesis, WLAN performance comprises many aspects of the network operation. Examples of metrics that can be used to measure performance are presented in Table 6. Later in this Chapter, a selected set of metrics is described in greater detail in order to describe the issues and common methods for estimating WLAN performance. Proposals relating to the estimation of the metric values are also presented.

Metrics, such as noise level, Signal to Noise Ratio (SNR) and link throughput are defined for individual devices or links between devices. In such cases, metrics are calculated for the entire network by calculating the average value of all devices or links. Metrics can be calculated either for the entire network, or individually for

Table 6. *Examples of performance metrics for WLAN.*

Metric	Description
Signal to noise ratio (SNR)	Ratio of received and noise signal in the receiver
Interference	Level of interference in the network
Link throughput	Throughput of a link between two devices
Packet loss rate	Percentage of packets not received due to collisions or low SNR
Capacity	The amount of traffic that can be transferred between terminals and the core network
Fairness	Measures how equally capacity is divided between different parts of the network
Coverage	Size of the physical area where the network is available
Packet delay	Delay of transmitted packets
Roaming delay	The length of a time period when WLAN service is not available because of the change of AP where terminal is associated

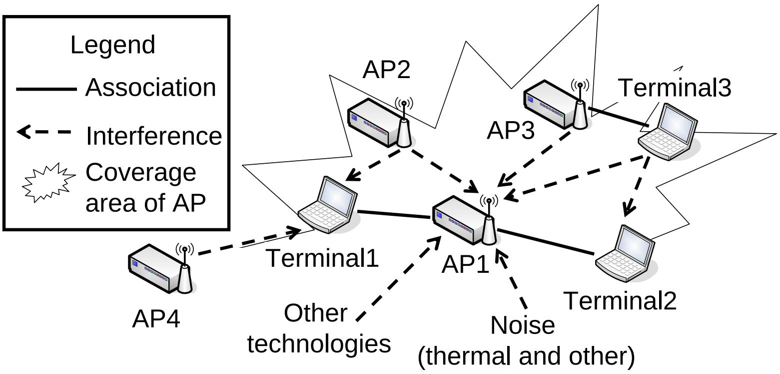


Fig. 12. *Interference sources for WLAN AP.*

each type of traffic. For example, packet loss rate, capacity, and packet delay can be different for web surfing and VoIP.

In order to create a performance model for WLAN it is necessary to define a set of metrics that are included in the model. The selection is affected by three factors. First, how much the changes in the network configuration affect the selected metric. For example, it is difficult to affect roaming delay by simply changing network configuration. Thus, this metric is not very useful when optimizing the network configuration. Second, how reliably the corresponding metric can be estimated. If the metric estimation is unreliable, it cannot be used to provide information about network performance. Third, the network administrator must be able to understand the meaning of the metric in order to configure the relative importance of each metric in the optimization.

4.1 SNR and Interference

The radio channel used for WLAN data transmission is shared between different users, networks and technologies. All these compete on the shared radio channel causing interference with each other. Figure 12 presents the interference sources of an individual AP. These include other technologies (e.g., 802.11 and Bluetooth both use the 2.4 GHz ISM band), other networks (802.11 WLAN has 14 frequency channels of which three can operate without interfering with each other), other terminals (terminals compete on the channel access), thermal noise, and human-made noise.

In general, a station is able to receive a packet successfully if the received SNR exceeds a threshold value that depends on the sensitivity of the receiver and the modulation used. Modulations with higher data rates are more sensitive to noise than those with lower data rates [99]. SNR is calculated by dividing the received signal (P_{signal}) by noise (P_{noise}). SNR is often expressed using a logarithmic decibel scale.

The strength of the received signal (P_{signal}) depends on the distance between transmitter and receiver but also on the prevailing signal propagation conditions in the environment. The same rules also apply to the strength of the noise signal (P_{noise}). Noise consists of all signals except the received signal.

The noise strength is often calculated as a sum of individual noise signals. This is commonly referenced as a *physical model* of successful transmission reception [31]. However, as noted by Rajaraman in [104], this is a slightly pessimistic model since in practice the signals often tend to cancel each other. This means that the number of interfering nodes does not significantly affect the interference range. A more important issue is the interfering traffic profile. This depends on the number of interferers as well as the transmission rates of each station. If an interfering station increases its sent rate, or there are more interfering stations, it naturally causes a decrease in the effective throughput of other stations.

Interference caused by other WLAN stations is commonly divided into co-channel and adjacent channel interference [138]. Co-channel interference is caused by other WLAN transmissions in the same frequency channel. Adjacent channel interference is caused by transmissions in adjacent or overlapping channels. This is especially important in IEEE 802.11b, g and n where channels in the 2.4 GHz frequency band partially overlap. WLAN receiver considers adjacent channel interface as noise (P_{noise}).

Interference between different radio systems can be minimized by properly separating the systems either geographically or by frequency. Minimizing the interference level is an important design factor for a wireless communication system. The operating environment also affects the signal propagation and network coverage area due to the presence of buildings and other obstacles. Signal attenuation depends on the wall materials in buildings. Accurately taking account of the environment is difficult but necessary for achieving reliable results in performance estimation.

4.1.1 Co-channel Interference

In 802.11, stations are unable to send and receive, or receive multiple transmissions simultaneously. By sharing the same channel, stations interfere with each other and thus reduce the achieved capacity. As described in Section 2.4, IEEE 802.11 MAC protocol uses CSMA/CA for controlling the channel access in DCF mode. The stations operating in the same channel use CSMA/CA to schedule their access to the medium. Thus, stations do not normally transmit simultaneously but they take turns and their transmissions do not affect the noise level. Instead, co-channel interference affects the amount of time each station is allowed to transmit. Over the long term, the transmission time is shared equally between stations. There exists a situation called *hidden terminal problem* when CSMA/CA is unable to schedule transmissions because not all stations are aware of each other [75]. When CSMA/CA fails, the stations transmit their packets simultaneously and collision occurs. In this case, the receiving station interprets the colliding packet as noise.

4.1.2 Adjacent Channel Interference

Interference from overlapping channels increases the noise floor in the channel. An increased noise level causes the sending station to change the used modulation to a one with higher noise tolerance. Packets can also be completely dropped or corrupted due to noise. This decreases link throughput and the achievable range between stations [99].

The distance between the channels affect how much the frequency spectrum overlaps. In IEEE 802.11b, g, and n (when using the 2.4 GHz band), the channel overlap should be at least five channels (> 22 MHz) to achieve an interference free setup [138]. The achieved capacity depends on the channel distance as described in publication [P1]. Throughput measurements based on channel distance have also been presented by Robinson [116], Rodrigues [118], and Villegas [140].

The number of radios that can operate simultaneously in a single AP is dependent on adjacent channel interference. Due to the small physical separation of radios in a one device, channel separation becomes even more critical. In [116], Robinson *et al.* have empirically studied the optimal number of radios, for which they propose a practical limit of two radios. Multiple radios have also been proposed by Alicherry *et al.* in [4]. According to their results, the practical limit is three radios.

4.2 Capacity Estimation

WLAN capacity can be estimated theoretically by calculating the asymptotic network capacity [31, 32]. This means that the capacity is estimated in a steady state and the results are valid when the network is large. The traffic pattern has a significant impact on the network capacity. The traffic pattern determines how the transmitters and receivers are distributed in the network. For a random traffic pattern, it has been demonstrated [31] that the network capacity of a single station is limited to

$$\Theta(W/\sqrt{n \log n}), \tag{1}$$

where W is the nominal capacity of the station and n is the number of stations in the network. In effect, this means that when the number of stations in the network increases, the capacity available for a single station decreases. This is because the stations are encumbered by the traffic generated by other stations. A random traffic pattern refers to a situation where senders and receivers have been selected randomly from the set of stations.

Capacity can also be estimated by modeling the operation of the IEEE 802.11 MAC protocol. A common method is to model DCF operation as a Markov chain [10, 139, 146]. This method also provides asymptotic results that are valid when the network is large. Asymptotic methods do not provide the exact capacity of a network with a given number of stations, particularly when the network is small [1].

A third method to estimate capacity, which is used in this thesis, is to concentrate on the maximum capacity that a particular network setup can achieve [96]. This differs from the asymptotic analysis by using detailed knowledge of locations, types, and configurations of the network devices. Certain assumptions, such as terminal locations and their traffic profiles, still need to be made [12]. Thus, the provided capacity estimates are statistical and present long term estimates. Estimating the maximum capacity of a particular network setup enables optimization of the network configuration, which makes it valuable for the network administrator.

Capacity is defined as the amount of traffic that a network is able to transfer between network devices. Because most of the traffic in a network is transferred between terminals and the core network, the capacity of a network can be calculated as a sum of the capacities of individual APs.

APs, terminals, neighbor networks, and the environment all affect the network capacity. The selected technology, AP locations, equipment, and configuration have the greatest effect. Configuration parameters include frequency channels, and transmission power. With regard to terminals, location, movement, and traffic profile are the key parameters, though these are also the most difficult to estimate.

4.2.1 WLAN Rate Adaptation

Throughput of a flow changes constantly during the flow lifetime. WLAN devices change the used modulation and transmission rate to avoid transmission errors when signal quality decreases. Despite the rate adaptation, transmission errors still occur and retransmissions are required.

Taking WLAN rate adaptation into account in capacity estimation is difficult because it is affected by the locations of the terminals, which are generally not known. Depending on the density of the AP deployment, each geographical location has a different set of possible APs that the terminal can associate with. AP is usually selected according to SNR but the exact method depends on the terminal device implementation and the logic used may also differ.

If network deployment is dense, it is more likely that a high SNR link can be established in each location. However, because the amount of non interfering channels is limited, especially in the 2.4 GHz band, this increases the amount of APs that interfere with each other.

WLAN rate adaptation affects the performance of WMN. If WMN backbone employs a link between two distant devices that has low signal strength, the link will use a modulation with a lower link rate to decrease transmission errors. Thus, the throughput achieved will be lower. This decreases the capacity of all devices whose traffic is routed through the particular link.

4.2.2 Multihopping

Capacity in WMN is inherently lower than in an infrastructure WLAN because APs are required to forward the packets of their neighbor mesh points [70]. Several radios are often used to reduce interference and to increase network capacity [2,4,116,119]. The simultaneous use of multiple wireless technologies with different frequency ranges, such as IEEE 802.11g and IEEE 802.11a, is also common [77]. The effective topology of the network defines the mesh points that can interfere with each other and sets a limit on the network capacity. Link level topology is defined by mesh point locations and configuration.

Effective topology is also affected by selected routes. Routing determines the actual nodes that participate in forwarding each transmitted packet flow in the network. Dynamic routing complicates capacity estimation because the capacity changes whenever the routes change. Due to low device mobility, the most suitable routing methods for WMNs are those based on proactive hop-by-hop routing [83, 106, 144]. Traditionally, routing has been based only on hop count but this does not account for the interference, varying link throughput, and traffic load. With an effective routing, it is possible to avoid interference hotspots and use high throughput links. Routing should use stable attributes based on the network topology to ensure routing stability. Fluctuating routing attributes, such as traffic load, may cause instability [144].

The routing method has a major impact on the overall network capacity. Depending on the behavior of a network, different capacity results are achieved with different routing protocols. An overview and comparison of protocols is presented in [77]. For a single station, the main points of interest are how optimal the found route is, the route discovery time (i.e., the time to find a new route), and how often routes change. The importance of route optimality is discussed in [67] by Jain *et al.* According to their results, using alternative routes around the interference hotspots can increase the capacity achieved. However, using a longer route usually causes a longer delay for the packets. This is not acceptable for applications requiring low delay. From the management point of view, the most important aspect of routing is the possibility to use any routing algorithm the network designer selects. The management algorithms must be able to adopt new routing algorithms according to the preferences of the user. The same routes should be used in planning and in the deployed network to guarantee the quality of the performance estimates.

The traffic pattern in WMNs differs from that in non-mesh WLANs due to multihopping. The pattern is not purely random but can be considered as more local since most of the traffic is transmitted between portals and end user terminals. Asymptotically local traffic patterns are studied by Kozat and Tassiulas in [81]. They propose that the capacity available for a single node is limited to

$$\Theta(W/\sqrt{\log n}). \tag{2}$$

The equation shows that WMNs have limitations in capacity that cannot be ignored and must be taken into account in the network planning.

4.2.3 Runtime Capacity Estimation

Capacity estimation for WLAN operational management can be achieved using three main methods. The first is to measure runtime channel utilization. As described in Section 2.8, the channel utilization is included in the channel load report defined in the IEEE 802.11k. A method for estimating runtime channel utilization has also been presented by Chen in [17]. The method utilizes the channel utilization information for implementing a QoS-aware routing.

The second method is to measure signal strength between AP and terminal. This provides information about the transmission rate of the link but does not consider co-channel interference. Signal strength statistics are also included in IEEE 802.11k reports.

The third method is to measure actual traffic in the network or generate traffic. This method has been utilized by Kim in [76]. The method utilizes existing network traffic as probes and measures MAC frame delivery ratio and link data rate.

Averages of the measured capacity can be calculated and used in management algorithms. IEEE 802.11k reports provide valuable information for performance estimation but are not available during the network planning phase.

4.3 Coverage Estimation

Coverage is a factor in performance because it defines the physical area where network services are available. The main difficulty in determining the network coverage is to estimate how the operating environment affects the signal strength in different locations. The WLAN signal can be blocked or reflected by obstacles such as walls and people. Coverage of an operational network can be measured, though often the network does not yet exist and estimates must be achieved by modeling the environment.

Effective methods for coverage estimation are also required. Signal strength estimates in various parts of the network should be accurate but the algorithm complexity should also be considered. Calculating the coverage for a large geographical area using a high density of calculation points may become computationally too exhaustive for practical use by WISP or by optimization algorithms.

IEEE 802.11k standard specifies the information required for determining coverage with the use of terminals in operational WLAN [33]. The standard defines the messages used to request terminals to measure the APs inside their communication range. It also provides a method for the terminal to report its present location if such information is available. The means for determining the geographical location of the terminal are not specified. However, if such information is available, it is simple for

AP to estimate its coverage as well as interference between terminals and neighbor APs.

4.4 Fairness Estimation

Fairness describes how the capacity is distributed across the network. When optimizing the WLAN capacity, it may happen that the capacity is concentrated on limited areas in the network. This can be prevented by including fairness as an optimization criterion during network planning.

A simple and computationally inexpensive method to calculate fairness is to use the fairness index defined by Jain [68]. It is calculated as

$$f = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2}, \tag{3}$$

where x_i is the capacity of AP i and n is the total amount of APs. The fairness index intuitively describes how equal the AP capacities are, using a value between 0 and 1. The performance model developed in the present thesis utilizes this method for calculating fairness [P2].

However, the fairness index described above does not provide the best possible output if the amount of interfering neighbor APs is significantly unequal between APs. Another common method to define fairness is max-min fairness [102]. Max-min fairness allows increasing the capacity of individual APs when this does not decrease the capacity of other APs. This leads to unfair capacity allocation if measured using the fairness index. However, calculating max-min fairness requires that the max-min fair capacity distribution is known. The fairness index defined by Jain makes an assumption that each AP should have equal capacity.

4.5 Using a Performance Model for Optimization

A performance model can be used by optimization algorithms in WLAN management. A key challenge is to assign proportional significance to each optimization objective, which are often mutually conflicting. This is a common problem in multi-objective optimization.

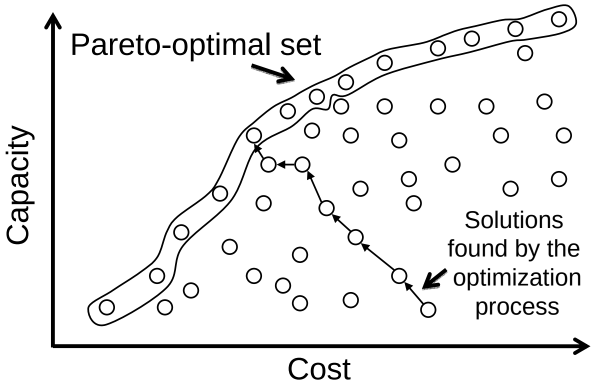


Fig. 13. Example of a pareto-optimal set.

A multiobjective optimization problem usually has no unique, perfect solution, but rather a set of alternative solutions known as a *Pareto-optimal set* [25, 26]. A pareto-optimal set is illustrated in Figure 13 with an example of two optimization objectives that are capacity and cost. Each circle in the figure represents a found solution, which means that there exists a configuration that provides a corresponding cost and capacity. A pareto-optimal set defines the optimality in the sense that a solution belongs to the set if none of the objectives can be improved without impairing other ones. Pareto-optimal set is sometimes called pareto front [103]. A pareto-optimal set is usually not continuous because configurations do not exist for all possible outputs. For a network designer, knowledge of the whole pareto-optimal set would be preferable because this would allow selection of the best configuration with no predefined requirements.

Finding the pareto-optimal set is difficult. This can be overcome by choosing the relative importance of the objectives prior to the optimization. In this way the optimization process can be guided toward the preferred solution, which is a member of a pareto-optimal set. This eliminates the need to find the whole pareto-optimal set.

5. SUMMARY OF RESULTS

This chapter summarizes the results of this thesis presented in publications [P1] - [P7]. The order of the presentation follows that of the publications.

Section 5.1 describes the development of the performance model. Section 5.2 presents the planning process that was developed along with the proposed algorithms. Section 5.3 considers the proposals for WLAN operational management. The results of this thesis are realized by means of two large scale prototypes, which are described in Section 5.4.

5.1 Performance Model for IEEE 802.11 WMNs

Figure 14 presents an overview of the architecture of the performance model that was developed here. A detailed presentation of the model is contained in publications [P2] and [P1]. The input of the model is a set of network parameters that describe the current state and configuration of the network. The parameters include AP locations, configurations, routes, and device costs. The main components of the performance

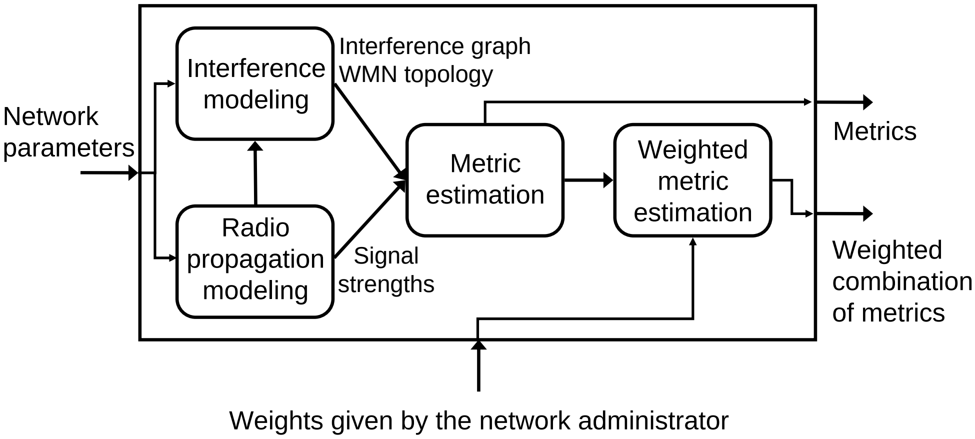


Fig. 14. *Performance model architecture.*

model are radio propagation modeling, interference modeling, metric estimation, and weighted metric estimation. The components are described in the following sections.

The performance model development started by estimating the capacity in a non-mesh WLAN. The first version is referred to as Performance Model 1 (PM1) and it was presented in publication [P1]. PM1 set out to estimate the capacity by modeling the effect of adjacent channel interference between the stations in the network. Performance Model 2 (PM2) was developed to provide support for WMNs, include other estimated metrics in addition to capacity, and support multiobjective optimization. PM2 was initially published in [P3]. PM2 was developed further by adding support for multirate operation and published in [P2].

Performance modeling methods introduced in this thesis are best suited to offline network planning. However, they can also be partially applied to WLAN operational management as demonstrated in publications [P1] and [P7].

5.1.1 Radio Propagation Modeling

Detailed information about the modeled WLAN and the operating environment is required in order to estimate its performance. Propagation modeling is required to estimate the signal strength between transmitter and receiver devices in the network. Signal propagation depends on the operating environment; the received signal strength can have large fluctuations depending on the circumstances. Various propagation models have been developed over the years to model signal propagation in different environments.

The effect of buildings and different types of walls was taken into account by using the Motley-Keenan model [74]. In this model, the affect of each wall is taken into account simply by adding a certain number of dBs to the propagation loss depending on the type and thickness of the wall [134].

Radio communication cannot be defined if either sender or receiver is unknown. This is problematic because often the details of the end user device are not known. For example, a different end user device, antenna or transmission power may completely alter the received signal strength and the coverage area. A *reference terminal* concept was developed for algorithms used in this thesis. A reference terminal is an estimate of the user terminal. It is important that the properties of the reference terminal are similar to those of an average user terminal. Otherwise, the quality of the performance estimation is compromised.

Radio propagation modeling supports performance estimation of a partially installed network. Thus, the signal strengths between some devices are not estimated but determined by measurement. Devices implementing the IEEE 802.11k standard can provide information about their neighbors inside the transmission range.

The MIMO antenna technology utilized in IEEE 802.11n introduces additional challenges for radio propagation modeling. MIMO utilizes multipath propagation, which means that radio signals reflect off objects within the transmission channel between the transmitter and the receiver. Thus, the receiver station may receive multiple instances of the transmitted signal, each traveling via a different route. MIMO utilizes multipath to increase the strength of the received signal and to send multiple spatial data streams simultaneously. The received signal and data rates depend on the active transmission mode as well as the propagation environment.

Several models have been developed to describe the behavior of the MIMO signal. A survey of the most prominent models is presented by Almers *et al.* in [5]. Often, the models first require a set of parameters describing the propagation environment. This allows more accurate modeling but restricts the usage of the model. Each environment, e.g. an office, has various very different environments that must all be modeled individually.

The performance models proposed in this thesis form an interference graph between stations in the network. The interference graph models each link in the network individually and allows usage of detailed information of the propagation environment for each individual link. Thus, the proposed performance model can also be used with devices utilizing IEEE 802.11n and MIMO. The usage of MIMO technology is targeted at improving the signal strength and data rate. Thus, when traditional radio propagation modeling is utilized with MIMO technology, the performance model provides a lower limit for the capacity and coverage of the network. Interference range is not increased because MIMO actively enhances the selected received signals and this is not applied to interference.

5.1.2 Interference Modeling

Interference modeling was designed on the basis of IEEE 802.11 operation, performed simulations, and measurements. Interference modeling can be divided into two parts. The first part models the throughput of a connection when interfered by another connection. Figure 15 presents a communication between two devices, in which there is interference from a third device. The figure also shows the difference

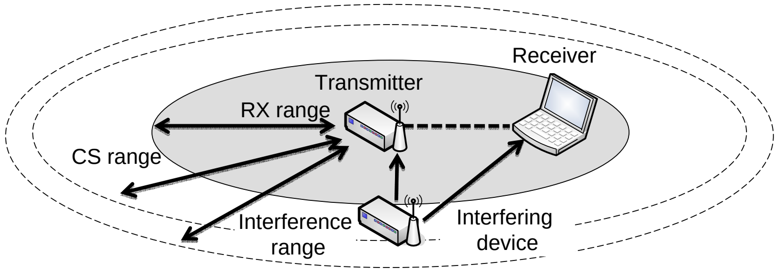


Fig. 15. *Transmission and carrier sense ranges.*

between transmission reception range (RX range), carrier sense range (CS range) and interference range. These ranges are defined only for illustration purposes and exist only for individual packets. Based on IEEE 802.11 MAC operation, the communication between two devices is possible if they are within each others' transmission range. However, when a third device is transmitting a packet inside a carrier sense range, i.e., the transmitter carrier is sensed, the device defers the transmission [36]. Interference range is the maximum distance in which another device can still interfere with the transmission. In certain cases as described in Section 4.1, the interference distance can be higher than the carrier sense distance. Publication [P1] contains more detailed discussion of the interference range and the effects of the interference range on performance estimation algorithms.

The capacity of a connection is calculated on the basis of the estimated interference using an interference graph and a collision domain concept from [70]. In this model, the capacity of a collision domain is shared equally between all stations transmitting inside a collision domain. Publication [P2] refines the collision domain concept by presenting an algorithm for calculating the capacity of the network.

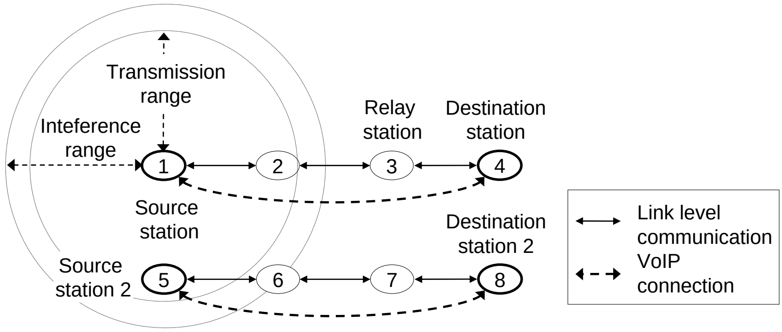


Fig. 16. *Two interfering bidirectional VoIP connections over 3 hops.*

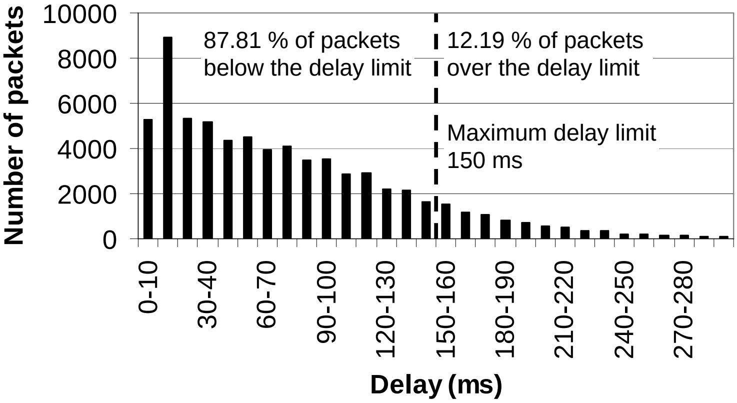


Fig. 17. *Delay histogram of two bidirectional VoIP connections with G.729 codec.*

Design of the interference modeling is based on research done on the operation of VoIP in a multihop network [P5]. The simulation results in publication [P5] provide significant insight into the interference between interfering connections in WMN. Figure 16 presents one simulation case from the publication. It consists of two bidirectional VoIP connections that are within each other's interference range. Both connections are forwarded by two relay stations. The WLAN technology utilized in the simulation is IEEE 802.11b. In the simulation, neither of the two VoIP connections achieves an acceptable voice quality in terms of Mean Opinion Score (MOS) [62]. Low voice quality is explained by mutual interference of links forwarding the packets. Another reason is the low bitrate of IEEE 802.11b. Interference caused delays due to excessive MAC layer retransmissions and deferred packet transmissions. Discounting retransmissions, the MAC layer dropped only 4.25 % of the transmitted packets. Thus, the resulting delays were the key reason for the low quality. The delay histogram of the received packets is presented in Figure 17. The histogram shows that 12.19 % of the packets exceeded the maximum delay limit of 150 ms. Consequently, this simulation result demonstrate that the capacity of a link must be calculated by taking all interfering links into account. This is essentially the principle of the collision domain concept.

The second part of interference modeling estimates the effect of adjacent channel interference caused by partially overlapping channels. This applies mostly to the 2.4 GHz band where channels are overlapping. The effect of partially overlapping channels was studied using a measurement [P1]. Interference decreases capacity when the channel distance is between zero and four. With five channels the channel separation is 25 MHz, which is enough to completely separate the channels as shown earlier in Figure 4. Although PM2 capacity estimation algorithm does not take overlapping channels into account, the method used for the purpose in PM1 can be applied to the algorithm. This has been implemented in the prototype implementation.

Interference modeling creates an interference graph of the network and estimates the achievable throughputs between stations in the network. Achievable throughput for each link is calculated by using the link rate and the time share that the link is allowed to transmit in the collision domain. Exact description of the utilized algorithm is presented in [P2].

5.1.3 Performance Model Metrics

The output of the performance model consists of seven metrics to estimate the individual physical characteristics of the WMN performance. The metrics are defined in publication [P2]. The metrics are capacity, goodput, coverage, cost, fairness, service capacity, and service fairness. These metrics were selected to provide information about different aspects of WLAN operation. Of these, the base metrics, capacity, coverage, cost and fairness, are orthogonal. Other metrics contain some amount of redundant information. Goodput is capacity divided by the amount of APs. Goodput metric is more suitable than capacity for measuring the interference state in the network. Service capacity and service fairness consider the corresponding metrics from

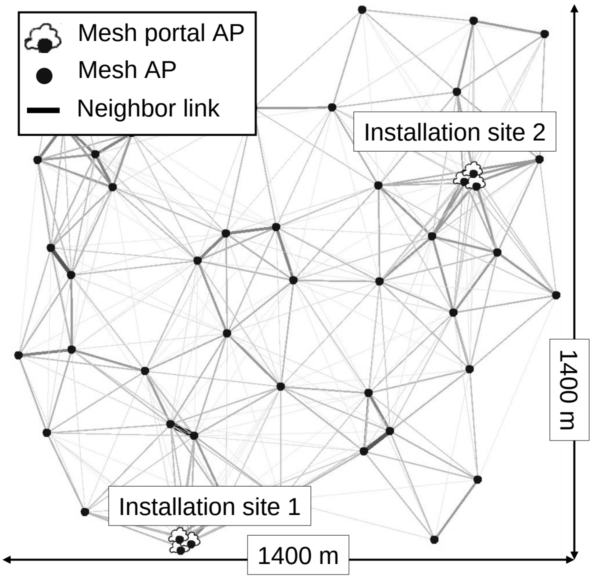


Fig. 18. WMN topology used in NS-2 simulations. Line thickness represents the link rate.

the perspective of the end user. For example, service capacity estimates the average capacity that the user has in the area.

Capacity metric is estimated with a capacity estimation algorithm and the interference modeling. When throughput of each link is known, throughputs for each terminal can be estimated by finding a bottleneck link between the terminal and mesh portal. Throughput of a terminal cannot exceed the throughput of the link with the lowest throughput in the route, which is the bottleneck link.

The performance model was validated by means of NS-2 simulations. Figure 18 presents a simulation setup [P2], which was utilized to evaluate capacity estimation algorithm. The setup consisted of 6 mesh portals and 30 non-portal APs with an area of 1400 m x 1400 m. The capacity was first estimated with PM2 and then compared to the results achieved with NS-2 simulation. For NS-2 simulations, three terminals were associated to each AP using a distance of 30 m between the AP and the terminal. A bidirectional constant bit rate connection with 1500 byte packet size was created between each terminal and mesh point. Requested throughputs for each connection were calculated by multiplying the capacity estimate created by PM2 by a throughput factor H_e. Value $H_e = 1$ means that the requested throughput in NS-2 simulation was exactly the value estimated by PM2. Figure 19 shows the result of NS-2 simulation when H_e is varied from 0.6 to 1.1. According the results, the PM2 estimated capacity and the simulated result begin to differ when $H_e = 0.8$. Consequently, PM2 produces a slightly overstated estimation of the capacity. However, this is understandable because PM2 does not take terminal locations into account. Thus, interference between terminals and APs slightly decreases the capacity, which is ignored by PM2.

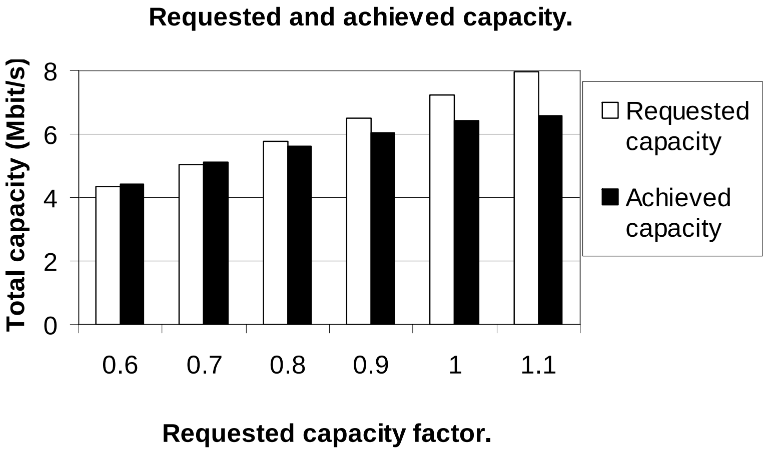


Fig. 19. NS-2 simulation results. Requested capacity compared to achieved capacity.

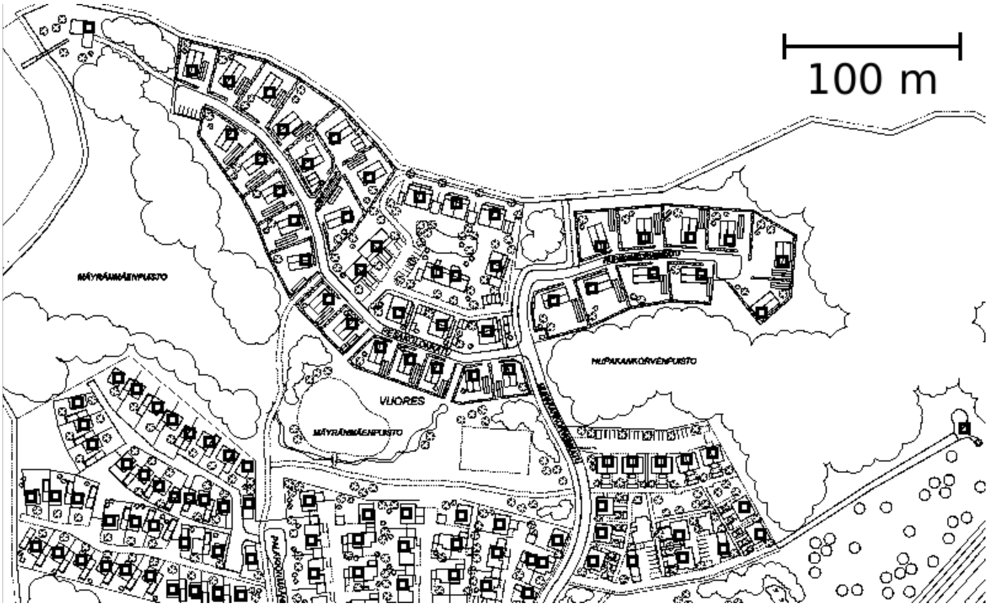


Fig. 20. *Deployment candidate sites in Vuores Mäyränmäki area.*

The accuracy of NS-2 simulations in this thesis was assured by using long simulation time. All simulations also used static routes calculated prior to the simulations. Consequently, no significant variation in the results of individual simulation runs were found, although confidence levels for the results were not calculated. Warm up periods were not used in the simulations but the affect is negligible due to long simulation time and pre-existing routes.

5.1.4 Multiobjective Optimization with the Performance Model

As an output, the performance model provides a weighted combination of the metrics for the simultaneous use of multiple evaluation criteria in WMN optimization. This allows the network designer to control the planning process by configuring the weights of each metric.

The performance model was utilized for WLAN AP placement optimization in publication [P4]. This example shows how multiple optimization criteria can be utilized simultaneously in optimization. Figure 20 shows the area where network plan is created. In the figure the candidate sites are indicated by black rectangles. The network plan was created with the HexagonGA algorithm described in [P4].

Figure 21 shows the capacity and coverage estimates of the resulting network plan

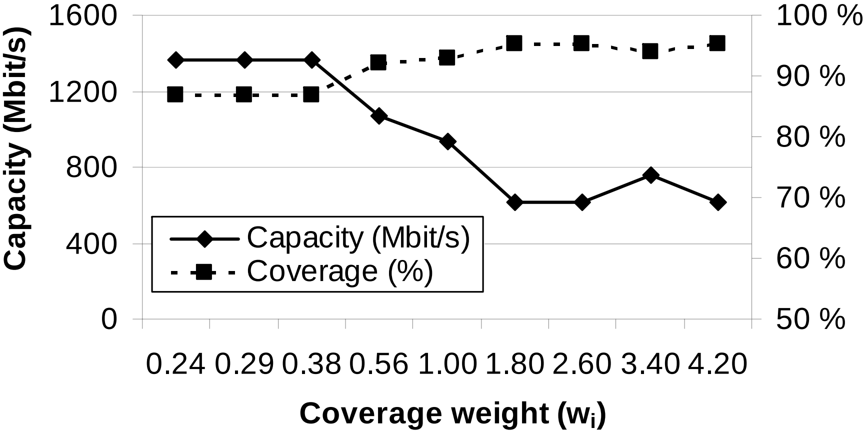


Fig. 21. *Capacity and coverage with coverage weight values from 0.24 to 4.2.*

with different coverage weights used in the optimization. Capacity weight was 1 and coverage weight was changed from 0.24 to 4.2 with 9 values. Due to calculation of the significance percentage value described in [P2], values less than 1 decrease the significance and values higher than 1 increase it.

According to the results, the achieved coverage can be increased by raising the coverage significance. However, this decreases the achieved capacity correspondingly. The reason for this behavior is that the HexagonGA algorithm adjusts the AP transmission powers during the optimization. Thus, coverage and capacity are mutually conflicting objectives. Increasing the total capacity of the network requires smaller transmission power, which effectively decreases the coverage in boundary areas of the network.

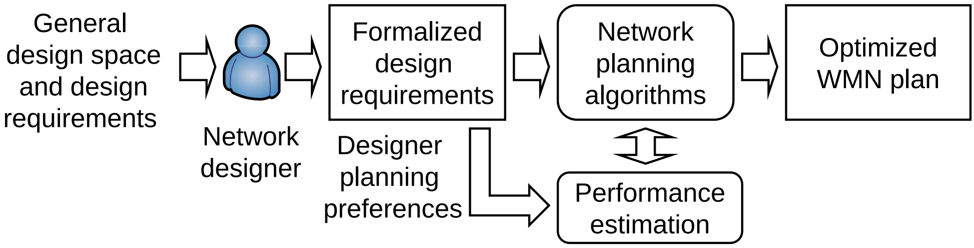


Fig. 22. *WLAN Planning Process.*

5.2 WLAN Planning Process

The proposed WLAN deployment planning process is described in Figure 22. The network designer creates a set of formalized design requirements that can be used by a network planning tool. The requirements form the input for network planning algorithms that create the optimal network plan. The performance model is configured by the network designer and used in the planning algorithms to enable network planning according to the preferences of the designer.

5.2.1 Design Requirement Formalization

The design requirements are often abstract and unclear even to the network designer. Formalization of the requirements means that requirements are written into a format, which is understandable for planning tools. The network designer specifies the environment containing information about the area, buildings, the propagation models used, and the possible mesh point locations. In addition, the locations of foreign APs can be collected with a site survey before deployment. The designer specifies the set of equipment and configuration settings that are allowed in the planning. The planning process is controlled by defining the weightings for the performance metrics. The designer can also specify strict limits for the metric values, for example, by defining a minimum allowed capacity.

5.2.2 Network Planning Algorithms

Design of the access network is the first and most important part of WMN deployment planning. The access network must provide coverage and adequate signal strength for all the required usage areas. Locations of the access network APs also define the locations for most of the mesh points in the network. The access network planning algorithm does not have to be specially designed for WMN. It is possible to design the access network separately prior to the mesh backbone network. Thus, a WLAN node placement algorithm such as HexagonGA [P4] is well-suited for the purpose. Section 3.5.1 contains more detailed discussion of existing node placement algorithms. When the access network is defined, the backbone network can be planned by selecting mesh portal locations and adding new mesh points where needed. New interfaces are added to APs for the backbone network. Using technologies with separate frequency bands, such as IEEE 802.11a, and g, enables independent planning for the access network and for the backbone network.

A centralized and a distributed algorithm for optimizing the channel assignment have been developed in the publications contained in this thesis. Distributed channel assignment algorithm [P1] is designed for a non-mesh WLAN. In the algorithm, each AP selects its channel independently according to the capacity estimation made with PM1. The centralized channel assignment algorithm is based on GA [69] and applies for non-mesh WLANs [P1] and WMNs [P3] [P2]. GA was selected because it is well-suited to multiobjective optimization [25]. In publication [P1], the algorithm was implemented using PM1 that does not support WMNs. WMN support was added by using PM2 in publications [P3] and [P2].

A network topology optimization algorithm was developed for WMNs in publication [P2]. The simple and effective algorithm is based on pruning and removes APs randomly provided the fitness value as defined by the performance model is not decreased. The algorithm can be used for non-mesh WLANs as well.

5.3 WLAN Operational Management

An architecture for WLAN operational management called Wireless Access Management System (WAMS) was developed during the research. WAMS defines the architecture needed for implementing the services in a WLAN hotspot. This includes the components, their interfaces, security levels, and the QoS control mechanisms.

5.3.1 Architecture Overview

WAMS defines eight components that participate in the service provisioning process. The components and their interfaces are presented in Figure 23. The components are user, authentication server, WAMS server, manageable AP (mAP), legacy AP (LegacyAP), manageable switch (mSwitch), manageable gateway (mGateway), and administrator client.

The WAMS server is responsible for managing the network. The WAMS server provides an interface *c* for the network administrator client. The interface is used for controlling the active configuration in WAMS. Devices in the managed network are either legacy devices from various vendors or proprietary manageable devices that implement the management functionality specified by WAMS. The functionality of the legacy devices is inadequate for the tasks required by service provisioning. Thus, enhanced functionality has been designed for the manageable devices.

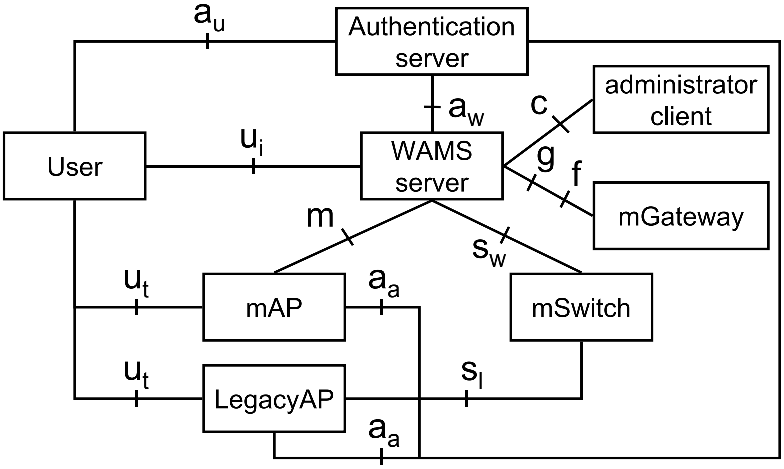


Fig. 23. Components and Interfaces of the WLAN Access Management System.

Manageable devices are mAP, mSwitch, and mGateway. The main function of mAP is to act as a WLAN AP with QoS and security control capabilities. The m interface is used by the WAMS server to configure traffic classes, packet classifiers for traffic flows, security parameters, and flow monitoring in mAP. The mAP uses the m interface to give information about the user, as well as the current traffic and resource state to the WAMS server.

The mSwitch manages a set of LegacyAPs. The s_w interface contains the same operations as m interface, except for the security configurations. Security level cannot be freely set for LegacyAPs. Instead, the s_w interface contains a method for checking the security level of the particular LegacyAP. The mSwitch is responsible for implementing the corresponding functionality and dealing with the LegacyAP management, including the QoS control. The s_l interface, between mSwitch and LegacyAP, is implemented using traditional management methods such as Simple Network Management Protocol (SNMP) [122]. Depending on the LegacyAP implementation, the s_l interface may not provide all the necessary information for mSwitch. However, all traffic from the particular LegacyAP flows through mSwitch and this makes it possible to collect the information from the data flows.

The mGateway is a router that acts as a gateway to the Internet. It also provides QoS control for traffic in the border of the management domain. The g interface is used for QoS control of the mGateway. Correspondingly, the f interface is used for controlling the firewall that also exists in the mGateway device.

The user has three interfaces with the system. The a_u interface is used when the user makes a contract with WISP and creates an account. This involves assigning a user name and a password for the user, as well as giving necessary billing information to WISP. The security level and service selections are controlled by the user by means of the u_i interface. This is also used for login and logout procedures and for downloading configuration files for the user terminal. The u_i interface is mainly unidirectional and implemented by the WAMS server. However, the user has one method for indicating the status of the active services. This method is needed when the user, for example, leaves the service area or the WAMS server informs the user about degraded service level.

The u_t is a standard data transmission interface between the user terminal and IEEE 802.11 AP. User management is based on the use of IEEE 802.1x compatible authentication server, such as RADIUS. This is convenient because it enables user roaming by making it possible to chain the authentication servers. If a particular user is not found from the authentication server of the management domain, it can exist in the database of the authentication server of some partner WISP. This way, the user can directly log in to the network without explicitly making a contract with WISP. The WAMS server uses the a_w interface to check user identity and access rights from the authentication server when the user is logging in. The a_a is a standard interface between the authentication server and IEEE 802.11 AP.

5.3.2 Management Extensions for Network Devices

Management extensions [P6] were added to the devices to enable advanced control. Figure 24 presents the architecture that was used in manageable devices. A framework called *mAP adaptor* was added to manageable devices, which is able to execute management functions. Management functions are independent of the device implementation. The mAP adaptor also contains additional services that are device specific and provide the required low level management interfaces for the management functions. Management signaling between the management functions operated directly between the devices in a Peer to Peer (P2P) fashion although a complete P2P protocol was not used. Instead, the WAMS server provided information about existing management functions in the network.

WAMS Frequency Management

A frequency management tool [P7] was implemented on top of the management architecture. It contained a centralized frequency management function in the WAMS

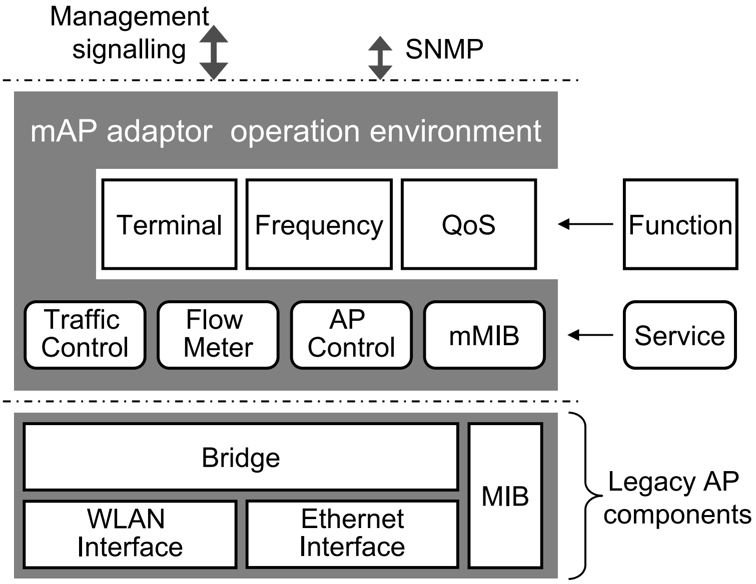


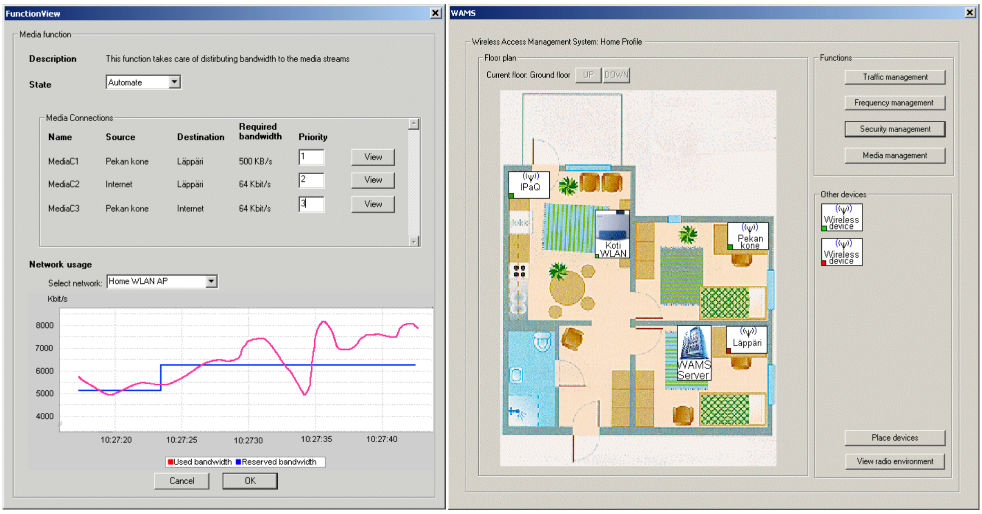
Fig. 24. *Manageable device architecture [P6].*

server that calculated the optimal frequency assignment for mAPs. The frequency management function used PM1 for capacity estimation and GA to optimize the channel setup in the network. The mAPs also had frequency management functions, which were responsible for providing information for the frequency management function in the WAMS server. The WAMS server also provided a User Interface (UI) for the network administrator.

5.4 Prototypes

Two prototypes were used to verify the results of this research. The first prototype is called WAMS and it was developed at the Department of Computer Systems at Tampere University of Technology from 2002 to 2005. WAMS is a prototype management tool for WLAN operational management. WAMS was used as a test platform for the management architecture and frequency management functionality presented in publications [P6], [P1], and [P7]. Initial plans for WAMS architecture were presented in [P10].

The second prototype is called Site Designer and was developed between 2005 and 2007. Site Designer is a prototype WLAN planning tool and was used for providing the results of publications [P1], [P2], [P3], [P4], and [P5].



FunctionView

Media function

Description This function takes care of distirbuting bandwidth to the media streams

State Automate

Media Connections

Name	Source	Destination	Required bandwidth	Priority	
MediaC1	Pekan kone	Läppäri	500 KB/s	1	View
MediaC2	Internet	Läppäri	64 Kbit/s	2	View
MediaC3	Pekan kone	Internet	64 Kbit/s	3	View

Network usage

Select network: Home WLAN AP

WAMS

Wireless Access Management System: Home Profile

Floor plan

Current floor: Ground floor

Fig. 25. *Example views from WAMS prototype UI [P10]. Capacity usage monitoring view (left) and Terminal monitoring view (right).*

5.4.1 Wireless Access Management System

The WAMS prototype consists of a WAMS server and a set of mAPs. The WAMS server contains all network level management functionality and UI for the network administrator.

The mAP implementation was based on the Linux operating system because of its rich variety of existing services such as Traffic Control [6], HostAP device driver [39] and Bridge [89]. The physical platform is a laptop PC. The main component, the mAP adaptor, is implemented jointly on top of the Java Virtual Machine (JVM) [71] and Linux [90]. The Java programming language was selected for rapid development and platform independence.

The WAMS server was also implemented using Java and it runs on top of both Linux and Windows. In addition to the frequency management, the WAMS prototype contains functionality for monitoring APs and terminals, managing traffic capacity reservations in AP interfaces, controlling terminal associations, and monitoring data flows inside the network. Figure 25 shows two views of the WAMS prototype.

Figure 26 presents an example of the QoS management using the WAMS prototype and mAP [P6]. The WLAN technology used in the prototype was IEEE 802.11b. The example setup consists of two terminals (A, and B), both receiving two 2.2 Mbit/s data flows from the gateway. In the test, the data rates received in the terminals were measured. At the beginning of the test, the traffic is not controlled and the

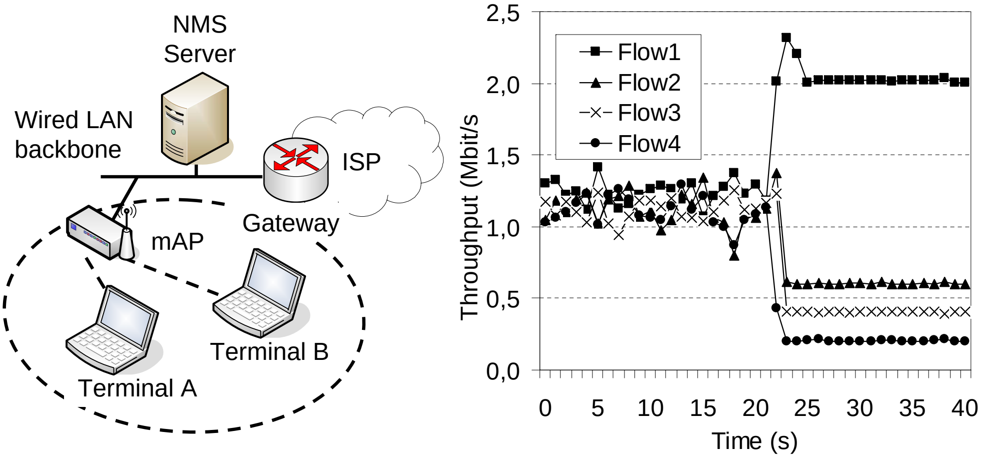


Fig. 26. *The setup for QoS management (left) and QoS management test results (right).*

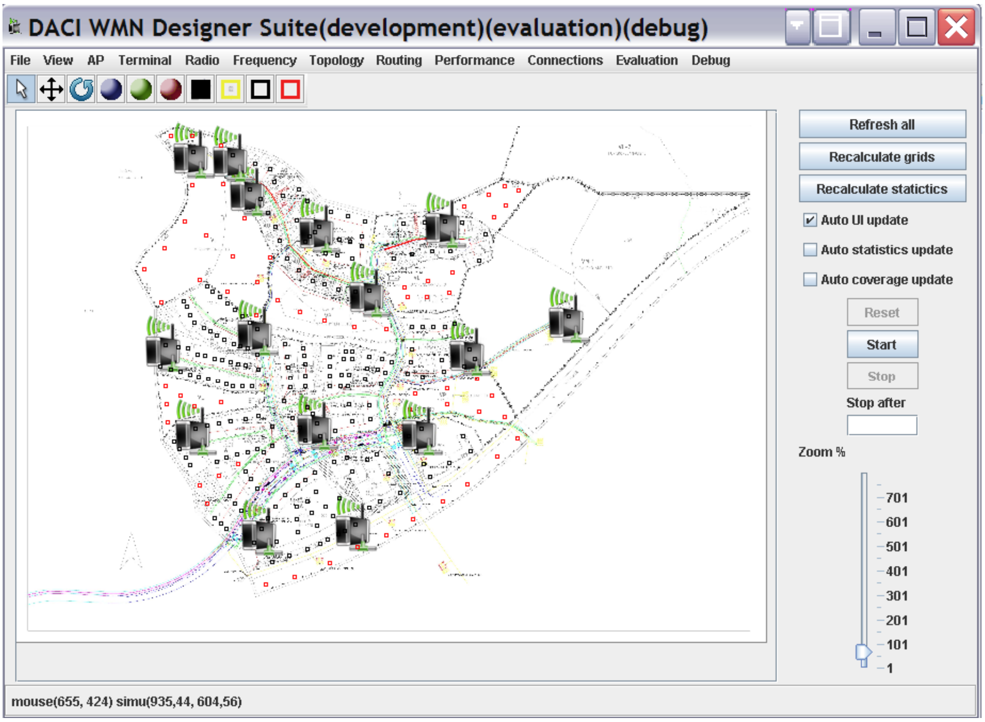
achieved data rate of each flow is roughly equal. However, the measurement shows rapid variations in the achieved rate due to contention between the flows. The traffic control in mAP was activated at 20 s from start. Each flow was configured to have a different rate (200, 400, 600, and 2000 kbit/s). According to the measurements, the traffic control is able to limit the rate to the requested values and also completely remove earlier rate variation.

5.4.2 Site Designer

The history of the Site Designer consists of two versions. The development of the concepts and algorithms presented in the publications included in this thesis were done during the implementation of version 1. Figure 27 shows the main UI of Site Designer version 1.

The development of version 2 started at the beginning of year 2007. The goal of version 2 was to redesign the prototype to support the flexible addition of new functionality and usage over a network connection. The main requirement for the networked operation was to run proprietary management functionality in a server without releasing the code for the user.

Site Designer implements the deployment planning process described in Section 5.2. The configuration of the formalized design requirements is done with UI and stored using eXtensible Markup Language (XML) based configuration language. Initial implementation of importing site survey measurements is also added to the prototype.



☑ Auto UI update
☐ Auto statistics update
☐ Auto coverage update

mouse(655, 424) simu(935,44, 604,56)

Fig. 27. *Main view of the Site Designer version 1.*

Currently, site survey information containing foreign APs can be taken into account in the planning.

The WMN performance estimation model is included in the prototype and used extensively by the included planning algorithms. The model can also be used for visualization of the network coverage, capacity, or signal strength, as in Figure 28. The performance estimation model provides information on the number and type of services that can be supported. The network designer plans the WMN deployment using the tool by (1) specifying the formalized design requirements using UI, (2) running the HexagonGA algorithm [P4] for selecting mesh AP locations, (3) specifying additional mesh point locations and radio interfaces for the backbone network, and (4) optimizing the backbone topology by selecting frequency channels [P3][P2] for backbone mesh points.

The prototype includes channel assignment algorithms for both non-mesh WLANs and WMNs. Development of advanced backbone network planning algorithm is still future work. Currently, the mesh portal locations, additional mesh points, and radio interfaces are specified manually.

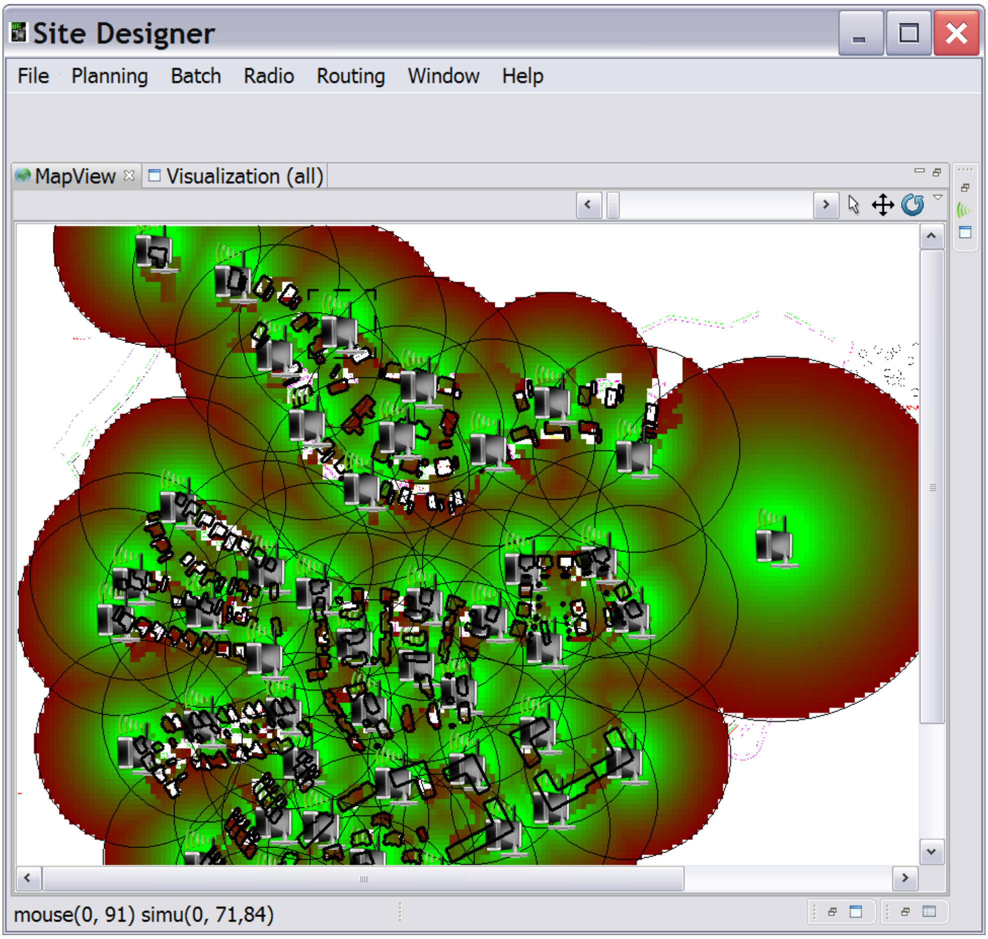
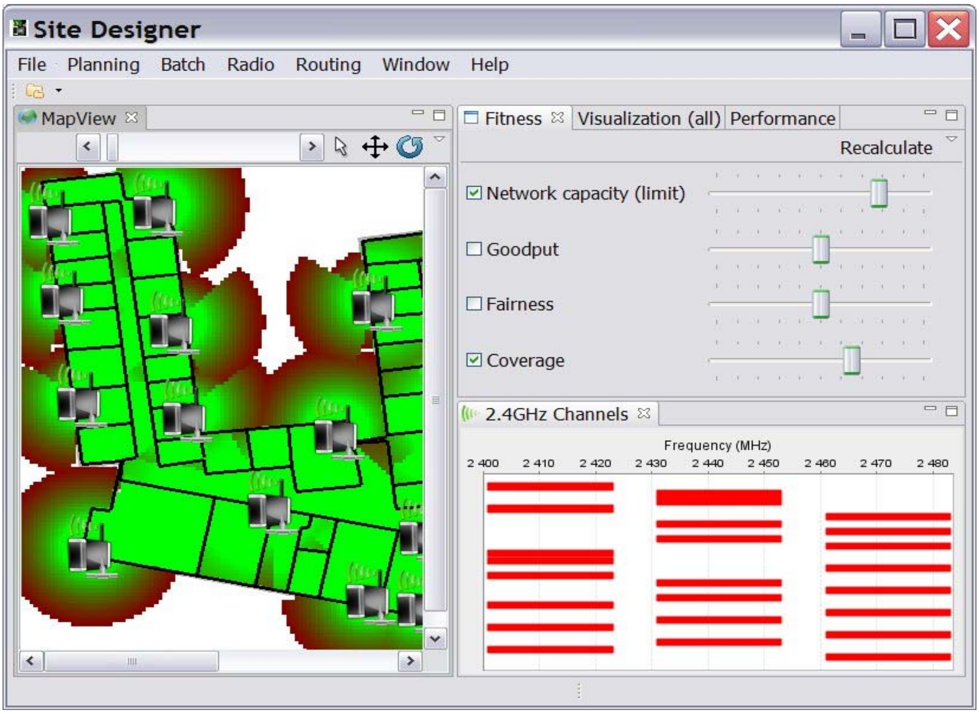


Fig. 28. Signal strength visualization in the Site Designer version 2.

The prototype is also a development platform for WMN deployment methods and contains an interface with the NS-2 simulator [98] for simulation and result verification. The prototype generates Tool Control Language (TCL) script for NS-2 based on the WMN configuration. The prototype aids algorithm development by enabling testing and evaluation, and network visualization.

The prototype supports detailed parameterization of the equipment used. Device radio parameters can be set globally, or optionally individual parameters can be set for each AP. These include WLAN adapter sensitivity, cables, and antenna gains for both omni and directional antennas. Currently supported WLAN physical layers are IEEE 802.11 a, b, and g. The prototype supports multirate operation by defining receiver sensitivity levels for each transmission rate in WLAN adapter configuration.



☑ Network capacity (limit)
☐ Goodput
☐ Fairness
☑ Coverage

Fig. 29. *Main view of the Site Designer version 2.*

The Site Designer tool provides a propagation model framework for the developed management algorithms. It allows new propagation models to be added as plugins. Existing models can also be configured by the network designer. In practice, the models used were FreeSpace, TwoRayGround, and Shadowing. These models are implemented in NS-2 network simulator [98], which was used to verify the results. Signal attenuation caused by walls is also taken into account by specifying buildings, attenuation of wall materials, as well as wall and antenna heights.

The routing algorithm and the routing metrics can be freely selected. This allows performance estimation and optimization with various routing mechanisms. The current implementation contains the Floyd-Warshal algorithm with hop count, and Expected Transmission Time (ETT) [22] routing metrics. Hop count implements the basic shortest path routing. ETT is based on the expected transmission time for a packet using the particular link. WMN link level topology and routing can be visualized with the prototype. This is beneficial for the network designer for analyzing the WMN capacity.

The requirements for version 2 were met using an Eclipse Rich Client Platform (RCP) [110]. RCP allows implementation of the application using plugins on top of the

Eclipse framework. This provides a wide range of already existing UI functionality for the use of the developed application. Plugins use an UI definition language, which allows new functionality to be added to UI by adding new plugins. RCP architecture was used by creating a separate plugin for each key component of the Site Designer. For example new routing algorithms, planning algorithms, and device types can be added simply by adding new plugins to the framework.

Figure 29 presents the main view, frequency channel view, and the fitness configuration view of the prototype UI. The main view shows a graphical visualization of the simulated network. Network designer planning preferences are configured with the fitness configuration view. UI provides methods to set configuration for the network as well as methods to load and save network configurations.

At present, the Site Designer prototype has been used for municipal wireless network planning for Vuores, a new suburban development in the Tampere-Lempäälä area of Finland. When complete in 2015, Vuores will have about 13000 inhabitants and 5000 working places in an area of 12.6 km2. During the network planning project, manual network planning methods were found inadequate for an area as large as Vuores. Thus, Site Designer was utilized in the planning and Vuores has demonstrated to be a significant test site for the WLAN planning methods presented in this thesis. The main method for network deployment planning in Vuores was the HexagonGA algorithm presented in [P4]. Site Designer was shown to be an efficient and practical tool for network planning.

6. SUMMARY OF PUBLICATIONS

This chapter summarizes the contents of the publications and details the contribution of the author. The publications are based on the work carried out by the author between 2003 and 2007.

The publications [P6] and [P7] concentrate on the WLAN operational management, whereas [P3] and [P4] describe the algorithms for WLAN planning. The development of the performance model is described in [P1] and [P2], while [P5] provided background information for performance model development.

Publication [P1] presents a WLAN throughput estimation model for multicell WLAN. The model operates on traditional infrastructure WLAN and concentrates on estimation of interference between stations. The throughput estimation models are used for optimizing the WLAN frequency channels, where throughput is selected as the optimization criterion. In the evaluation, GA and a distributed optimization algorithm produce the final frequency plan. The publication evaluates four throughput estimation models using both optimization algorithms. The Site Designer prototype was also presented and used to compare the throughput estimation models. Usage of a throughput estimation model for frequency optimization in a real WLAN implementation was also evaluated with the WAMS prototype.

The algorithm design, simulations, and writing were carried out by the author. Implementation was done by the author with the assistance of Janne Sikiö, M.Sc. and Antti Koivisto, M.Sc. Prof. Marko Hännikäinen supervised the work and provided valuable advice on the methodology selected in the research. Prof. Timo D. Hämäläinen reviewed the writing style.

Publication [P2] presents a performance model developed for the deployment design of IEEE 802.11s WMN. The model was evaluated using an example algorithm for channel assignment and another for minimizing the number of mesh APs. Performance model and algorithms were implemented in the Site Designer prototype and evaluated by optimizing a network topology with different criteria and verified with NS-2 simulations.

The algorithm design, implementation, simulations and writing were done by the author. The work was supervised by Prof. Marko Hännikäinen, and Prof. Timo D. Hämäläinen reviewed the writing style.

Publication [P3] describes a configurable GA for optimizing channel assignment in mesh WLANs by using the performance model PM2 [P2]. The algorithm was implemented in Site Designer planning tool and evaluated with NS-2 simulations.

The algorithm design, implementation, simulations and writing were carried out by the author, while Prof. Marko Hännikäinen supervised the work. The publication was revised by Prof. Marko Hännikäinen, and Prof. Timo D. Hämäläinen reviewed the writing style.

Publication [P4] presents an algorithm to rapidly create a high quality network plan for IEEE 802.11 based WLAN according to assigned planning requirements. The algorithm uses a GA to explore the design space, and the performance model PM2 [P2] to provide feedback for the algorithm and for a network designer. The algorithm selects AP devices, locations, antennas, as well as AP configuration including transmission power and frequency channel. The algorithm was implemented in Site Designer planning tool.

The algorithm design, implementation, simulations and writing were done by the author. The publication was revised by Prof. Marko Hännikäinen, and Prof. Timo D. Hämäläinen reviewed the writing style.

Publication [P5] evaluates the performance of IEEE 802.11b WLAN in supporting multihop VoIP service. Evaluation was carried out using the NS-2 network simulator and MOS as criterion for measuring the quality of a VoIP connection. The results of this evaluation have been utilized in the design of the performance model PM2 [P2].

The simulations and writing of the publication were done by the author. Prof. Timo D. Hämäläinen proposed the contents of the publication and supervised the writing with Prof. Marko Hännikäinen.

Publication [P6] presents the design and prototype implementation of a manageable WLAN AP. The architecture was developed to allow AP functionality to be easily extended by the addition of new management functions and automated services. The prototype was implemented using a Linux platform.

The manageable WLAN AP architecture was designed by the author, while Prof. Marko Hännikäinen provided valuable ideas. The implementation was done by the author and assisted by Janne Sikiö, M.Sc. and Antti Koivisto, M.Sc. The publication was written by the author. Professors Marko Hännikäinen and Timo D. Hämäläinen supervised the work and revised the text.

Publication [P7] presents a practical tool for the frequency management in IEEE 802.11 WLANs. The tool minimizes interference between APs and consequently maximizes the effective capacity of the network. It also contains UI showing a view of the network state in the frequency domain. A WAMS prototype containing the tool was also presented.

The algorithm design was done by the author. The implementation was made by the author and assisted by Janne Sikiö, M.Sc. and Antti Koivisto, M.Sc. The author wrote the publication and Professors Marko Hännikäinen and Timo D. Hämäläinen revised the text.

7. CONCLUSIONS

The properties of a wireless communication channel undergo a constant change due to interference, changing environment, multipath signal propagation, and the movement of networking terminals. This poses problems for applications requiring high throughput or low delay, and advanced WLAN management functionality is needed to control QoS.

Performance modeling is a key to the development of advanced management algorithms. Without accurate knowledge about the quality of the created network plan or network installation, management algorithms cannot be controlled and the results are useless. Performance modeling can be used in WLAN planning and also in WLAN operation management. Simultaneous optimization of multiple objectives makes optimization difficult for WISP but it also complicates the development of the optimization algorithms. Optimization algorithms need to take into account the requirements of WISP in order to provide usable results.

The research presented in this thesis has provided results for estimating performance of both traditional WLANs and WMNs. The performance model developed here was embedded as a part of a proposed WLAN planning process. The performance model and the planning process can be utilized in WLAN management tools. An architecture for WLAN operational management called WAMS was also presented in this thesis. This provides a framework for implementing management extensions for WLAN devices to enable advanced network management functionality.

The performance model estimates a set of metrics that provides information about the network. The metrics are further refined according to the preferences set by WISP and are used in the optimization algorithms. The developed performance model enables the estimation of the maximum capacity of a particular network setup. This allows optimization of the network configuration, which makes it valuable for the network administrator. Selecting installation locations and configuration for WLAN APs manually is time consuming and requires advanced skills on the part of the network designer. Furthermore, finding the configuration with optimal capacity manually is practically impossible. Thus, a need exists for an algorithm that proposes AP locations and configuration for the network designer.

The feasibility of the developed performance model was demonstrated by implementing several optimization algorithms for WLAN channel assignment and topology optimization for both traditional and mesh WLANs. The algorithms optimize WLAN device locations, frequency channels and the number of required devices. The developed algorithms as well as the performance model were integrated into two prototype management tools; one for WLAN planning and one for WLAN operational management. The results obtained by the prototypes show that the performance model can provide significant advantages for WISP when designing or managing the network.

Experience using the prototypes also shows how the performance model and the optimization algorithms can be further developed. The performance model can be improved by including the modeling of the network terminals. It is difficult to estimate the locations and behavior of the terminals and incorporate these into the model. However, this would further improve the accuracy of the modeling result. In addition, the capacity requirements in the network differ according to location. A conference room, for example, is a location where the required amount of capacity is greater.

The way in which the network administrator controls the multiobjective optimization during the planning process can also be improved. Currently, the network administrator gives preferences to each metric and the optimization is done using a single parameter representing all metrics with given weightings. However, selecting the weightings for each metric is difficult and may require multiple attempts before the network administrator is satisfied with the result. As described in Section 4.5, the optimization process could result in a set of optimal results instead of a single result. Each of the result in this pareto set would represent a solution, which cannot be improved without degrading the result based on some performance metric.

Future work can be continued by developing new algorithms for WLAN planning and optimization. One topic is the WMN channel selection using all possible frequency channels instead of three channels utilized in the algorithm presented in this thesis. Another topic is WMN backbone generation, which would involve all planning tasks including backbone network locations, effective WMN topology, selected equipment and configuration.

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