Medium Access Control in IEEE 802.11s
Wireless Mesh Networks

Von der Fakultät für Elektrotechnik und Informationstechnik der
Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung
des akademischen Grades eines Doktors der Ingenieurwissenschaften
genehmigte Dissertation

vorgelegt von

Diplom-Ingenieur
Guido R. Hiertz

aus Köln

Berichter:    Univ.-Prof. Dr.-Ing. Bernhard Walke
              Univ.-Prof. Dr. rer. nat. habil. Carmelita Görg

Tag der mündlichen Prüfung: 22. Dezember 2011
To my family

In remembrance of Mok († 2002)
ABSTRACT

Standard 802.11 of the Institute of Electrical and Electronics Engineers (IEEE) has become the dominating solution for Wireless Local Area Networks (WLANs). Its simple and robust medium access protocol has paved the way for a mass market that is expected to ship one billion IEEE 802.11 devices in 2011. From the beginning of its standardization in 1990 until September 2011 twenty amendments have extended IEEE 802.11 for various applications. Examples are support for Quality of Service (QoS) that enables Voice over IP (VoIP) over WLAN and Consumer Electronic (CE) related applications, an extension for car to car communication that helps to enable new safety features, and intelligent radio resource management that targets new spectrum. These amendments make IEEE 802.11 a truly ubiquitous solution that is used in industrial machinery, point-to-point links, CE devices, computers, cars, mobile phones and many more products.

Until the introduction of its latest amendment — IEEE 802.11s — WLANs are typically used to extend wired networks. In this case, the WLAN forms the last hop of a wired backhaul and the latter is needed to interconnect the central entities that bridge the wired to the wireless network. These entities, denoted as Access Point (AP), allow only for single-hop communication on the Wireless Medium (WM). To bring wireless network access to unserved areas requires the provisioning of wired backhaul, therefore. IEEE 802.11s fills this gap. It introduces mesh networking that brings wireless multi-hop communication. With IEEE 802.11s the infrastructure dependency of WLAN is cut and self-contained Wireless Mesh Networks (WMNs) of arbitrary topology can be formed. Furthermore, these IEEE 802.11s WMNs may serve as transparent backhaul for other, external networks. A data frame's source and destination may be in- or outside of the WMN. Medium Access Control (MAC) layer based routing delivers the frame over multiple hops. The current medium access protocols of IEEE 802.11 have not been designed for this multi-hop communication, however.

The thesis describes the new medium access protocol that IEEE 802.11s introduces. The protocol is based on distributed reservations that allow for scheduled access to the WM. It is derived from an invention that is used in standards for Wireless Personal Area Networks (WPANs). The
thesis outlines the author’s inventions and the standards that apply it. The publicly available, event-driven protocol simulator Wireless Access Radio Protocol 2 (WARP2) is used to evaluate the performance of the invention and the new medium access protocol of IEEE 802.11s.

Bis zur Verabschiedung der jüngsten Ergänzung — IEEE 802.11s — waren WLANs jedoch meistens nur eine Ergänzung von drahtgebundenen Netzen. In diesem Fall dient das WLAN als letzter Hop eines Festnetzes, an das drahtlose Stationen mittels einer Basisstation angebunden werden. Diese Basisstationen werden in IEEE 802.11 als Access Point (AP) bezeichnet und benötigen das Festnetz um untereinander kommunizieren zu können. Um ein WLAN bereitstellen zu können, musste bislang also bereits ein Festnetz vorhanden sein. Die Norm IEEE 802.11s vermeidet diese Abhängigkeit, indem sie die für drahtlose Multi-Hop Kommunikation notwendigen Mechanismen spezifiziert. Mittels IEEE 802.11s entwickelt sich das WLAN von einem Anhangel des Festnetzes zu einem von diesem unabhängigen Wireless Mesh Network (WMN), das beliebige Topologien unterstützt. Überdies können IEEE 802.11s WMNs als transparente Verbindung für beliebige andere, externe Netze dienen. Jegliche Datenquelle und -senke kann sich dabei inner- oder außerhalb des WMNs befinden. Das in der Medienzugriffsschicht befindliche Routing sorgt für die Zustellung der Daten über mehrere, drahtlose Hops. Für drahtlose Multi-Hop-Kommunikation sind die verschiedenen IEEE 802.11 Medienzugriffsprotokolle jedoch nicht entwickelt worden und daher wenig geeignet.
In dieser Arbeit wird ein speziell für WMNs gestaltetes Medienzugriffssprotokoll beschrieben, welches IEEE 802.11s einführt. Es basiert auf einem verteilten Reservierungsverfahren des Autors, das koordinierten Zugriff auf den Funkkanal ermöglicht und in ähnlicher Form bereits in Normen für Wireless Personal Area Networks (WPANs) genutzt wird. Die vorliegende Arbeit erläutert die zugehörigen Erfindungen des Autors und die Normen, in welcher diese eingesetzt werden. Mittels des öffentlich zugänglichen Protokollsimulators Wireless Access Radio Protocol 2 (WARP2) wird die Leistungsfähigkeit des neuen Kanalzugriffverfahrens in dieser Arbeit bewertet.
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CHAPTER 1

Introduction

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Wireless networks have become ubiquitous. With cheap and reliable products Wireless Fidelity (Wi-Fi) (Institute of Electrical and Electronics Engineers (IEEE) 802.11 [265]), Bluetooth (IEEE 802.15.1 [266]), and World-wide Interoperability for Microwave Access (WiMAX) (IEEE 802.16 [267]) developed mass markets. The IEEE 802.15.1, IEEE 802.15.3 [268], and IEEE 802.16 standards describe topologies with a master, Piconet Controller (PNC) or Base Station (BS) in the network that has full control over the Wireless Medium (WM). Although almost all IEEE 802.11 Wireless Local Area Networks (WLANs) use decentralized medium access they operate in infrastructure mode, which forms a star topology with the Access Point (AP) in its center.

Similar to the early days of wired networking, these wireless networks are in the state to form detached communication islands. Several wireless networks may solely interconnect if their central entities attach to the same wired infrastructure. Since in-band bridging is not foreseen, data cannot be relayed on the WM. Thus, current wireless networks are simply last-hop extensions of their wired backbones. Therefore, deployment of large scale wireless networks becomes expensive and ad-hoc operation is nearly impossible. To overcome this drawback, Wireless Mesh Networks (WMNs) provide the solution.

WMNs form arbitrary topologies and operate at different layers. [15,313] classify and outline several concepts. The withdrawn mesh concept of the 2004 version of the IEEE 802.16 [269] standard, the high and low rate Wireless Personal Area Network (WPAN) mesh concept of the IEEE 802.15.5 [270] recommended practice, and the WLAN mesh concept of the IEEE
802.11s [271] draft amendment describe WMNs that operate in the Medium Access Control (MAC) layer. The introduction of routing at the MAC layer requires multi-hop operation that affects for example

- Security,
- Interworking,
- Medium Access,

and other MAC layer functions. IEEE 802.15.5 for example describes an ad hoc routing protocol and a synchronization mechanism that are needed when a WMN shall be established on top of the centrally coordinated medium access of the IEEE 802.15.3 standard. The Wireless Relay Network (WRN) concept, that IEEE 802.16j [272] describes, alters the general medium access rules neither. In contrast to the aforementioned IEEE 802.15.5, however, the IEEE 802.16j WRN approach accounts much better for the centralized structure of the basic IEEE 802.16 standard. In contrast, the Internet Engineering Task Force (IETF) Mobile Ad-hoc Networks (MANET) [343] develops Internet Protocol (IP) based ad hoc routing protocols that operate on top of several wireless technologies. Without sufficient interfaces to the MAC layer, link state information is of limited accuracy, however. Accordingly, performance cannot be optimal.

Yet, the most advanced mesh project is IEEE 802.11s. It defines not only a hybrid routing scheme but also introduces an optional amendment to the MAC layer, a new security concept, considers intra-mesh congestion and provides address extensions for the integration with other networks. In this thesis the authors describes his contributions to IEEE 802.11s and presents a performance analysis of the upcoming standard.

1.1 Motivation

Often, WMNs suffer from poor performance when medium access protocols designed for wireless single-hop networks are reused. WMNs are designed to interconnect devices that are outside of mutual range. On the one hand, the so called Listen Before Talk (LBT) medium access control mechanisms suffer from frame collisions when devices cannot mutually sense each other. On the other hand, centrally controlled medium access protocols require extra signaling for the coordination of the medium access schedules that the central controllers control in their cells. Both traditional wireless single-hop medium access protocols do not perform well when
used in a mesh topology. To account for the multi-hop transmissions that occur in WMNs, a new approach is needed. In this thesis, the author describes this approach and evaluates its performance.

Standard IEEE 802.11 medium access Coordination Functions (CFs) and different enhancements are proposed to IEEE 802.11 Task Group (TG) “S.” However, only a single new CF was adopted by IEEE 802.11. This CF is based on inventions of the author. The provision of detailed analysis in this thesis helps to understand its performance advantage in WMNs over the previously existing IEEE 802.11 CFs.

1.2 Objectives of this thesis

In this thesis the author describes and surveys a distributed medium access reservation mechanism that he developed. The so called Distributed Reservation Protocol (DRP) targets highly efficient spectrum sharing without relying on central medium access control. In contrast to contention based protocols, DRP allows for coordinated medium access. Due to avoiding frame collisions, DRP’s signaling overhead can be compensated for. The author proves DRP’s eligibility and high efficiency for wireless communication in single and multi-hop wireless networks:

1. This thesis evaluates the performance of different Acknowledgment scheme introduced by IEEE 802.11e. The correspondence of analysis and simulation based performance study validates the implementation of the simulation tool Wireless Access Radio Protocol 2 (WARP2).

2. This thesis demonstrates the appropriate nature of DRP for high speed WPANs. Therefore, the author contributed to the development of the simulation tool WARP2 that he uses to compare the performance of DRP with other medium access protocols in much detail. Because of its performance advantage DRP builds the foundation of the world’s first Ultrawideband (UWB) standard International Organization for Standardization (ISO)/International Engineering Consortium (IEC) 26907 and the 60 GHz standard ISO/IEC 13156.

3. This thesis outlines the author’s multi-hop extenstions to DRP and evaluates the performance of the modified approach in WMNs. The author focuses especially on the WLAN mesh standard IEEE 802.11s. This thesis motivates the need for a MAC protocol that is designed for the multi-hop transmissions required by WMNs.
4. This thesis surveys the performance improvements of spatial frequency reuse. The author developed the Mesh Networks Alliance (MNA) protocol that incorporates DRP, introduces uni-directional transmissions, and separates acknowledgments to allow for concurrent transmissions. The MNA protocol has been proposed to IEEE 802.11s.

5. As part of the MNA protocol this thesis introduces a scheme that reliably measures the interference situation between neighboring devices. The scheme helps to identify time slots where concurrent frame transmissions are possible.

6. This thesis introduces the IEEE 802.11s MCF coordinated channel access (MCCA) protocol. MCCA is a compromise solution based on MNA. This thesis outlines how the author modified his original proposal (MNA) and where his ideas are accepted in the final standard. With MCCA, the author introduces the first distributedly scheduled, slot based medium access protocol to the IEEE 802.11 standard.

7. Based on the reference scenarios adopted by IEEE 802.11s the author compares the MNA protocol with Enhanced Distributed Channel Access (EDCA) and MCCA. Further, this thesis outlines the author’s contributions to IEEE 802.11s.

1.3 Contributions to standardization of this thesis

In the joint research projects, the author’s work has been generously supported by Philips Research Aachen and Philips Research Eindhoven. Several of his inventions have been proposed and integrated into recent wireless communication standards. The following list outlines the wireless communication technologies that the author’s work influences.

ISO/IEC 26907 — Philips introduced the author’s ideas on decentralized reservation protocols to the Multiband OFDM Alliance (MBOA) and the ensuing WiMedia Alliance (WiMedia). Subsequent to the acceptance of the author’s contributions to WiMedia’s UWB specification, Ecma International — European association for standardizing information and communication systems (ECMA) accepted the specification as ECMA-368. In the course of fast track processing ISO/IEC published ECMA-368 as ISO/IEC 29607.
ISO/IEC 13156 — ECMA-387 adopts the ECMA-368 MAC for operation in the 60 GHz band. ISO/IEC also includes ECMA-387 into its family of standards as IEC/IEC 13156.

IEEE 802.11e — The author was the first to provide simulative detailed performance analysis of the Quality of Service (QoS) enhancing features of IEEE 802.11e. Thanks to the Department of Communication Networks, RWTH Aachen University (ComNets)/Philips collaboration the simulation results influenced the process of its standardization. Since then the simulation results obtained with WARP2 serve as a reference [314] to following simulation tools like ns-2 [344].

IEEE 802.11s — Since 2003 the author represented Philips in a total of more than fifty IEEE plenary, interim and ad hoc meetings. Beginning with the IEEE 802.11 Mesh Study Group (SG) the author contributed to the IEEE 802.11s WLAN Mesh amendment on behalf of Philips. The author served as vice chairman of the TG “s” from 2010 until its ratification at the end of 2011.

IEEE 802.15.5 — In 2004, the WPAN Mesh SG was initiated. Since then the author represented Philips in the IEEE 802.15.5 TG that developed the Recommended Practice for Mesh Topology Capability in WPANs.

Wi-Fi Alliance — Since its initiation in 2006 the author represented Philips in the Wi-Fi Alliance (WFA) Mesh Marketing TG. The author contributed to the development of the Market Requirements Document (MRD) that outlines the contents of the certification plan, which is to be defined by a subsequent technical TG.

1.4 Outline

Chapter 2 provides a basic overview to wireless communication. This thesis outlines important signal parameters that are used to explain the fundamental ideas of communication protocols introduced in later chapters. Chapter 3 outlines the simulation tool WARP2 that the author uses to survey different wireless communication protocols. In Chapter 4 the author outlines the principles of the IEEE 802.11 standard and its details that are important for the WLAN mesh amendment IEEE 802.11s. In Chapter 5 the author briefly introduces the UWB project IEEE 802.15.3a that WiMedia contributed to. In 6 the author introduces the DRP that he invented. DRP provides a deterministic medium access protocol. WiMedia
Chapter 1 – Introduction

implements DRP in its MAC protocol. The author outlines this protocol and the WiMedia’s WPAN standard in Chapter 7. Chapter 8 motivates the need for an enhanced MAC CF for WMNs. Chapter 9 explains the author's proposal for the IEEE 802.11s standard. The author outlines how he evolved DRP and his IEEE 802.11s proposal through several steps into the finally accepted IEEE 802.11s medium access protocol. In Chapter 10 the author provides simulation results and compares the author's initial protocol proposal to the finally accepted version. Chapter 11 provides a summary and highlights the main insights and contributions of this thesis. Throughout this thesis the author follows the style guide recommendations in [345,346]. All mathematical notations and unit descriptions in this thesis comply with [273].
Basics of Wireless Communication

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This section depicts the fundamentals of wireless communication. First, the Signal to Interference plus Noise Ratio (SINR) is introduced in Section 2.1. The SINR describes a criterion that a radio transmission must meet for successful reception at the receiver side. Since the author’s proposal to IEEE 802.11s in Chapter 9 uses techniques to estimate the SINR that occurs with concurrent frame exchanges, he briefly outlines the rules of radio propagation and its effect on the SINR in Section 2.2.

2.1 Signal to Interference plus Noise Ratio

Let \( R \) denote an element of the set of Modulation and Coding Schemes (MCSs). Then, \( P_{\text{min}}(R) \) denotes the minimal power a device needs for successful reception of a frame that is transmitted at MCS \( R \). However, \( P_{\text{min}}(R) \) is not the only requirement a wireless signal needs to meet for successful reception. As the wireless medium is shared, other simultaneous radio transmissions may occur. To successfully receive a radio transmission, the power level of the wanted signal must be several degrees higher than any other interfering signal arriving at the receiver at the same time. The ratio between the power of the wanted signal and any unwanted transmissions is called Signal to Interference Ratio (SIR). Device \( s_n \) receives the emission of power of device \( s_m, m \neq n \) at a level of \( P_n(m) \). However, \( P_n(m) \) may fluctuate due to fading processes and therefore depends on time – \( P_n(m, t) \). For device \( s_n \) the amount of power received at time \( t_0 \) is given by

\[
P_{n,\text{total}}(t_0) = \sum_{m=1}^{N} P_n(m, t_0)
\]  

(2.1)
Chapter 2 – Basics of Wireless Communication

with \( m \neq n \). \( P_{n,\text{total}}(t_0) \) denotes the total sum of power received at \( s_n \) at time \( t_0 \). For simplicity reasons stationary conditions are assumed. Therefore, time dependency is not considered in the following. With Eq. 2.1 the SIR can be defined as

\[
\text{SIR}_n(m) = \frac{P_n(m)}{N \sum_{k=1}^{N} P_n(k), \ k \notin (n, m)} \tag{2.2}
\]

where \( s_n \) receives a transmission of device \( s_m \) while \( N - 2 \) devices \( s_k \) concurrently emit other unwanted power to the Wireless Medium (WM).

Assuming a single transmission at a time \((k \in \varnothing)\), the SIR becomes infinite. However, in real wireless system noise must be taken into account. Since noise is unwanted power at the receiver it is treated as interference. Noise is of thermal, galactic and atmospheric nature for example. Thermal noise is an inherent effect in any wireless receiver and a source of interference.

Thermal noise depends on the temperature of the receiver. With Boltzmann’s constant \( k_B \), the receiver temperature \( T \) and the signal bandwidth \( \Delta f \), it is calculated as

\[
P_{\text{Noise}_\text{thermal}} = k_B \cdot T \cdot \Delta f + N_f \tag{2.3}
\]

Signal to Noise Ratio (SNR) denotes the ratio between the wanted power \( P_n(m) \) that is received by device \( s_n \) when device \( s_m \) transmits and noise power is present at device \( s_n \)

\[
\text{SNR}_n(m) = \frac{P_n(m)}{P_{n,\text{Noise}_\text{thermal}}} \tag{2.4}
\]

The SINR expresses the overall ratio of the wanted signal to any other unwanted power at the receiver side

\[
\text{SINR}_n(m) = \frac{P_n(m)}{P_{n,\text{Noise}_\text{thermal}} + \sum_{k=1}^{N} P_n(k), \ k \notin (n, m)} \tag{2.5}
\]

The SINR is the definitive mean value to consider when discussing frame reception success probability. \( P_n(m) \) is a random variable following an environmental specific propagation law. In the following it is set equal to its mean value observed during the received frame duration. In the optimum case of a single transmitter and a single receiver with no other harmful transmission at the same time, Eq. 2.5 equals Eq. 2.4. Hence,
thermal noise is the lower boundary that limits transmission range. For any data transmission from device $s_m$ to device $s_n$ that uses MCS $R$, a frame reception succeeds if $P_n(m) > P_{\text{min}}(R)$ and $\text{SINR}_n(m) > \text{SINR}_{\text{min}}(R)$. Each MCS $R$ has a minimal SINR$_{\text{min}}(R)$ that must be met or otherwise the frame transmission fails.

## 2.2 Radio propagation

In wireless communication, free space conditions assume the absence of anything else than the Wireless Medium (WM). A radio transmission is said to be isotropic, if its energy is disseminated equally in any direction by an idealized punctiformed source [1]. Under free space conditions, the power $P_n(m)$ that a device $s_n$ receives from the transmission of an isotropic transmitter $s_m$, $m \neq n$ depends on the power $P(m)$ emitted by device $s_m$ and the distance $d_{n,m}$ between device $s_n$ and device $s_m$

$$P_n(m) = \frac{P(m)}{d_{n,m}^2} \cdot \left(\frac{c}{4\pi f}\right)^2$$

(2.6)

where $f$ denotes the frequency of the radio transmission and $c$ the speed of light. The attenuation $A$

$$A = \frac{P_n(m)}{P(m)}$$

(2.7)

increases by the power of two with increasing distance or transmission frequency. Both, device $s_n$ and device $s_m$ may use directional antennas. The transmission gain $g_{\text{Tx}}$ and the receiver gain $g_{\text{Rx}}$ help to reduce the attenuation to

$$A = \frac{g_{\text{Tx}} \cdot g_{\text{Rx}}}{d_{n,m}^2} \cdot \left(\frac{c}{4\pi f}\right)^2.$$ 

(2.8)

Factors $g_{\text{Tx}}$ and $g_{\text{Rx}}$ anticipate attenuation of the ideal antenna gains $g_m$ and $g_n$ if their directions of maximum gains are not aligned. In a realistic environment, free space conditions rarely exist. Then, multi-path effects occur. Multi-path denotes the fact where a device $s_n$ receives energy of $s_m$’s transmission not only via Line Of Sight (LOS) but also via non Line Of Sight (non-LOS) paths. Due to reflection, indirect paths contribute to the total emissions that reach $s_n$. However, emissions on an indirect path reach $s_n$ delayed when compared to the direct path. Due to diffraction of radio waves, scattering and fading effects, exact modeling of radio signal propagation becomes difficult. Radio channel models characterize various
radio channel environments in- and outdoors. As an example, [2] presents the Berg [54], the Hata-Okumura [16], the Walfisch-Ikegami [3, 17], and the Dual-slope [55] models. Depending on the wavelength of transmission frequency $f$ and the specific scenario, multi-path effects may in- or decrease $P_n(m)$. Let $\alpha$ summarize all effects that occur due to non free space attenuation. This leads to

$$d_{n,m}^\gamma = \alpha \cdot g_m \cdot g_n$$

(2.9)

where $\gamma$ denotes a generalized attenuation factor for signals arriving from device $s_m$ at device $s_n$. Thus, Eq. 2.6 becomes

$$P_n(m) = \frac{P(m)}{d_{n,m}^\gamma} \cdot \left(\frac{c}{4\pi f}\right)^2.$$

(2.10)

From Eq. 2.5 and Eq. 2.10 follows

$$\text{SINR}_n(m) = \frac{P(m)}{d_{n,m}^\gamma} \cdot \left(\frac{c}{4\pi f}\right)^2, \; k \notin (n, m)$$

(2.11)

as the general equation for the Signal to Interference plus Noise Ratio (SINR) at receiver $s_n$. Typical values for $\gamma$ are between 4 to 6 for indoors scenarios and 2.5 to 5 outdoors.
CHAPTER 3

The Wireless Access Radio Protocol 2 (WARP2) simulation environment has been developed at the Department of Communication Networks, RWTH Aachen University (ComNets). The author contributed to the development of WARP2. WARP2 is implemented in Specification and Description Language (SDL) using Telelogic’s TAU SDL suite. SDL is a standardized programming language driven by events on a realtime basis. The author implemented the new Coordination Functions (CFs) introduced with IEEE 802.11e and delivered the first results on their performance. These results serve as a reference to other simulation tools [314]. The latter confirm the author’s findings.

In the following the author provides a basic overview to WARP2 and its concepts. In subsequent chapters, the author uses WARP2 to compare the performance of the medium access protocols that he developed. WARP2 is available for download for the scientific community at [347] since October 2011.

3.1 Introduction

The initial design goal of WARP2 was to evaluate the coexistence between European Telecommunications Standards Institute (ETSI) High Performance Local Area Network 2 (HiperLAN/2) and IEEE 802.11a in the 5 GHz band. Later revisions of WARP2 introduce the IEEE 802.11e, 802.11n, 802.11p and 802.11s amendment as well as other protocols like ISO/IEC 26907. Fig. 3.1 presents the building blocks of WARP2.
Figure 3.1: Generic structure of the WARP2 simulation environment.
Section 3.2 introduces the Physical Layer (PHY) model that WARP2 implements. Section 3.3 outlines the WARP2 traffic generators. They generate the frames that traverse the WARP2 protocol stack and its PHY model. The evaluation methods presented in Section 3.4 help to analyze the performance of the implemented protocols in various simulation set-ups. Section 3.5 presents details of the implemented IEEE 802.11 protocol stack.

### 3.2 Physical layer (PHY) model

WARP2 emulates the Wireless Medium (WM) in accordance with the channel model described in [56, 57]. The model enables the user to survey the characteristics of the implemented protocols under any desired circumstances and to study the robustness against errors on the WM.

The user may specify the minimal signal strength needed for frame reception and preamble synchronization of the Orthogonal Frequency Division Multiplexing (OFDM) PHY that WARP2 emulates. Furthermore, WARP2 allows to specify the thermal noise at the receiver side and the global attenuation value $\gamma$ (Eq. 2.9). To provide shadowing in a given scenario, the user may add walls, doors, and other elements. These obstacles add additional, user configurable attenuation to the direct path between two devices. Table 3.1 outlines the achievable OFDM preamble synchronization range depending on the Modulation and Coding Scheme (MCS) mode and the attenuation factor $\gamma$.

The total attenuation leads to the Signal to Interference plus Noise Ratio (SINR) of each frame reception. WARP2 implements different error models that simulate the unpredictable behavior of the WM. The models consider the calculated SINR to modify the mean value of the random frame drop probability that simulates the variation of the signal quality of a real system.

For basic performance analysis, no errors on the WM can be assumed. Another simplistic PHY model assumes equally distributed errors. Then, frames are dropped on a random basis. A more realistic model assumes error free reception as long as a frame’s SINR exceeds a minimal threshold. Additionally, a random drop probability can be added for those frames that exceed the necessary SINR. Table driven error models further enhance the accuracy of the model. They increase the error probability with decreasing SINR. Fig. 3.2 provides an example for four different MCSs. In addition, the error probability may increase with increasing frame lengths.
Table 3.1: Maximum distance for successful OFDM preamble synchronization. Columns 3–4 simulate a mean $\gamma = 3.5$, columns 5–6 are valid in free space scenarios for $\gamma = 2$.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>$\gamma = 3.5$</th>
<th>$\gamma = 2$</th>
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<tr>
<td></td>
<td>Transmit Power (mW)</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>Binary Phase Shift Keying (BPSK)</td>
<td>1/2</td>
<td>58 m</td>
<td>92 m</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>54 m</td>
<td>86 m</td>
</tr>
<tr>
<td>Quarternary Phase Shift Keying (QPSK)</td>
<td>1/2</td>
<td>47 m</td>
<td>75 m</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>41 m</td>
<td>66 m</td>
</tr>
<tr>
<td>16-Quadrature Amplitude Modulation (QAM)</td>
<td>1/2</td>
<td>34 m</td>
<td>54 m</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>26 m</td>
<td>41 m</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>20 m</td>
<td>32 m</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>19 m</td>
<td>30 m</td>
</tr>
</tbody>
</table>

Figure 3.2: Frame error rate as a function of SINR.
To vary the SINR during frame reception, [324] introduces Ricean and log-normal fading processes. Fig. 3.3 presents the block diagram where Ricean fading is considered for the receive signal (power $P_{Rx}$) and log-normal fading for the signals arriving from interfering devices.

### 3.3 Traffic generator

The WARP2 traffic generator resides in the application layer. It generates frames of arbitrary length according to the following traffic source models:

- Poisson
- Constant Bit Rate (CBR)
- HTTP
- FTP
- MPEG
- Tracefile of
  - MPEG-Video
  - Ethernet segment traffic

In addition, [324] introduces a traffic generator that superposes two negative exponential distributions for frame length variation exemplified by...
Fig. 3.4. The respective traffic generator varies the frame rate keeping the selected target data rate.

The offered traffic coming from the sources mentioned can be adjusted in steps of 1 kb/s. Frames are marked with their creation time and a unique sequence number such that the transmission delay and the frame loss can be traced. Frames may carry information about the route to choose. Accordingly, WARP2 offers an environment to survey multi-hop scenarios.

### 3.4 Evaluation

To evaluate the performance behavior of the protocol under study, WARP2 extends the frame format by time stamps and route specific information. Thereby, WARP2 measures several values that help to evaluate

- throughput,
- frame loss, and
- delay (single and multi-hop).

Delay results are represented by their empirical Complementary Cumulative Distribution Function (CCDF) where the discrete Limited Relative Error (LRE) algorithm is applied to measure and take into account the local
correlations of the stochastic data [18, 19] provided by WARP2. All results presented in this thesis are within a maximum limited relative error of 5%. The LRE algorithm has been proven to be substantially superior to other known methods to provide statistical confidence in stochastic system level simulation results [58].

3.5 WARP 2 IEEE 802.11 model

The initial WARP2 design bases on the SDL description of a subset of Medium Access Control (MAC) functions presented in [274]. Although part of the normative description of the IEEE 802.11 protocol, later revisions [265] re-categorized the SDL specification as informative. Fig. 3.5 presents the block diagram of WARP2.
Figure 3.6: Multiple collisions in a BSS. MSDUs are not fragmented.

Since the IEEE 802.11 medium access bases on a Listen Before Talk (LBT) scheme, WARP2 offers means to select the power threshold for busy medium detection. Both, OFDM preamble and absolute energy detection settings are supported. Fig. 3.6 presents a screenshot of a WARP2 simulation. The WARP2 Graphical User Interface (GUI) developed in [325] helps to survey a simulation scenario. Fig. 3.6 presents an IEEE 802.11 frame exchange sequences and frame collisions.


## IEEE 802.11

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Standard IEEE 802.11 describes a system concept for Wireless Local Area Networks (WLANs). The author contributed to the WLAN mesh standard IEEE 802.11s as described in subsequent chapters. Proposals to the IEEE 802.11 standard need to integrate with the IEEE 802 family of standards and therefore have to meet the overall system concept requirements and basic principles. Accordingly, in this chapter the author introduces important elements of the IEEE 802.11 standard that relate to his thesis. Furthermore, he develops an analytical model of different acknowledgment schemes in IEEE 802.11 and compares them with simulation results gained under the Wireless Access Radio Protocol 2 (WARP2) simulator. The analytical model
Chapter 4 – IEEE 802.11

IEEE 802.11 verifies the correctness of the IEEE 802.11 implementation in the WARP2 simulation tool.

4.1 Introduction

IEEE 802.11 describes the standard for WLANs. With more than 15 amendments the initial IEEE 802.11-1997 standard [275] has grown from over 400 to more than 2000 pages [276]. Thus in the following, those parts of IEEE 802.11-2010 [276] are highlighted that relate most to this work. A comprehensive introduction into the IEEE 802.11 standard can be found in [1, 4–7, 20].

The remainder of this chapter is organized as follows. In Section 4.2 the author introduces the IEEE 802.11 system and its interworking concept. Next, the author introduces the IEEE 802.11 Physical Layer (PHY) in Section 4.3. Section 4.5 explains the Coordination Functions (CFs) that IEEE 802.11 relies on for access to the Wireless Medium (WM). In Section 4.7 the author provides simulation based analysis of basic IEEE 802.11 features.

4.2 System concept

IEEE 802.11 denotes any implementation of a standard compliant Medium Access Control (MAC) and PHY layer as Station (STA) [265]. A group of two or more STAs may form a Basic Service Set (BSS). IEEE 802.11 distinguishes between the

- Independent Basic Service Set (IBSS), and the
- infrastructure BSS.

Only the latter may provide access to external networks. For identification, a BSS has a Service Set Identifier (SSID) and a Basic Service Set Identification (BSSID). The SSID is a user administered string of up to 32 B length and may be treated as the name of a WLAN. Like an IEEE 802 MAC address, the BSSID is 48 b in length and uniquely identifies a BSS.

4.2.1 Independent Basic Service Set (IBSS)

In the IBSS, STAs have no access to external networks. The IBSS provides spontaneous connectivity to form an ad-hoc network. The individual/group bit and the universal/local bit [277] of the BSSID are set to zero. The remaining 46 b of the BSSID contain a random value that the
4.3 Physical Layer

The initial IEEE 802.11-1997 [275] standard and its revision IEEE 802.11-1999 [274] provide three different PHY technologies. They define a Frequency Hopping Spread Spectrum (FHSS) and a Direct Sequence Spread Spectrum (DSSS) PHY in the unlicensed 2.4 GHz band, and an infrared PHY at 316 - 353 THz. All three provide a basic data rate of 1 Mb/s with an
Figure 4.2: BSSs \(A\) and \(D\) form an ESS. STAs B, C, E and, F can roam within the ESS. The APs A and D interconnect via the DS.

Figure 4.3: Here, IEEE 802.3 provides the DSM. A portal is needed to connect the non-802.11 network with the IEEE 802.11 network.

optional 2\(\text{Mb/s}\) mode. IEEE 802.11b is a high rate extension of the DSSS PHY that introduces two Modulation and Coding Schemes (MCSs) supporting up to 11\(\text{Mb/s}\). IEEE 802.11a introduces Orthogonal Frequency Division Multiplexing (OFDM) transmissions in the 5 GHz band. Eight different MCSs provide up to 54\(\text{Mb/s}\). IEEE 802.11h and IEEE 802.11j add mechanisms that meet regulatory requirements for operation in the 5 GHz band in Europe resp. Japan. IEEE 802.11g adapts the IEEE 802.11a OFDM PHY for usage in the 2.4 GHz band. Additional IEEE 802.11g mechanisms en-
able coexistence with IEEE 802.11b devices. While IEEE 802.11j introduces 10 MHz in addition to the standard 20 MHz channels, the IEEE 802.11-2007 revision [265] amends 5 MHz channels. IEEE 802.11n [278] adds 76 different MCSs that deliver up to 600 \( \text{Mb/s} \) data rate. IEEE 802.11n implements Multiple Input/Multiple Output (MIMO) technology and allows for the optional usage of 40 MHz channels.

### 4.4 Frame format

IEEE 802.11 distinguishes between three frame types:

- Data
- Control
- Management.

Except for some control frames, all frames contain a frame body that is surrounded by a MAC frame header and a Frame Check Sequence (FCS). Located at the end of each frame, the FCS enables stations to detect frame transmission errors. Transmitted as the first part of a frame, the MAC frame header carries a frame control, a sequence control, a duration and up to four address fields. With 16 b in length, the sequence control field allows for the detection of duplicate transmissions. The latter may occur, when a STA retransmits a frame because of the absence of an indication of a successful frame reception. Some amendments add header fields. Examples are IEEE 802.11e [279] that adds the Quality of Service (QoS) control field or IEEE 802.11n [278] that signals MIMO related and other settings in the High Throughput (HT) control field, see Fig. 4.4.

#### 4.4.1 Frame Control field

The frame control field indicates the IEEE 802.11 protocol version as well as the type of the current frame. Frames of type data, management or control are further differentiated into special subtypes.
4.4.2 Duration/ID field

The Duration/ID field is 16 b in length. When the field’s Most Significant Bit (MSB) is set to zero, the field indicates the amount of µs until the end of the current frame exchange. The duration field is present in all frames of a frame exchange sequence. STAs in the surroundings of the frame exchange initiator or responder may overhear the duration field. Then, they set their Network Allocation Vector (NAV) to the indicated duration. As long as a STA’s NAV is set, it refrains from accessing the WM.

4.4.3 Address fields

The IEEE 802.11 frame format provides four fields. Address field 1 contains the immediate receiver. Address field 2 contains the MAC address of the STA that sends the frame. Since multiple WLANs may overlap, the third address field contains the so called BSSID that uniquely identifies each BSS. In an infrastructure BSS, the BSSID equals the MAC address of the AP. Only within an ESS, where a frame traverses the DS, a fourth address field is necessary to forward frames from one BSS to another.

When STA B in Fig. 4.2 sends a frame to STA F, the following transmissions occur:

- Within BSS A, STA B sends a frame to AP A.
- The frame leaves BSS A via AP A.
- The frame traverses the DS.
- The frame enters BSS D at AP D.
- Within BSS D, AP D delivers the frame to STA F.

In this forwarding process, Source Address (SA) denotes B’s address and Destination Address (DA) denotes F’s address. Transmitter Address (TA) and Receiver Address (RA) denote the immediate transmitter respectively receiver. As shown in Fig. 4.5, address fields 1 and 2 always contain the RA and TA. Accordingly, address fields 1 and 2 change with every forwarding step.

4.5 Medium Access Control (MAC) Layer

Similar to IEEE 802.3, the basic IEEE 802.11 MAC operates as a Listen Before Talk (LBT) scheme. This is known as Carrier Sense Multiple Ac-
4.5 Medium Access Control (MAC) Layer

Figure 4.5: STA B’s transmission to STA F leaves BSS $\emptyset$, traverses the DS and finally enters BSS $\emptyset$.

cess (CSMA). In contrast to Collision Detection (CD) that IEEE 802.3 combines with CSMA, IEEE 802.11 applies Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). This is because of the radio environment where collisions of concurrent frame transmissions cannot be immediately detected.

In the following, the author introduces the IEEE 802.11 medium access protocols. Subsequent to the explanation of the basic frame exchange sequence in Section 4.5.1, Section 4.5.2 introduces the IEEE 802.11 Collision Avoidance (CA) mechanism. Afterwards, Section 4.5.3 outlines the different medium access protocols. In Section 4.5.4, the author discusses enhancements that increase the efficiency of the IEEE 802.11 MAC.

4.5.1 Frame exchange sequence

Wireless networks cannot apply CD. Therefore, IEEE 802.11 STAs send an Acknowledgment (ACK) frame to the sending station for every successfully received frame. The reception of an ACK indicates to the sending station that the transmitted MAC Protocol Data Unit (MPDU) has been successfully received, see Fig. 4.6. The Short Interframe Space (SIFS) between the frame and its ACK provides both STAs with the ability to turn around their Transceiver (TRX). The duration of SIFS is a technology parameter that depends on the PHY in use. Within a SIFS duration after the end of the frame transmission resp. reception, the transmitting station switches its transceiver from transmitting to receiving and vice versa at the receiving station. If the transmitting station cannot receive an ACK within an ACK-
Successful frame exchange.

Due to a frame reception error STA 2 does not send an ACK in response.

Although STA 2 successfully received the data frame, STA 1 retransmits the frame due to a failed reception of the ACK.

(a) Successful frame exchange. (b) The receiver does not send an ACK because of a frame error. (c) The data frame was successfully received, but the ACK is interfered.

Figure 4.6: Frame exchange between two STAs. Each successful reception is acknowledged by the receiving STA.

Timeout, it assumes the transmission to have failed. Also, the receiving station does not send an ACK if it cannot decode the frame or the calculation of the FCS indicates an error. Thus, the sender assumes that the transmission has failed. The reception of the ACK, however, may also fail. For both cases shown in Fig. 4.6, the sending station will retransmit the frame. The receiving station acknowledges correctly received retransmitted frames. Based on the frame sequence number, however, it discards any frame that has successfully received already.

4.5.2 Carrier Sensing (CS)

The basic IEEE 802.11 MAC implements a variant of the ALOHA protocol [21–23, 59]. As an LBT approach, IEEE 802.11 stations use two Carrier Sense (CS) mechanisms to determine the state of the WM:

- Clear Channel Assessment (CCA) and
- Virtual Carrier Sense (V-CS).

Only when both mechanisms sense the WM as idle, a station may attempt to transmit. While V-CS is a function of the MAC, the PHY implements CCA. Fig. 4.7 presents an example that considers an IEEE OFDM PHY. With other PHYS, CCA may consist of different elements.

4.5.2.1 Clear Channel Assessment (CCA)

With an OFDM PHY like IEEE 802.11a [276, 280], the IEEE 802.11 CCA considers two major input signals for decision making. On the one hand, any signal that exceeds a certain threshold causes an IEEE 802.11a STA to consider the WM as busy. The so-called Energy Detection (ED) observes any
signal independent of its shaping or modulation. On the other hand, Physical Carrier Sense (P-CS) detects frames that have a valid OFDM preamble. Independent of an IEEE 802.11a STA’s ability to track the whole frame, it considers the WM to be busy for a duration indicated in the length field of the frame’s Physical Layer Convergence Protocol (PLCP) header. The PLCP prepends the preamble and header that are necessary to identify a frame on the WM. If the station solely detects a valid PLCP preamble, it may sense the WM as idle once the observed signal strength falls below a certain threshold.

### 4.5.2.2 Virtual Carrier Sensing

The NAV is an addition to the physical sensing of the WM. It is used as a means of V-CS. The NAV is a timer that continuously decrements irrespective of the status of the WM. As long as its NAV is set, an STA does not initiate a frame transmission (see Fig. 4.8).

An STA learns about the NAV duration by overhearing neighboring frame exchanges. It refrain from accessing the WM for a duration that it reads from the Duration/ID field contained in the MPDU (see Section 4.4.2). Subsequent frames may update the NAV setting so that the whole frame

---

**Figure 4.7:** V-CS operates independent of the PHY. Here, IEEE 802.11a provides an example of the PHY’s CCA.
IEEE 802.11 Coordination Functions

IEEE 802.11 provides several CFs that organize access to the WM. According to the basic principles of a LBT scheme, an STA must sense the WM as idle before it may initiate a frame transmission. Section 4.5.3.1 introduces the different Interframe Spaces (IFSs) that IEEE 802.11 requires for P-CS. Following the detection of an idle WM, STAs use one of the CFs described in Section 4.5.3.2, Section 4.5.3.3 or Section 4.5.3.4 to access the WM.

4.5.3.1 Inter Frame Space (IFS)

IEEE 802.11 denotes the time between two consecutive MAC frames as IFS. Two values define an IFS duration:

- **Short Interframe Space (SIFS)** separates a frame and its immediate reply. E.g. an ACK frame follows a data frame after a SIFS duration. To prevent frame exchanges from interruption, stations use IFSs greater than SIFS for accessing the WM. The duration of SIFS depends on the PHY in use.

- **aSlotTime** defines the duration of slot. STAs wait for a random amount of slots during the backoff process, see Section 4.5.3.2. The duration of aSlotTime depends on the PHY.
4.5 Medium Access Control (MAC) Layer

All other IFSs have a duration of a SIFS and one or more aSlotTime.

**Point (Coordination Function) Interframe Space (PIFS)** has duration of \( SIFS + aSlotTime \). Only a Point Coordinator (PC) (Section 4.5.3.3) or a Hybrid Coordinator (HC) (Section 4.5.3.4) may access the WM after a duration of PIFS.

**Distributed Coordination Function Interframe Space (DIFS)** has duration of \( SIFS + 2 \cdot aSlotTime \).

**Arbitration Interframe Space (AIFS)** has been introduced with the extensions of IEEE 802.11e [279]. The duration of AIFS depends on the frame priority. Each priority uses a different Access Category (AC). The Arbitration IFS Number (AIFSN) defines the duration of an AC as \( SIFS + AIFSN \cdot aSlotTime \).

**Extended Interframe Space (EIFS)** provides precaution when an STA cannot successfully detect the end of a frame exchange sequence. The reception of a frame with an incorrect FCS or the indication of a PHY reception error forces an STA to refrain from accessing the WM for duration of \( SIFS + ACKTxTime + AIFS \). ACKTxTime denotes the duration that the transmission of an ACK frame at the most basic MCS takes. STAs that do not implement IEEE 802.11e [279] wait for a DIFS period instead of AIFS. Consequently, an STA waiting for a duration of EIFS does not interrupt the ACK reception.

### 4.5.3.2 Distributed Coordination Function (DCF)

The Distributed Coordination Function (DCF) defines the basic medium access mechanism of IEEE 802.11. STAs use CS to detect that no transmission on the WM is in progress. Once an STA detects the WM as being idle for a duration of DIFS, it performs the backoff procedure. An STA, that performs the backoff procedure, senses the WM during the so called backoff interval. The duration of the backoff interval is determined by the backoff counter. For every duration of aSlotTime that the STA detects the WM as idle, it decrements its backoff counter. Once the backoff counter is zero, the STA transmits. If the STA senses the WM as busy before the backoff counter reaches zero, the STA stops the backoff procedure. When a STA stops the backoff procedure it suspends decrementing the backoff counter. Once the STA finds the WM idle for a duration of DIFS again, it performs the backoff procedure again.

To determine the backoff counter, the STA draws a uniformly distributed number between zero and Contention Window (CW). Since each STA inde-
pendently selects a random backoff counter, the probability of more than one STA starting to transmit at the same time is reduced. Thus, the backoff procedure implements CA. Initially, \( CW_{\text{min}} \) which is a PHY dependent value. When its transmission fails, i.e., the transmitted data frame has not been acknowledged, the STA increases the CW according to Eq. 4.1:

\[
CW_{n+1} = (CW_n + 1) \cdot 2 - 1
\] (4.1)

Afterwards, the STA determines a new random slot counter and follows the same rules to send the frame again. Once the transmission succeeds, the STA reset its CW to \( CW_{\text{min}} \) and starts a new backoff procedure.

STAs perform the so called post-backoff independent of the presence of frames in their transmission queue. Thus, any two frame transmissions are separated by at least one backoff interval. Once an STA performed the post-backoff, it transmits any MAC Service Data Unit (MSDU) immediately without any additional backoff as long as the MSDU arrived while the STA sensed the WM as idle for at least a duration of DIFS.

### 4.5.3.3 Point Coordination Function (PCF)

The Point Coordination Function (PCF) offers contention free MSDU delivery. The PCF relies on a central STA known as PC. The latter is collocated with an AP and coordinates access to the WM during the so called Contention Free Period (CFP). The CFP repetition interval has duration of one or more beacon intervals (see Section 4.6.2 for beacon frame generation). Any CFP begins with a beacon frame transmission. Among other informa-

---

**Figure 4.9:** Backoff sequence with comparison of SIFS, PIFS, DIFS, and AIFS.
4.5 Medium Access Control (MAC) Layer

Figure 4.10: The PC polls STA 2 during the CFP.

tion, the beacon frame informs STAs about the duration of the CFP and the nominal beginning of the next CFP. Although it is optional for an STA to support the PCF, it is mandatory for an STAs to preset its NAV at the beginning of and for the duration of the CFP indicated in the beacon frame. Thus, STAs cannot attempt to access the WM during the CFP. Solely the PC initiates any frame exchange sequence during the CFP. Due to the absence of competition for accessing the WM, the PC does not perform the backoff procedure. Instead, it accesses the WM after having detecting it as idle for PIFS duration. Then, the PC transmits either a data or CF-Poll frame. The latter frame grants the receiving station the right to transmit.

For increased efficiency the PC can piggyback the CF-Poll into a frame for its STAs. After a SIFS duration, the polled STA transmits any pending MPDU. The STA includes an outstanding acknowledgment for data received from the PC into its own frame transmission. If the PC received no response from a polled STA after PIFS, it polls the next STA, or ends the CFP. Thus no idle period longer than PIFS occurs during CFP. The PC continues with polling other STAs until the CFP expires. A specific control frame, called CF-End, is transmitted by the PC as the last frame within the CFP to signal the end of the CFP. STAs that receive the CF-End frame reset their NAV. A Contention Period (CP) forms the remaining duration of the CFP repetition interval. It is mandatory for the PC that a CP provides sufficient duration to allow at least one MSDU delivery under DCF. Fig. 4.10 presents an example PCF frame exchange sequence.

4.5.3.4 Hybrid Coordination Function (HCF)

For QoS support, IEEE 802.11 [265] provides the Hybrid Coordination Function (HCF). HCF has been introduced with the amendments of IEEE
Table 4.1: IEEE 802.1D User Priorities and IEEE 802.11 Access Categories

<table>
<thead>
<tr>
<th>IEEE 802.1D UP</th>
<th>IEEE 802.1D Traffic Type</th>
<th>IEEE 802.11e AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Background</td>
<td>AC_BK</td>
</tr>
<tr>
<td>2</td>
<td>Spare</td>
<td>AC_BK</td>
</tr>
<tr>
<td>0</td>
<td>Best Effort</td>
<td>AC_BE</td>
</tr>
<tr>
<td>3</td>
<td>Excellent Effort</td>
<td>AC_BE</td>
</tr>
<tr>
<td>4</td>
<td>Controlled Load</td>
<td>AC_VI</td>
</tr>
<tr>
<td>5</td>
<td>Video, &lt;100 ms latency and jitter</td>
<td>AC_VI</td>
</tr>
<tr>
<td>6</td>
<td>Voice, &lt;10 ms latency and jitter</td>
<td>AC_VO</td>
</tr>
<tr>
<td>7</td>
<td>Network Control</td>
<td>AC_VO</td>
</tr>
</tbody>
</table>

IEEE 802.11e [279]. Compliant implementations are denoted as QoS STA and QoS AP respectively. Where DCF and PCF grant an STA permission to transmit a single MSDU, HCF assigns the so-called Transmission Opportunity (TXOP) to a QoS STA. A TXOP defines the maximum duration a QoS STA may transmit. Depending on the MCSs in use, the QoS STA may be able to transmit several MPDUs to one or more receivers.

For accessing the WM, HCF combines the centralized HCF Controlled Channel Access (HCCA) and the decentralized Enhanced Distributed Channel Access (EDCA). The author explains the latter in Section 4.5.3.4.1. As an improved variant of the basic DCF, EDCA provides means for traffic prioritization. With EDCA, QoS STAs contend for TXOPs. In contrast, HCCA provides QoS guarantee. It relies on the HC that centrally assigns TXOPs to associated QoS STAs. HCCA is introduced in Section 4.5.3.4.2.

### 4.5.3.4.1 Enhanced Distributed Channel Access (EDCA)

In accordance with Annex G of IEEE 802.1D-2004 [281], EDCA supports up to eight User Priorities (UPs). However, QoS STAs implement four frame queues only. Thus, one IEEE 802.11 AC combines two UPs, see Table 4.1.

Each AC behaves like a virtual STA that independently competes for the WM. To contend for the WM, an AC uses its own set of backoff parameters. These are denoted as EDCA parameter set and consist of

- AIFSN,
- $CW_{min}$,
Figure 4.11: An AC behaves like a virtual STA. Lower priority ACs defer to higher priority ACs with internal collisions.

- $CW_{\text{max}}$, and
- TXOPLimit

per AC. Section 4.5.3.1 describes how AIFSN determines the AIFS duration of an AC. Similar to DIFS of the DCF, an AC must continuously detect the WM as idle for a duration of AIFS before initiating the backoff procedure. $CW_{\text{min}}$ defines the initial and $CW_{\text{max}}$ the maximum CW size of the backoff. When two or more ACs within a QoS STA detect the WM as idle, a virtual collision occurs. Then, the AC of highest priority receives the right to transmit. Lower priority ACs, that are involved in the collision, defer. Thus, they increase their CW and perform the backoff procedure again. Once an AC may transmit, the TXOPLimit defines the maximum duration of its frame exchanges.

The QoS AP broadcasts the EDCA parameter set of each AC in its beacon frame. It may change the setting with any beacon transmission.

4.5.3.4.2 Hybrid Coordination Function Controlled Channel Access (HCCA)  HCCA works as a centralized medium access protocol. In contrast to PCF, the central coordinator, denoted as HC, operates during the
CFP and CP. The HC accesses the WM after an idle period of PIFS without performing the backoff procedure. Thus, the provisioning of a CFP becomes obsolete. Instead, the HC may initiate the so called Controlled Access Phase (CAP) at any time. Therefore, the HC transmits a QoS CF-Poll frame to one of its associated QoS STAs. The frame incorporates a TXOPLimit that indicates the receiving STA the maximum TXOP duration allowed for transmission. Furthermore, the QoS CFPoll frame sets the NAV of other STAs for the same duration. Hence, the CAP operates like a flexible CFP. If the QoS STA finishes early, the HC may take over the remaining TXOP duration for its own transmission. Additionally, the HC may reset the NAV of all STAs by sending a CF-End frame.

Since the HC controls the duration of TXOPs obtained by contention via the EDCA parameter set that the collocated QoS AP transmits in its beacon frames, it is able to predict the latest transmission end of any frame exchange sequence in its BSS. Due to the HC having full control over the WM, HCCA enables QoS guarantee. In IEEE 802.11, the latter is denoted as parameterized QoS support. QoS STAs may negotiate with the HC about the set-up of a traffic stream. The QoS STA provides the HC with a Traffic Specification (TSPEC) that describe the traffic stream. Based on the total amount of traffic streams admitted, the HC decides to reject or accept the traffic stream. If it accepts the stream, the HC develops a scheduling plan to poll the QoS STA according to its traffic needs. Performance evaluation of EDCA and HCCA are provided in [24,60].

### 4.5.3.5 Frame transmission failure & recovery procedure

The absence of a response frame indicates an STA that its frame transmission failed. All retransmissions of that MPDU are made with the Retry field set to 1. To prevent infinite retransmissions, each STA incorporates two retry counters. The STA compares the length of the transmitted MPDU against `dot11RTSThreshold`. All failed transmissions of MPDUs of a length less than or equal to this limit and all failed Request To Send (RTS) frames increment the Short Retry Count (SRC) counter. If the SRC reaches `dot11ShortRetryLimit` the STA discards the MPDU. All MSDUs or MAC Management Protocol Data Units (MMPDUs) of a length greater than `dot11RTSThreshold` whose transmission attempts fail increment the Long Retry Count (LRC). Again no more retransmission attempts are made, when LRC is equal to `dot11LongRetryLimit`. Whenever an MPDU is successfully transmitted SRC and LRC are reset.

With EDCA, each AC maintains its own SRC and LRC. The virtual collision described in Section 4.5.3.4.1 does not cause an increase of the
4.5 Medium Access Control (MAC) Layer

Figure 4.12: The circles indicate the CCA range of each STA. STA 2 is capable of communicating with both other STAs, but STA 1 and 3 cannot detect frames of each other. They are mutually hidden.

counters, however. Only a frame loss on the physical WM requires an AC to increase its retry counter.

4.5.3.6 Hidden Station Problem and Request to Send (RTS)/Clear to Send (CTS)

In radio systems based on CS the hidden station problem may occur. This problem arises when a station is able to successfully receive frames from two different stations but the two stations cannot receive frames from each other (see Fig. 4.12).

In this case, an STA may sense the WM as idle even when other hidden STAs are transmitting. This may result in a frame collision at the receiving STA. To reduce the hidden STA problem inherent in CSMA, IEEE 802.11 defines a mechanism that can be optionally used. Before transmitting data frames, an STA has the option to transmit an RTS frame. The addressed STA replies with a Clear To Send (CTS) frame. The RTS contains a duration field that covers the following CTS, data and ACK frame. Indicating the same NAV end, the CTS frame has a slightly shorter duration. Consequently, STAs close to the transmitting STA and hidden STAs close to the receiving STA have their NAV set and do not start any transmissions during the upcoming frame exchange. Thus, the probability of a collision because of hidden STAs reduces. Since the Request To Send/Clear To Send (RTS/CTS) handshake involves some overhead, it is enabled for MSDUs with sizes larger than \( aRTSThreshold \) only.
Table 4.2: IEEE 802.11 MAC enhancements.

<table>
<thead>
<tr>
<th>Description</th>
<th>Amendment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA</td>
<td>Acknowledges several frames with a single reply frame.</td>
</tr>
<tr>
<td>DLS</td>
<td>Allows for direct frame exchange between STAs in an infrastructure BSS.</td>
</tr>
<tr>
<td>AP independent DLS</td>
<td>STAs may establish DLS without an AP involved in the setup procedure.</td>
</tr>
<tr>
<td>Reduced Interframe Space (RIFS)</td>
<td>When no TRX turnaround is needed, RIFS allows for faster transmission of consecutive frames.</td>
</tr>
<tr>
<td>RD exchange sequence</td>
<td>TXOP owner may grant time to the receiver for data transmission in reverse direction</td>
</tr>
<tr>
<td>Frame Aggregation</td>
<td>Groups MSDUs and MPDUs in larger frames.</td>
</tr>
</tbody>
</table>

4.5.4 IEEE 802.11 MAC enhancements

Several amendments of IEEE 802.11 introduce enhancements that improve the performance of the MAC. On the one hand, TXOPs, Block Acknowledgment mechanism (BA), frame aggregation, and the Reverse Direction (RD) frame exchange provide the ability to transmit several MSDUs with each successful contention for the WM. On the other hand, Direct-Link Setup (DLS) helps to avoid an unnecessary indirection via the AP when STAs are in mutual range. Table 4.2 provides an overview.

In Section 4.5.4.1.1 the author highlights the BA and its operation. He compares simulation results of the BA with analytical results in Section 4.7.

4.5.4.1 Acknowledgment policies amended by IEEE 802.11e

IEEE 802.11e introduces the TXOP. During a TXOP a QoS STA may transmit several frames. However, each frame needs to be individually acknowledged. Thus, several TRX turnarounds occur during a TXOP. To reduce the amount of TRX turnarounds, IEEE 802.11e introduces two additional ACK policies:
• No ACK and

• Block ACK.

When the frame exchange initiator selects the No ACK policy, it refrains from receiving ACK frames. This is useful when higher layer protocols generate delay sensitive data that cannot be retransmitted. In contrast, the BA does not affect the reliability of a frame exchange. However, it increases efficiency since a group of MPDUs can be acknowledged with a single frame. Fig. 4.13 compares a TXOP that contains a BA frame exchange with a TXOP that contains a standard frame exchange sequence.

4.5.4.1.1 Block Acknowledgment (BA) policy

A Block Acknowledgment (BlockAck) frame aggregates several ACK frames. It consists of a bitmap of 128 B. This BlockAck bitmap indicates the status of reception of up to 64 MSDUs. Thus, 2 B are used to indicate the successful reception of an MSDU or fragments (MPDU) thereof. BlockAck can be sent immediately or delayed. The latter gives a receiver more time to do computing on the received frames. Hence, it allows for software implementations (e.g. using a hardware driver).

To use the BA the sender transmits an Add Block Acknowledgment (ADDBA) request to the recipient. Afterwards the recipient responds to the request by denying or accepting the usage of the BA. The receiver indicates the buffer size that being used. The number of buffers and the BA policy may be changed at any time.

Having successfully set up a BA the initiator may use the BA limited by the following constraints only:
Chapter 4 – IEEE 802.11

Figure 4.14: BA frames may be split across multiple TXOPs.

- All transmissions are limited by the TXOP duration. A BA frame exchange may not exceed this limit. However, a BlockAck request may be demanded in subsequent TXOPs to the current one.

- The originator may not transmit more frames than the receiver has indicated to be able to buffer.

- A protective mechanism is to guarantee a consistent NAV setting at neighboring STAs. Therefore, the first frame in a BA TXOP is acknowledged individually or an RTS/CTS handshake may precede the BA sequence.

- A BA frame exchange may only start using a bitmap indicating an MSDU boundary.

The originator may split MSDUs across several TXOPs, see Fig. 4.14.

When using the delayed BA, the receiver responds with an ACK frame instead of a BlockAck frame. This indicates to the originator that the receiver has successfully understood the end of the BA transmission. As soon as the BA frames can be acknowledged the receiving STA transmits the BlockAck as its earliest frame with highest priority. In contrast to the delayed BA the immediate BA avoids the need of a separate TXOP for the BlockAck transmission, see Fig. 4.15.

After a recipient receives a Block Acknowledgment Request (BlockAckReq) it shall indicate to the higher layer all received frames of a sequence number less than the number indicated in the request frame. If the buffer is filled up while new MPDUs are arriving the first successfully received MSDU is indicated to the higher layer.

Tearing down an established BA session is accomplished by transmitting a “DELBA” frame. The recipient sends a standard ACK frame to acknowledge the session end.

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4.6 MAC sublayer Management Entity (MLME) services

The MAC sublayer Management Entity (MLME) resides in the management plane. It configures and controls the MAC that resides in the user plane. The MLME provides Service Access Points (SAPs) through which the Station Management Entity (SME) and higher layers call its services. Using Get and Set primitives, the SME and higher layers modify the MAC Management Information Base (MIB) that the MLME contains. One of these services is the synchronization service that is introduced in the following.

4.6.1 Synchronization

The Timing Synchronization Function (TSF) implements a STA’s local timer that it synchronizes to the BSS’s common clock. The TSF contains an unsigned integer of 8 B length that is used as a timer. The TSF timer represent the time measured in µs. To synchronize the TSF timer, STAs use a management frame, called beacon. As beacons are transmitted periodically, every STA knows when the next beacon frame will arrive; this time is called Target Beacon Transmission Time (TBTT). It is announced in every beacon frame. The beacon interval denotes the time between two consecutive beacon frames.

Figure 4.15: Message Sequence Chart on the frame exchange procedure using BA. The reception of MSDUs may be interrupted at any time. Thus, only after having received a BlockACK Request in the same or in a subsequent TXOP the receiver replies by a BlockAck frame.
Figure 4.16: STAs 2 and 3 change their TSF timers to the value received in the beacon of the AP. In case of an IBSS only STA 3 would adapt its TSF timer, because it is the only one with a TSF timer earlier than in the beacon frame.

In an infrastructure BSS solely the AP generates beacon frames. To synchronize with the AP’s clock, its associated STAs set their local TSF timer to the value of the TSF timer contained in the beacon frame. In an IBSS, STAs adjust their local TSF timer to the fastest clock. Therefore, a STA copies the TSF timer of a beacon frame of its IBSS only when its local TSF timer contains an earlier value. Fig. 4.16 presents an example.

### 4.6.2 Beacon transmission

Beacon frame transmission works differently in an IBSS and an infrastructure BSS. In the latter case, the central AP transmits a beacon frame at every TBTT. A QoS AP uses Access Category Voice (AC_VO) for beacon frame transmission, other AP use standard DCF settings.

In an IBSS all STAs take part in the beacon frame generation. At TBTT each STA draws a random counter $n$ of the interval $[0 \ldots 2 \cdot CW\text{min}]$. It then waits $n \cdot a\text{SlotTime}$. If it received no beacon during this time, it broadcasts a beacon. Otherwise it cancels the beacon transmission and continues to operate normally.
Among the timing information needed to synchronize the BSS, the beacon delivers protocol related parameters, regarding

- the BSSID,
- the beacon interval,
- supported MCSs,
- PHY depending parameters,
- announcements to STAs in Power Save (PS) mode,
- the CFP,
- regulatory, and other elements.
4.7 Survey of the IEEE 802.11e Block
Acknowledgment mechanism

Studies [25–27, 61–63, 321] have independently shown that the efficiency of IEEE 802.11 depends on the MCS in use. With IEEE 802.11a [280], IEEE 802.11b [282], IEEE 802.11g [283], and IEEE 802.11n [278] several MCSs are available in IEEE 802.11. Within the same IEEE 802.11 PHY, the same signaling overhead remains static for each MCS. Hence the efficiency of IEEE 802.11 reduces with fast MCSs. Therefore IEEE 802.11e introduces a new ACK scheme to reduce the overhead. In the following, the author presents his findings [64, 326].

4.7.1 Analysis

A closed form solution for the theoretical limit of the maximum throughput with BA is given in the following. This limit allows to verify the simulation results. An IEEE 802.11 STA maximizes throughput if a single STA continuously transmits MSDUs and no other STA attempts to initiate frame exchanges, concurrently. Then, no collisions occur. Furthermore the WM is assumed to be error-free and frames are never retransmitted therefore.

4.7.1.1 Maximum achievable throughput without BA

When using IEEE 802.11e EDCA every transmission starts with a backoff. The mean duration for the backoff depends on the AC. The AC determines the fixed waiting time AIFS. The minimum size of the CW also depends on the AC. Assuming an error free transmission the CW is never increased. Thus the number of slots is drawn from the interval [0, CWmin]. As the random number of slots is drawn from a uniform distribution its mean value is $\frac{CW_{\text{min}}}{2}$

$$\text{Duration(Backoff)} = AIFS + \frac{CW_{\text{min}}}{2} \cdot a\text{SlotTime} \quad (4.2)$$

In the simulations the author considers the IEEE 802.11a PHY. Table 4.3 gives an overview of some important PHY characteristics. The number of bytes to be transmitted is calculated as

42
\[ MAC-PDU = MAC-SDU + MAC-Overhead \]
\[ = MAC-SDU + 34\text{ B} \]

\[ PHY-SDU = MAC-PDU \] \hspace{1cm} (4.3)

\[ PHY-PDU = PHY-SDU + \text{Service-Bits} + \text{Tail-Bits} \]
\[ = PHY-SDU + 2\text{ B} + 6\text{ b}. \]

Table 4.3: Parameters for the IEEE 802.11a OFDM PHY

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{DPBS}</td>
<td>Data bits per OFDM symbol</td>
<td>depends on MCS</td>
</tr>
<tr>
<td>MAC-Overhead</td>
<td>Needed for addressing, NAV etc.</td>
<td>34 B</td>
</tr>
<tr>
<td>Tail-Bits</td>
<td>Needed for the OFDM convolutional encoder</td>
<td>6 b</td>
</tr>
<tr>
<td>Service-Bits</td>
<td>Reserved for future use</td>
<td>2 B</td>
</tr>
<tr>
<td>T-SYM</td>
<td>OFDM Symbol interval</td>
<td>4 ( \mu \text{s} )</td>
</tr>
<tr>
<td>T-PLCP-Preamble</td>
<td>PLCP preamble duration</td>
<td>Sum of T-Short and T-Long</td>
</tr>
<tr>
<td>T-Short</td>
<td>Short training sequence (10 symbols)</td>
<td>8 ( \mu \text{s} )</td>
</tr>
<tr>
<td>T-Long</td>
<td>Long training sequence (2 symbols)</td>
<td>8 ( \mu \text{s} )</td>
</tr>
<tr>
<td>T-SIGNAL</td>
<td>Contains information on the transmission rate and the length of the TxVector</td>
<td>4 ( \mu \text{s} )</td>
</tr>
</tbody>
</table>

The \textit{MAC-Overhead} cannot be easily determined. Depending on the transmission direction (to a STA in the same BSS or in the ESS, to or from an AP et cetera) the number of address fields varies. Additionally legacy MPDUs will have another length than QoS 802.11e MPDUs. A \textit{MAC-Overhead} of 34 B occurs with four address fields and without encryption.

Thus the number of OFDM symbols to be transmitted is given by

\[ N(\text{OFDM}) = \lceil (PHY-PDU \cdot \frac{8\text{ b}}{1\text{ B}}) / N_{DBPS} \rceil \] \hspace{1cm} (4.4)
Therefore, the transmission duration including the PHY Preamble, PLCP header, and Training Sequence is given by

\[
\text{Duration} = N(OFDM) \cdot (T-SYM + T-SIGNAL) + T-\text{PLCP-Preamble}
\]
\[
= N(OFDM) \cdot 4\,\mu s + 4\,\mu s + T-\text{PLCP-Preamble}
\]
\[
= N(OFDM) \cdot 4\,\mu s + (T-\text{Short} + T-\text{Long})
\]
\[
= N(OFDM) \cdot 4\,\mu s + 20\,\mu s.
\]

(4.5)

This leads to the duration of any control, data or management frame. The number of MSDUs transmitted in a row must not be larger than the buffer size indicated by the receiver, therefore \( N_{MT} < BA_{\text{Buffersize}} \). Also, IEEE 802.11e the value TXOPLimit restricts the duration for which a QoS Station (QSTA) may use the WM. Other restrictions regarding the number of MSDUs are not made, however. Thus a QSTA may transmit a number of \( N_{MT} \) MSDUs per TXOP. Therefore, the duration during which the WM is busy is given by Eq. 4.6.

\[
\text{Dur.(Trans.)} = \sum_{i=1}^{N_{MT}} \text{Dur.}(N(OFDM(\text{PHY-PDU}_i + \text{ACK})))
\]

(4.6)

If RTS/CTS is used, Eq. 4.7, its duration must be added to the WM busy time

\[
\text{Dur.(Prot. Frames)} = \begin{cases} 
0 & \text{without RTS/CTS} \\
\text{Dur.}(N(OFDM(\text{RTS} + \text{CTS}))) & \text{with RTS/CTS}
\end{cases}
\]

(4.7)

The duration of all IFSs needed to transmit \( N_{MT} \) MSDUs is given in Eq. 4.8. It also depends on the usage of RTS/CTS.

\[
\text{Dur.(IFS)} = \begin{cases} 
(2 \cdot N_{MT} - 1) \cdot \text{SIFS} & \text{without RTS/CTS} \\
(2 \cdot N_{MT} + 1) \cdot \text{SIFS} & \text{with RTS/CTS}
\end{cases}
\]

(4.8)

Hence, the total throughput given in \( \text{b/s} \) is
Throughput = MAC-SDU ·

\[ \text{Duration}(\text{Backoff}, \text{Protective Frames}, \text{Transmission}, IFS)^{-1} \cdot \frac{8}{1} \text{b/s} \quad (4.9) \]

### 4.7.1.2 Maximum achievable throughput with BA

Similar to Eq. 4.7.1.1 the maximum throughput for a given set of backoff values and TXOPLimit can be calculated when using BA. Owing to the QoS control field, 2 B must be added to the MAC-Overhead in Eq. 4.5. Assuming that immediate BA is used Eq. 4.6 becomes

\[ \text{Dur.}(\text{Trans.}) = \text{Dur.}(N(\text{OFDM(BlockACK, BlockACKReq)})) + \sum_{i=1}^{N_{MT}} \text{Dur.}(N(\text{OFDM(PHY-PDU}_i))) \quad (4.10) \]

According to IEEE 802.11e a protective mechanism like RTS/CTS is used to avoid collisions during the frame burst. Therefore, Eq. 4.7 changes to Eq. 4.11 and must be added to Eq. 4.10. If no protective mechanism is used the first MPDU to be transmitted in each burst shall be acknowledged individually to allow the set up of a NAV protection for consecutive frames. Hence, Eq. 4.7 changes to

\[ \text{Dur.}(\text{Prot. Frames}) = \begin{cases} 
\text{Dur.}(N(\text{OFDM(ACK)})) & \text{without RTS/CTS} \\
\text{Dur.}(N(\text{OFDM(RTS,CTS)})) & \text{with RTS/CTS} 
\end{cases} \quad (4.11) \]

With the usage of RTS/CTS the number of IFSs needed for BA increases by one in contrast to the number of IFSs without. Therefore the duration of IFSs needed to transmit \( N_{MT} \) MSDUs is given as

\[ \text{Duration}(\text{IFS}) = \begin{cases} 
(N_{MT} + 2) \cdot \text{SIFS} & \text{without RTS/CTS} \\
(N_{MT} + 3) \cdot \text{SIFS} & \text{with RTS/CTS} 
\end{cases} \quad (4.12) \]

The total medium busy time is calculated as the sum of Eq. 4.10, Eq. 4.11 and Eq. 4.12. Hence the maximum throughput in \text{b/s} is calculated as


\[
\text{Throughput} = \text{MAC-SDU} \cdot \frac{\text{Duration(Backoff, ProtectiveFrames, Transmission, IFS)}}{8b} \cdot \frac{8b}{1B}.
\]

(4.13)

### 4.7.1.3 Analytical Comparison of BA and Standard ACK Procedure

Comparing Eq. 4.8 and Eq. 4.12 the advantages of BA are obvious. First, BA reduces the number of SIFSs in a burst of data transmission by approximately 50%. Second, in Eq. 4.10 the number of ACK frames does not depend on the number of transmitted MPDUs. Thus the impact of the additional overhead of frames like BlockACK and BlockACKReq becomes negligible.

### 4.7.2 Simulation based analysis

To validate the implementation of IEEE 802.11 in the WARP2 simulation environment a scenario is used that consists of a sending and a receiving STA and compares the measured throughput with the results calculated by Eq. 4.13. Since the STAs are placed very close to each other almost no frame loss occurs. At the time the simulations were performed [284] was the latest draft of IEEE 802.11e. It did not require any protective mechanism for BA. Thus, the simulations study a protocol slightly different from the final standard [276, 279].

The TXOPLimit used in this scenario is bounded to 64 TXOP slots. Each slot has 32\,\mu s duration resulting in an overall TXOPLimit of 2048\,\mu s. The simulations are performed using three different PHY modes (64-Quadature Amplitude Modulation (QAM)\(^{3/4}\), 16-QAM\(^{1/2}\) and Binary Phase Shift Keying (BPSK)\(^{3/4}\)), four packet sizes (1500 B, 1024 B, 512 B, and 48 B) and three different BA buffer sizes (64, 32, and 8) for the transmit and receive buffers. For comparison a simulation with standard ACK policy (no BA) is included. It is assumed that Data and Control frames are transmitted with the same MCS.

In Fig. 4.18, 4.19, and 4.20 the solid lines indicate the analytical result calculated by Eq. 4.13 while marks show the simulation results. The simulation results clearly correspond to the results of the author’s analytical model of IEEE 802.11e. Accordingly, the correct implementation of the simulation tool WARP2 can be considered validated per this case. Especially, short frames benefit from the usage of BA with all MCSs. Large 1500 B
frames benefit mainly with fast MCSs since in IEEE 802.11 the overhead for large frames is less compared to short frames. Considering the impacts of BA on the delay (see Fig. 4.21 to 4.23) and implementation issues a buffer size of 32 seems to be an optimum, a buffer size of 64 offers only minor advantages but almost doubles the mean delay.
Figure 4.19: Throughput versus offered traffic with 16-QAM\(^{1/2}\) MCS and various BA buffer sizes.
4.7 Survey of the IEEE 802.11e Block Acknowledgment mechanism

Figure 4.20: Throughput versus offered traffic with BPSK³/₄ MCS and various BA buffer sizes.

(a) MSDU size is 1500 B.

(b) MSDU size is 1024 B.

(c) MSDU size is 512 B.

(d) MSDU size is 48 B.
Figure 4.21: CCDF of the MSDU end to end delay with 64-QAM $3/4$ MCS and various BA buffer sizes.

(a) MSDU size is 1500 B.
(b) MSDU size is 1024 B.
(c) MSDU size is 512 B.
(d) MSDU size is 48 B.
4.7 Survey of the IEEE 802.11e Block Acknowledgment mechanism

Figure 4.22: CCDF of the MSDU end to end delay with 16-QAM\(^{1/2}\) MCS and various BA buffer sizes.
Figure 4.23: CCDF of the MSDU end to end delay with BPSK$^{3/4}$ MCS and various BA buffer sizes.

(a) MSDU size is 1500 B.

(b) MSDU size is 1024 B.

(c) MSDU size is 512 B.

(d) MSDU size is 48 B.
Decisions of the United States (US) Federal Communication Commission (FCC) paved the way for a new regulatory regime where already assigned spectrum may be reused by new technologies. Long before the introduction of TV white spaces (TVWS) technology, Ultrawideband (UWB) was seen as a promising candidate for the envisaged spectra. The WiMedia Alliance (WiMedia) developed a UWB proposal to IEEE 802.15 that incorporates the medium access protocol Distributed Reservation Protocol (DRP) developed by the author and a reservation propagation mechanism also proposed by the author. In this chapter the author outlines the activities of IEEE 802.15 related to UWB and US FCC’s ruling.

5.1 Introduction

The IEEE 802.15 Working Group (WG) develops standards for Wireless Personal Area Networks (WPANs). Its standards target portable and mobile computing devices as well as wireless sensors. Examples are IEEE 802.15.1 [266] that is known as Bluetooth (BT), and IEEE 802.15.4 [285] that is marketed as ZigBee. In Section 5.2.1 the author presents the IEEE 802.15.3a amendment that targeted at an UWB Physical Layer (PHY) for IEEE 802.15.3 [268]. Section 5.3 briefly outlines the recommended practice for mesh networking IEEE 802.15.5 [270].
5.2 IEEE 802.15.3

IEEE 802.15.3 defines a High Rate (HR) WPAN Medium Access Control (MAC) protocol and PHY. It aims at high speed WPANs providing connectivity to Personal Computers (PCs) and Personal Digital Assistants (PDAs), synchronization mechanisms for digital cameras, music players, and other Consumer Electronic (CE) devices. Its single carrier based PHY provides Modulation and Coding Schemes (MCSs) capable of supporting 11, 22, 33, 44, and 55 Mb/s data rates. The IEEE 802.15.3 MAC relies on central control. A single logical device, called Piconet Controller (PNC), coordinates access to the Wireless Medium (WM). Details about the IEEE 802.15.3 operation can be found in [8].

5.2.1 IEEE 802.15.3a

IEEE 802.15.3a developed a high rate alternative PHY for IEEE 802.15.3. Section 5.2.1.1 outlines the decision of the US FCC that builds the foundation for the new radio technology. Section 5.2.1.2 explains the history of the IEEE 802.15.3a Task Group (TG).

5.2.1.1 FCC decision 02-48

In February 2002, the US FCC announced a new spectrum ruling [315] for the UWB radio technology. In its revision [316–318] of the rules regarding UWB, the FCC defines a UWB device as any radio implementation that occupies more than 20% of the center frequency or a minimum of 500 MHz of the 3.1 GHz to 10.6 GHz radio spectrum. To avoid interference to incumbent users, the FCC limits the maximum spectral transmission power density to -41.3 dBm/MHz for in- and outdoor use.

Five years after the US FCC’s decision on UWB technology, the Commission of the European Union (EU) issued a decision [319] that grants similar operation procedures in Europe. From 2011 on, however, UWB devices need to comply with new spectrum policies that include advanced interference mitigation procedures. Fig. 5.1 provides an overview of the current regulations.

5.2.1.2 WPAN High Rate Alternative PHY Task Group

Soon after the FCC’s decision to allow UWB technology to reuse a large portion of already licensed spectrum, several companies initiated the formation of a new Study Group (SG) within the IEEE 802.15 WG. This SG
developed the Project Authorization Request (PAR) and Five Criteria (5C) documents [145, 146] that form the baseline of the IEEE 802.15.3a TG. The PAR seeks for a new PHY technology that achieves at least 100 Mb/s at a distance of 10 m and 200 Mb/s at a distance of 4 m. Owing to the intended usage in CE, the Call for Proposals (CFP) mentions low complexity designs and low power consumption as additional goals for proposals. Yet before its approval at the IEEE New Standards Committee (NesCom) in December 2002, the new TG IEEE 802.15.3a issued a CFP in November. In its CFP the TG asked for the submission of proposals until March 2003. This CFP resulted in 24 proposal submissions out of which 23 considered UWB.

At the end of the downselection process, two competing proposals were left. While the Multiband OFDM Alliance (MBOA) proposed an Orthogonal Frequency Division Multiplexing (OFDM) based solution, the UWB Forum favored a Direct Sequence (DS) spread spectrum (impulse radio) solution. Due to an equal amount of IEEE 802.15 voting members in both alliances, no proposal received the required majority of 75% to become the baseline standard. Accordingly, the IEEE 802.15.3a TG requested to be disbanded in January 2006 [147]. Unlike the UWB Forum that dissolved in 2007, the MBOA continued to develop its UWB standard. The author presents the outcome of MBOA’s efforts in Chapter 7.

5.3 IEEE 802.15.5

IEEE 802.15.5 describes mesh topology capability in WPANs. As a recommended practice it is the least normative kind of IEEE Standards As-
IEEE 802.15.5 considers low (IEEE 802.15.4) and high rate (IEEE 802.15.3) applications. The author’s contributions [148–155] led to a joint proposal [156] and an initial draft. Because of the dissolution of IEEE 802.15.3a, the Department of Communication Networks, RWTH Aachen University (ComNets) and Philips re-evaluated their joint research efforts in the IEEE 802.15 WG. As a consequence, attendance of IEEE 802.15.5 meetings was reduced. Unfortunately, this led to the removal of our MAC related concepts in later revisions of the draft and the final document [270].
The author developed the Distributed Reservation Protocol (DRP) [112–115] as a means to reduce contention among IEEE 802.11 Stations (STAs). The DRP prevents frame collisions and increases the medium access efficiency. While initially being used in single hop wireless networks, later work extends DRP to support multi-hop networks. In this chapter the author outlines the basic principles of DRP.

6.1 Introduction

Standard IEEE 802.11 defines contention based (Distributed Coordination Function (DCF) and Enhanced Distributed Channel Access (EDCA)) and contention free medium access protocols (Point Coordination Function (PCF) and HCF Controlled Channel Access (HCCA)). The latter rely on centralized scheduling. However, existing products implement the contention based medium access protocols only that suffer from frame collisions. Depending on the frame length and the Modulation and Coding Scheme (MCS) it was transmitted at, the Wireless Medium (WM) may be occupied for a long time by a collided frame. To avoid frame collisions, the author has developed the DRP.

6.2 Basic principle

With DRP, STAs operating in Independent Basic Service Set (IBSS) mode exchange information about planned transmissions. Fig. 6.1 provides
Figure 6.1: With DRP STAs exchange reservation information contained in Data and ACK frames.

an example. STA A announce a reservation to STA B. STA B confirms the reservation in its Acknowledgment (ACK) frame. STAs C and D overhear the frame exchange and thus refrain from medium access during the reserved time period.

In case the receiving STA cannot accept the requested reservation, it may propose a different future time period in its ACK frame. The reservation initiating STA may propose this time period with its next reservation setup attempt.

Fig. 6.2 presents an overview on the frame structure. DRP frames are defined as a new subtype of DATA frames. The reservation information is contained in the Frame Body. DRP includes a field that prioritizes overlapping or competing reservation requests. Higher priority DRP requests defer lower DRP sessions. A DRP request that has the same priority than an existing DRP schedule defers to the previously existing.

The Next DRP field indicates the duration until the next scheduled transmission measured from the end of the currently transmitted frame. The DRP Duration field signals the duration that the WM should be reserved then. Because of interference, DRP STAs may not be able to overhear all DRP information of their neighbors. Since the Periodicity field indicates a sequence of reservations, a DRP STA refrains from channel access even if it did not receive the most recent reservation request but only one of
Reservation information contained in beacon frames

Legacy IEEE 802.11 STAs without DRP capability cannot read the reservation information, however. If legacy STAs are present, a DRP reservation may be delayed because of a legacy STA accessing the WM shortly before the reserved time period starts, see Fig. 6.3. To increase robustness from concurrently transmitting legacy STAs, the author proposes to transmit the reservation information in beacon frames.

6.3 Reservation information contained in beacon frames

Standard IEEE 802.11 specifies the PCF that relies on the Contention Free Period (CFP). Regardless of the Basic Service Set (BSS) that a CFP is announced for, a STA presets its Network Allocation Vector (NAV) to any CFP that it learns of, see Fig. 6.4. Thus, STAs refrain from access to the WM even when a beacon frame of an overlapping BSS contains a CFP announcement.

Therefore, to carry reservation information the author proposes to use beacon frames that include a CFP IE. The reservation initiator transmits the intended reservation in a Data frame. The receiving STA replies with a Beacon frame that announces a CFP at the proposed time instant. The initiator also replies with another beacon frame to inform STAs in its neighborhood.

Fig. 6.5 presents the IEs that DRP adds to the beacon frame. The Basic Service Set Identification (BSSID) field helps to pretend as an overlapping BSS that uses CFP. The CF Parameter Set indicates the duration of the

Figure 6.2: The new frame structure includes the necessary reservation request elements inside the frame body. A new subtype indicates the reservation request.
Chapter 6 – Distributed Reservation Protocol

STA C’s transmission collides with reservation

STA C & D are legacy 802.11 STAs.

STA A & B are DRP capable. STA A’s reservation with STA B is delayed by STA C’s transmission.

Figure 6.3: STAs without DRP capability may delay reservations.

Legacy STAs C & D form a BSS. They cannot read DRP reservation information.

The BSS of STA A & B overlaps with STA C & D’s BSS.

Figure 6.4: Beacon frames contain the CFP IE. Legacy STAs preset their NAV to remain silent during any CFP they learn of.
next reservation and silences neighboring STAs. The DRP Beacon, the DRP Destination Medium Access Control (MAC) address and the Traffic Category (TC) field indicate the acceptance of a reservation or an alternative reservation, the intended receiver and the priority of the reservation.

DRP was never proposed to the IEEE 802.11 Working Group (WG). However, it became the basic principle for the WiMedia Alliance (WiMedia) Wireless Personal Area Network (WPAN) protocol that applies Ultrawideband (UWB) transmission.

To reduce the signaling overhead, the DRP specification in standard ISO/IEC 26907 introduces medium access slots used for reservations that have fixed duration. Furthermore, beacon frames are grouped to be transmitted at the beginning of a so called superframe according to proposal of the author as described in Chapter 7.
7.1 Introduction

The industry consortium WiMedia was founded in September 2002 [348]. Initially, WiMedia targeted a radio agnostic convergence layer that allows for the wireless implementation of several wired technologies such as Universal Serial Bus (USB) [286,349], IEEE 1394 [287–292] or Digital Living Network Alliance (DLNA). Due to its radio technology independent approach,
WiMedia had member companies of the UWB Forum and the Multiband OFDM Alliance (MBOA). The industry alliances’ competition for the IEEE 802.15.3a standard (see Section 5.2.1) continued within WiMedia. Soon after the last member of the competing UWB Forum left WiMedia, however, the latter announced its support for the MBOA MAC and Physical Layer (PHY) specification. Finally in March 2005, MBOA and WiMedia merged. Owing to its superior public perception the partners and their common radio platform are known as WiMedia since then. Fig. 7.1 presents the timeline.

Section 7.2 briefly discusses MBOA. Section 7.3 introduces Ecma International — European association for standardizing information and communication systems (ECMA) and its standard ECMA-368 [293]. The adoption of standard ECMA-368 in December 2005 enabled WiMedia to forward its radio specification to ISO/IEC on a fast track. Section 7.4 describes the standard ISO/IEC 26907 that was adopted in March 2007. Section 7.6 contains simulation results for the ISO/IEC 26907 MAC protocol.
7.2 Multiband OFDM Alliance

The MBOA was formed in June 2003. Its initial goal was the development of a proposal to IEEE 802.15.3a (Section 5.2.1). In contrast to the impulse radio technology favored by the UWB Forum, the MBOA protocol relies on Orthogonal Frequency Division Multiplexing (OFDM) at the PHY. Soon the MBOA realized that the MAC layer defined in IEEE 802.15.3 [8] and amended in IEEE 802.15.3b [294] is not well suited for ad hoc, short range communication that the group aims to support. Accordingly, MBOA called for proposals for a MAC specification. Together with ComNets’s research partner Philips Research the author invented and developed a distributed MAC protocol that replaces the centralized IEEE 802.15.3 protocol. During the following downselection process, Philips decided to base major parts of the MBOA MAC protocol on the author’s inventions [112–115].

7.2.1 Regulatory decision on MB-OFDM

Although the Federal Communication Commission (FCC) Ultrawideband (UWB) spectrum regulation is technologically neutral, the compliance of the MBOA PHY specification with the FCC rules [316–318] was questioned. In March 2005, however, the FCC explicitly approved the MBOA waiver request to grant spectrum access for its Multiband OFDM (MB-OFDM) technology.

7.2.2 Wireless USB

The Wireless USB Promoter Group was first to select the MBOA MAC and PHY specification as the basis of its Wireless USB (WUSB) solution. Since February 2004, the Certified Wireless USB program [295–298] bases on the MBOA technology.

7.3 ECMA-368

ECMA standardizes Consumer Electronic (CE) and communications technology. As a non-profit industry association ECMA may propose its standards for fast track adoption at ISO/IEC. WiMedia’s MAC and PHY specification and the according MAC/PHY interface specification were adopted as ECMA-368 [293] and ECMA-369 [299] in December 2005. In the following section the author describes standards ISO/IEC 26907 and 26908 that were accepted in March 2007.
7.4 ISO/IEC 26907

Standard ISO/IEC 26907 describes a MAC and PHY for ultrawideband communication. In Section 7.4.1 its overall system concept is described. Following, the PHY design is outlined in Section 7.4.2. Next the MAC design is explained in Section 7.4.3. In Section 7.6 a simulation based analysis of the ISO/IEC 26907 standard is provided.

7.4.1 System concept

Standard ISO/IEC 26907 defines the lowest two layers of the ISO/Open System Interconnection (OSI) reference model. The interface between the MAC and PHY is described in standard ISO/IEC 26908. In ISO/IEC 26907, higher layers are denoted as MAC clients. The MAC receives MAC Service Data Units (MSDUs) at the MAC Service Access Point (SAP). Access to external networks rely on the Protocol Adaptation Layer (PAL) that is not specified within ISO/IEC 26907 but in WiMedia. The PAL enables WUSB, next generation Bluetooth [28, 66, 67] or other protocols to operate on top of ISO/IEC 26907. In [300], WiMedia specifies the WiMedia Logical Link Control Protocol that integrates ISO/IEC 26907 with Internet Protocol (IP) based networks, see Fig. 7.2.

To provide support for Quality of Service (QoS) ISO/IEC 26907 combines the efficiency of Time Division Multiple Access (TDMA) based systems with packet based technology. The standard divides time into superframes, which comprise 256 Medium Access Slots (MASs) of 256 $\mu$s each. At the beginning of a superframe the so called Beacon Period (BP) implements a period used for organizing medium access in the subsequent data period, see Fig. 7.3. Section 7.4.3.1 outlines the BP and its structure.

7.4.1.1 Addressing — Device ID

To reduce overhead, ISO/IEC 26907 transforms the standard IEEE 802 MAC addresses of 6 B length into a shorter Device Identifier (DevId) of 2 B length. A "Generated DevId" is a randomly chosen address. However, a device may not use a DevId, which is already in use. Any device that detects a DevId conflict announces the conflict shall regenerate its DevId.

7.4.2 Physical Layer

The ISO/IEC 26907 PHY achieves data rates of up to 480 $\text{Mb}/\text{s}$. In between 3168 MHz and 10560 MHz six band groups are defined, see Fig. 5.1. Support
7.4 ISO/IEC 26907

Figure 7.2: Mapping between WiMedia system concept, standard ISO/IEC 26907 and the IEEE 802 protocol stack.

Figure 7.3: The ISO/IEC 26907 divides the superframe into 256 MASs. Each superframe begins with a BP followed by the Data Period.
Table 7.1: ISO/IEC 26907 OFDM PHY parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of data subcarriers</td>
<td>100</td>
</tr>
<tr>
<td>Number of pilot subcarriers</td>
<td>12</td>
</tr>
<tr>
<td>Number of guard subcarriers</td>
<td>10</td>
</tr>
<tr>
<td>Number of total subcarriers</td>
<td>122</td>
</tr>
<tr>
<td>Subcarrier frequency spacing</td>
<td>4.125 MHz</td>
</tr>
<tr>
<td>Symbol interval duration</td>
<td>312.5 ns</td>
</tr>
</tbody>
</table>

of band group 1 is mandatory for all devices. Support for all other band groups remains optional. Except for the highest band group, all band groups consist of three frequency bands. One frequency band in ISO/IEC 26907 occupies 528 MHz and is divided into 128 OFDM subcarriers. 122 out of the 128 OFDM subcarriers are used for data pilot and guard subcarriers as shown in Table 7.1.

Up to seven Time-Frequency Codes (TFCs) in conjunction with five frequency band groups provide a total of thirty logical channels in the UWB frequency band. Each TFC provides a hopping sequence that is applied to a band group. According to the TFC pattern, devices either hop through the frequency bands in their band group, referred to as Time Frequency Interleaving (TFI), or keep transmitting in a single band, namely Fixed Frequency Interleaving (FFI). Hopping is done per OFDM symbol. Each symbol lasts 312.5 ns.

Convolution coding with a basic rate of 1/3 and the constraint length of 7 is used for Forward Error Correction (FEC). Further coding rates of 1/2, 5/8 and 3/4 are achieved through bit puncturing. Robustness is increased owing to bit interleaving. In the ISO/IEC 26907 PHY, each symbol interleaving block corresponds to six consecutive OFDM symbols. Table 7.2 gives the information on the data rate, modulation and coding rate of the ISO/IEC 26907 MCSs.

### 7.4.3 Medium Access Control Layer

ISO/IEC 26907 introduces the Prioritized Contention Access (PCA) and the DRP. PCA is a variant of Enhanced Distributed Channel Access (EDCA) that the author explains in Section 4.5.3.4.1. Section 7.4.3.2.2 outlines the contention free access to the Wireless Medium (WM) that DRP provides.
Table 7.2: ISO/IEC 26907 MCSs.

<table>
<thead>
<tr>
<th>Data rate (Mb/s)</th>
<th>Modulation</th>
<th>Coding rate</th>
<th>Coded bits per 6 OFDM symbols (NCBP6S)</th>
<th>Info bits per 6 OFDM symbols (NIBP6S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.3</td>
<td>1/3</td>
<td>300</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>1/2</td>
<td>300</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>106.7</td>
<td>1/3</td>
<td>600</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>1/2</td>
<td>600</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>5/8</td>
<td>600</td>
<td>375</td>
<td></td>
</tr>
<tr>
<td>320</td>
<td>1/2</td>
<td>1200</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>5/8</td>
<td>1200</td>
<td>750</td>
<td></td>
</tr>
<tr>
<td>480</td>
<td>3/4</td>
<td>1200</td>
<td>900</td>
<td></td>
</tr>
</tbody>
</table>

7.4.3.1 Beacon Period and Beacon frames

Each superframe starts with a BP, see Fig. 7.3. ISO/IEC 26907 organizes this BP according to the author’s invention [112]. The maximum length of the BP is defined as \( m_{\text{MaxBPLength}} \) which is a multiple of MASs. In the BP, each MAS consists of three beacon slots. Devices use the beacon slots to sequentially transmit beacon frames at the lowest MCS. Each beacon frame must not exceed a length of \( m_{\text{MaxBeaconLength}} \) which is equal to \( m_{\text{BeaconSlotLength}} - \text{Short Interframe Space (SIFS)} - m_{\text{GuardTime}} \). \( m_{\text{BeaconSlotLength}} \) is one third of a MAS, i.e. 85 \( \mu \)s. The \( m_{\text{GuardTime}} \) is 12 \( \mu \)s. Hence, a beacon frame lasts at most 63 \( \mu \)s.

With every received beacon frame a device learns about its direct neighborhood. In a beacon frame, a device broadcasts its knowledge about the beacon slot occupancy. A device’s BP occupancy list broadcasts to other devices which beacon slots are occupied by which \( \text{DevId} \). Thus, a neighboring device also learns about its neighbor’s neighborhood. Therefore, if during the last three superframes a device does not receive a beacon frame in a beacon slot and it does not learn via neighbor beacon frames that the slot is occupied it treats the slot as empty.

Furthermore, devices learn about DevId conflicts via the BP occupancy list of neighboring devices. A device considers its DevId to be in conflict with another device, if a neighboring device announces this DevId for a beacon slot that the device did not transmit a beacon in.
Once a device is powered up it scans for an empty beacon slot during at least one superframe. Then it may announce its presence in a randomly chosen beacon slot in between the highest-numbered beacon slot and the end of the BP. If all beacon slots are occupied, a device proceeds to send during the Signal BP and prolongs the BP by adding its beacon frame to the succeeding MAS of the BP of the next superframe. The Singal BP consists of $m_{SignalSlotCount}$ beacon slots at the beginning of each BP and is used by devices that join the network. Fig. 7.4 presents a scenario where device 38 intends to join the network.

Device 38 transmits outside the reception range of device 12 but inside the reception ranges of devices 2, 5, 9, 14, and 79. The latter devices inform device 12 about the new device 38 and the beacon slot that it occupies. Fig. 7.5 presents the BP occupancy when device 38 joins the network. [29, 68, 327] evaluate the beacon frame collision probability that is inherent due to the random selection of a beacon slot.

To detect beacon frame collisions, a device aperiodically skips its beacon frame transmission. Additionally, a device may detect a beacon frame collision if neighboring devices report an empty beacon slot or a different DevId for the beacon slot that it uses. Establishing a single, joint BP with overlapping WPANs is important for energy conservation, since the BP is the only period throughout which a device must stay awake and be able to receive. Thus, battery powered devices may stay in sleep mode during the data period and solely need to power up during the BP and DRP based data MASs they are involved in.
7.4.3.2 Data Period

The duration of the BP determines the amount MASs left for the Data Period. During the Data Period, devices access the WM using PCA or DRP. With both Coordination Functions (CFs) an ISO/IEC 26907 device transmits frames of arbitrary length of up to 4095 B.

7.4.3.2.1 Prioritized Contention Access (PCA) PCA is a variant of the IEEE 802.11 EDCA that is explained in Section 4.5.3.4.1. Table 7.3 presents the medium access values for PCA that are slightly different.
Table 7.3: PCA medium access parameters.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Access Category (AC)</th>
<th>CWmin</th>
<th>CWmax</th>
<th>Transmission Opportunity (TXOP) Limit</th>
<th>Arbitration IFS Number (AIFSN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Access Category Background (AC_BK)</td>
<td>15</td>
<td>1023</td>
<td>1 frame</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Access Category Best Effort (AC_BE)</td>
<td>15</td>
<td>1023</td>
<td>1 frame</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Access Category Video (AC_VI)</td>
<td>7</td>
<td>511</td>
<td>1024 µs</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Access Category Voice (AC_VO)</td>
<td>3</td>
<td>255</td>
<td>256 µs</td>
<td>1</td>
</tr>
</tbody>
</table>

from the ones in Table 4.1. Owing to the ISO/IEC 26907 PHY, a SlotTime equals 9 µs.

Unlike IEEE 802.11 EDCA, the duration of a TXOP gained under PCA is restricted by reservations established by the DRP. When accessing the WM through PCA, a device respects all existing reservations. Fig. 7.6 presents a corresponding example where a TXOP gained under PCA must be shorten due to a DRP reservation following.

### 7.4.3.2.2 Distributed Reservation Protocol (DRP)

DRP implements a distributed reservation protocol. The reservation protocol bases on the author’s invention presented in [113]. This invention extends the basic ideas for collision free access to the WM described in [65,69,114–116]. While the Request To Send/Clear To Send (RTS/CTS) handshake presented
Figure 7.6: Unlike IEEE 802.11e, a TXOP must be shorten when it conflicts with a reserved period.

Figure 7.7: Example BP and Data Period. Having joined the network, device 38 announces the DRP reservation of MASs $n$ to $n+2$ in its beacon frame.

in Section 4.5.3.6 provides means for an immediate reservation of the WM, DRP enables reservation of the WM in the future (the next superframe). Thus, devices can coordinate their access to the WM and a distributed, scheduled access to the WM becomes possible.

Through the collision free organization of the BP, devices can listen to the information provided in their neighbor's beacon frames. Thereby, devices learn about the MASs that are blocked by their neighbors. A beacon frame provides information about the beginning and the duration of a device's reservations, e. g. device 38, see Fig. 7.7.

The reservation set-up procedure relies on a two way handshake. The reservation initiator may use either explicit or implicit means to negotiate
a reservation with the intended receiver. With explicit DRP negotiation, the initiator generates a DRP Request frame and sends it to the intended receivers. The DRP Request frame carries the so called **DRP Information Elements (DRPIEs)** that convey information about the proposed reservation information. A unicast DRP Request is acknowledged immediately by the receiver. A multicast DRP Request frame remains unacknowledged. Afterwards, the intended receiver or receivers respond with a DRP Response frame, which establishes the reservation. An implicit DRP negotiation uses the beacon frame. The device that starts a DRP reservation includes the proposed DRPIE in its beacon frame. The intended receiver responds in its next own beacon frame with a corresponding Information Element (IE).

In either case of implicit or explicit DRP negotiation the receiver indicates to the reservation initiator whether the reservation is acceptable, needs to be shifted or must be declined. Once a reservation has been established, the reservation owner and the intended receiver inform their neighbors about the reservation set up. Therefore, they include the final reservation information in DRPIEs in their own beacon frames. From then on, the device that initiated a reservation is referred to as reservation owner.

ISO/IEC 26907 differentiates between five reservation types.

**Hard reservation** A hard reservation enables the device owning the MAS to start its transmission immediately at the beginning of the reserved MASs, since all other devices must complete their transmissions a SIFS plus a guard interval before the reserved MAS. The reserved MAS itself shall be used by the reserving device and its communication partners only. To support isochronous real time (rt) traffic via DRP no other transmissions are permitted during a hard reservation. However, the reservation owner can initiate an Unused DRP reservation announcement (UDA) and Unused DRP reservation response (UDR) a frame exchange that signals the release of a hard reservation. Following, neighboring devices may reuse unused reservation time.

**Private reservation** A private reservation provides for proprietary medium access mechanisms. ISO/IEC 26907 does not describe the organization of a private reservation. As with the hard reservation, unused time should be released to neighboring devices.

**Soft reservation** For less strict QoS demands, DRP provides soft reservations. During a soft reservation the reservation owner accesses the medium with PCA using the highest priority Arbitration Interframe
Space (AIFS) and without performing a backoff. All other devices have to wait for an additional random time after AIFS according to PCA. If the reservation owner does not fully use the reserved MASs, other devices can access the WM to claim unused reservation time.

**Alien BP reservation** When multiple ISO/IEC 26907 networks overlap, each network uses its own BPs. Until the BPs can be aligned, an alien reservation secures the BP from interference.

**PCA reservation** In dedicating time for PCA medium access, the PCA reservation helps to avoid that the WM becomes fully blocked by DRP reservations. Whereas the Contention Period (CP) of IEEE 802.11 presented Section 4.5.3.3 has a minimum static duration, the PCA reservation can be adapted to the needs of the network.

At present, most implementations rely on DRP only. Neither WUSB [295–297] nor the Bluetooth (BT) UWB PAL foresee PCA usage.

### 7.4.3.3 Optional MAC enhancements

To reduce the Packet Error Rate (PER) MSDUs may be optionally fragmented with both ISO/IEC 26907 CFs. Although the RTS/CTS handshake introduced in Section 4.5.3.6 is not needed with DRP, it may be applied with both CFs.

#### 7.4.3.3.1 Acknowledgment policies

ISO/IEC 26907 implements the Acknowledgment (ACK) policies described in Section 4.5.4.1. The ACK policy field in the frame control field inside the MAC header indicates the desired ACK procedure. Prior to the Block Acknowledgment mechanism (BA) frame exchange sequence shown in Fig. 7.8, a BA handshake is required to negotiate the maximum number and size of the frames that the receiver can buffer.

#### 7.4.3.3.2 Minimum Interframe Spacing

With BA, a device sends an uninterrupted burst of MSDUs. Without individual ACKs no time for a Transceiver (TRX) turn around is needed. Accordingly, ISO/IEC 26907 allows to reduce the Interframe Space (IFS) between consecutive MSDUs. Therefore, Minimum Interframe Spacing (MIFS) equals Reduced Inter-frame Space (RIFS) of IEEE 802.11n [278]. Fig. 7.9 presents a BA burst that uses MIFS.
Figure 7.8: ISO/IEC 26907 introduces block acknowledgments for improved efficiency.

Figure 7.9: Without the need for a TRX turnaround the time between consecutive frames can be reduced.

### 7.4.3.3 Frame Aggregation

To further enhance efficiency, ISO/IEC 26907 devices can aggregate MSDUs into a single frame, see Fig. 7.10. This can be further enhanced by transmitting several aggregations in a BA burst.

Unlike the IEEE 802.11n frame aggregation, ISO/IEC 26907 provides no concatenation of MPDUs. The aggregation of several MSDUs is presented in Fig. 7.11. The aggregation header indicates the length of each MSDU contained within the aggregate.

Figure 7.10: Frame aggregation groups several MSDUs into a single MPDU.
7.5 ISO/IEC 13156 — 60 GHz extension


7.6 Simulation based analysis

The author presents WARP2 simulation results that he published in [8, 71, 72]. At the time of publication revision 0.93 of the MBOA MAC specification [303] was the most recent one. Additional results can be found in [328, 329]. Furthermore, [73] studies ISO/IEC 26907 in mesh configurations.
Owing to the short range nature of UWB based WPANs, all devices are assumed to be within mutual receive range so that no hidden stations are considered in the simulation studies.

### 7.6.1 PCA and DRP comparison with single transmitter and single receiver

Fig. 7.12 presents the results of a simple scenario where one device transmits to another device. The transmitting device is assumed to always have a full buffer of frames to send. To evaluate the upper bound capacity limit of the ISO/IEC 26907 MAC layer, an error-free WM is assumed. The simulation results show the impact on throughput versus load of ISO/IEC 26907’s ACK scheme and frame aggregation under both, DRP and PCA. The minimum BP size is eight MAS. Frames sent under the rules of PCA use the AC_VI access parameters see Table 7.3. With BA, the device sends 16 frames in a sequence. The frame aggregation timeout value is set to 100 μs. Furthermore, the simulations employ MIFS between frames sent in a burst and the according BA mode preamble specified in [304]. A fixed MCS is assumed, namely DCM$^{3/4}$ that achieves a data rate of 480 Mb/s.

Fig. 7.12 indicates that DRP outperforms PCA when both use the same ACK policy. The highest throughput can be achieved with no ACK transmissions. The BA scheme achieves slightly less throughput. With immediate ACK the efficiency severely drops. Frame aggregation is very important for an efficient packet oriented MAC. The throughput for small-size MSDUs achieved with frame aggregation is comparable to the throughput of large MSDUs. In general, with frame aggregation the efficiency can be further enhanced owing to the absence of IFSs between consecutive MSDUs.

At the time the simulations were performed, [303] was the most recent specification. Revision 0.93 of the MBOA MAC specification describes a maximum PLCP Service Data Unit (PSDU) size of 4095 B. Thus, MSDUs larger than 2047 B cannot be aggregated. The simulation results show that the performance significantly reduces in this case. Beyond the aggregation limit, throughput increases with increasing frame size. With frames of 4000 B size throughput becomes similar to an aggregate of two frames of 2000 B size. Influenced by the results published, WiMedia has increased the maximum PSDU size to 16384 B in its latest MAC specification [305].
Figure 7.12: PCA and DRP saturation throughput versus frame size.

7.6.2 PCA and DRP comparison in a duplex communication scenario

Fig. 7.13 presents the results of a second scenario where over a full duplex link devices exchange frames with immediate MSDU acknowledgement on successful reception. Throughput and delay of the duplex link are evaluated in both directions (“route”) of the link in three cases under Poisson traffic with 1800 B MSDU size for all ACs.

In the first case, DRP is used by both devices while PCA assuming voice and background AC are studied in the other two cases, respectively. Devices do not apply frame aggregation. With DRP devices benefit from collision free medium access. Under low offered traffic, with a limited number of contending devices, the aggressive medium access settings of PCA for the voice AC achieves throughput very similar to that of DRP. In contrast, the throughput for best effort traffic sent as background AC reaches its saturation throughput at much lower offered traffic. This is because of the large AIFS related overhead applied for this AC. The system is saturated at about 80 Mb/s offered traffic.
Fig. 7.13: Throughput versus offered traffic.

Fig. 7.14 presents the Complementary Cumulative Distribution Function (CCDF) of the MSDU delay for two cases, non-saturated and saturated system. With DRP, delay is strictly bounded even under overload and service guarantee is possible. Owing to its contention based access, in an overloaded system, the delay of frames transmitted using PCA becomes unbounded. QoS can no longer be guaranteed.

7.6.3 Coexistence of DRP and PCA

Scenario 3 assumes a 480 Mb/s channel where links (R1 . . . R9) are active with the traffic load as given in Table 7.4. R1 and R2 carry high quality Voice over IP (VoIP) traffic (150 kb/s) with 120 B MSDU size. R3 and R4 carry High Definition Television (HDTV) streaming data each 24 Mb/s with 1500 B MSDU size. R5 and R6 carry file transfers at 30 Mb/s and route 7 carries 100 Mb/s with 1500 B MSDU size. R1 . . . R7 apply DRP. In addition, two PCA links participate in this scenario with AC_VO and 1500 B MSDU size (R8-9). With a traffic load of 608.3 Mb/s the channel is overloaded. As visible from Table 7.4, DRP serves all its links (R1 . . . R7), independent of traffic
category, perfectly in that the offered traffic is carried. The links R8 and R9 served with PCA only carry about 6.5% of the offered traffic and contribute substantially to the fact that the total throughput (206 Mb/s) is less than 50% of the offered traffic. Apparently DRP reserves the needed capacity of the channel and PCA suffers from that.

Fig. 7.15 shows the delay CCDFs of the links. Because DRP operates on reserved channel capacity, the delay is bounded. Since PCA operates on an overloaded channel, MSDUs served with PCA routes experience unbounded delay. PCA MSDUs can only try to get access to the channel when a MAS is not reserved by DRP, otherwise they have to wait till the end of the DRP reservation and contend for the access again. Clearly coexistence of DRP and PCA is very unbalanced in favor of DRP.
Table 7.4: Offered traffic, transmission settings and throughput per route.

<table>
<thead>
<tr>
<th>Route</th>
<th>Offered traffic (Mb/s)</th>
<th>MSDU size (B)</th>
<th>Access Method</th>
<th>ACK policy</th>
<th>Throughput (Mb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0.15</td>
<td>120</td>
<td>DRP</td>
<td>No</td>
<td>0.15</td>
</tr>
<tr>
<td>R2</td>
<td>0.15</td>
<td>120</td>
<td>DRP</td>
<td>No</td>
<td>0.15</td>
</tr>
<tr>
<td>R3</td>
<td>24</td>
<td>1500</td>
<td>DRP</td>
<td>No</td>
<td>23.98</td>
</tr>
<tr>
<td>R4</td>
<td>24</td>
<td>1500</td>
<td>DRP</td>
<td>No</td>
<td>23.98</td>
</tr>
<tr>
<td>R5</td>
<td>30</td>
<td>1500</td>
<td>DRP</td>
<td>BA</td>
<td>30.00</td>
</tr>
<tr>
<td>R6</td>
<td>30</td>
<td>1500</td>
<td>DRP</td>
<td>BA</td>
<td>30.02</td>
</tr>
<tr>
<td>R7</td>
<td>100</td>
<td>1500</td>
<td>PCA</td>
<td>Immediate</td>
<td>99.89</td>
</tr>
<tr>
<td>R8</td>
<td>200</td>
<td>1500</td>
<td>PCA</td>
<td>Immediate</td>
<td>13.00</td>
</tr>
<tr>
<td>R9</td>
<td>200</td>
<td>1500</td>
<td>PCA</td>
<td>Immediate</td>
<td>12.82</td>
</tr>
</tbody>
</table>

Figure 7.15: CCDF of the transmission delay.
Wireless Mesh Networks

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  8.5.1 Standard development ............................................. 90

Wireless Mesh Networks (WMNs) rely on multi-hop communication where frames are relayed between devices. Current wireless communication standards are designed for single-hop communication, however. In this chapter the author focuses on medium access in WMNs and introduce the spatial reuse distance. The spatial reuse distance describes the minimal separation between two devices that is necessary for uninterfered frame transmission. With optimal settings, concurrent transmissions allow to partially compensate the performance degradation introduced by transmitting frames on a multi-hop path.

8.1 Introduction

Current Wireless Personal Area Network (WPAN) (IEEE 802.15.1) and Wireless Local Area Network (WLAN) (IEEE 802.11) standards operate in the unlicensed 2.4 GHz and 5 GHz bands. There however, transmit power limitations imposed by regulatory requirements limit the achievable range (coverage). To overcome the range limitation of single-hop communication, data packets can traverse over multiple wireless hops. Consequently, WMNs are called for.
Figure 8.1: Optimal spatial frequency reuse with equidistant device positions and fixed frame size.

8.2 Exploiting the Capacity of the Wireless Medium — Spatial Frequency Reuse

In WMNs, frames directed to a non-direct neighbor destination may be relayed via intermediate nodes. With relaying, the Wireless Medium (WM) at the relay node is occupied twice. First, the relay node receives the frame. Afterwards, it retransmits the frame. Fig. 8.1 presents an example. Under the assumptions of symmetric channel propagation conditions, the interference range being less than two times the reception range, static frame sizes, equidistant placement of mesh devices, and constant transmission power, the optimum spatial reuse distance in this string topology is 3 hops [74].

Let $S_N$ denote the set of $N$ devices in a WMN. The set $S_n$ denotes the set of devices that device $d_n$, $n \in (1 \ldots N)$ can communicate with. $d_k \notin S_n$ if frame transmission of device $d_k$ cannot be received by device $d_n$. In WMNs path selection (routing) protocols search for ordered sequences of sets $S_n, S_o, \ldots S_z, S_k$ such that device $d_n$ can receive data from device $d_k$ with devices $d_o, \ldots d_z$ operating as relays. Thus, a WMN can be seen as a set of continuously overlapping wireless single hop networks. It is a characteristic of WMNs that each device can communicate with a sub-set of the total amount of devices only. Hence, two problems unknown to
single-hop wireless networks emerge. On the one hand, indirect neighbors that are hidden become a major source of interference. On the other hand, exposed\(^1\) devices are prevented to benefit from concurrent transmissions. The latter reduces spatial frequency channel reuse. Under the assumption of immobile devices, the direct and indirect neighborhood of each device is time-invariant. However, moving obstacles may nevertheless introduce time dependency. Only under the assumption of reciprocal channel conditions, \(d_n\) is part of the set \(S_m\) if device \(d_m\) is part of \(S_n\). Then, the set \(S_n\) becomes the set of devices to which \(d_n\) can directly communicate and exchange frames with. In many scenarios reciprocal channel conditions may be assumed, however this assumption is not true for the general case [320]. For any transmission to \(d_n\) of a device \(d_m\) that is part of the set \(S_n\), other simultaneous emissions of power of devices \(d_k\) with \(k \notin (n, m)\) on the wireless channel are interference-free if (see Eq. 2.5)

\[
\frac{P_n(m)}{P_{n, \text{Noise thermal}} + \sum_{k=1}^{N} P_n(k)} < \text{SINR}_{\min}(R), \ k \notin (n, m) \tag{8.1}
\]

where device \(d_m\) transmits to device \(d_n\) using Modulation and Coding Scheme (MCS) \(R\). Thus, the determination of possible simultaneous transmissions becomes a combinatorial problem, as shown in [322].

The previous assumptions are very stringent and lack several aspects of wireless communication networks. For any \(n \neq m\), \(P_n(m)\) is known at the receiver side only. Thus, solely device \(d_n\) has knowledge about \(P_n(m)\). To identify opportunities for concurrent transmissions, each device \(d_k, k \notin (n, m)\) needs to determine its impact on \(\text{SINR}(P_n(m))\), Eq. 8.1. If simultaneous transmissions of device \(d_k\) lead to \(\text{SINR}(P_n(m)) < \text{SINR}_{\min}(R(m))\) the device will not be allowed to transmit concurrently. However, \(R(m)\) used for transmission of device \(d_m\) to \(d_n\) may not be known at \(d_k\). Hence, it cannot determine \(\text{SINR}_{\min}(R(m))\). Furthermore, the latter value may be dependent on the receiver of device \(d_k\): \(\text{SINR}_{\min}(R(m, n))\). With variability in manufacturing of the transceiver, even similar hardware may have different sensitivity. Therefore, \(\text{SINR}_{\min}(R(m, n))\) cannot be easily determined. A common worst case \(\text{SINR}_{\min}(R)\) must be assumed by any transmitting device \(d_n\), which is sufficient for all devices in the WMN. However, such worst case assumption reduces spatial frequency reuse.

In unsynchronized, packet oriented WMNs, frames of arbitrary size are transmitted at any time. Due to unpredictable frame length and the

\(^1\)A device is called “exposed,” if it is blocked from medium access although it could transmit concurrently to another ongoing frame exchange.
unknown frame transmission MCS $R(m)$, it may be impossible for devices that are neighbors to $d_n$ to identify start time and duration of the frame reception. As device $d_k$ needs to avoid interference to any of its direct and indirect neighbors, opportunities for concurrent frame transmission become unlikely if neighboring devices begin receiving at arbitrary times for an unpredictable period.

### 8.3 Maximum throughput in an example scenario

Fig. 8.2 presents an example scenario with a building in the middle. The author assumes that all Stations (STAs) employ the IEEE 802.11a. Six STAs receive data from the Internet via a two and a three hop path. STAs 1a, 1b, and 1c associate with the Access Point (AP) that collocates with mesh STA 1. STAs 2a, 2b, and 2c associate with the AP that collocates with mesh STA 2. Mesh STA 1 connects to mesh STA 4 via mesh STA 3. Mesh STA 2 has direct connection to mesh STA 4. In the following, frames of 80 B size are considered. The mesh STAs are separated by 25 m and therefore use Quarternary Phase Shift Keying (QPSK)$^{3/4}$ as MCS. STAs 1a to 2c are close to their respective APs. Therefore 64-Quadrature Amplitude Modulation (QAM)$^{3/4}$ is used in the respective Basic Service Sets (BSSs). Under the simplified assumption that only neighboring devices interfere with each other, concurrent links can be identified. In the following, “∥” denotes “concurrent to” and “→” denotes transmits MAC Service Data Unit (MSDU) to.” Thus, the following is possible: (mesh STA 4 → mesh STA 3) ∥ (AP 2 → {STA 2a | STA 2b | STA 2c}) and (mesh STA 4 → mesh STA 2) ∥ (mesh STA 3 → mesh STA 1). However, (AP 1 → {STA 1a | STA 1b | STA 1c}) cannot operate simultaneously to any other link.

Hence, an optimum transmission sequence could be {(mesh STA 4 → mesh STA 3) ∥ (AP 2 → STA 2a), (mesh STA 4 → mesh STA 2) ∥ (mesh STA 3 → mesh STA 1), (AP 1 → STA 1a), (mesh STA 4 → mesh STA 3) ∥ (AP 2 → STA 2b)}, (mesh STA 4 → mesh STA 2) ∥ (mesh STA 3 → mesh STA 1), (AP 1 → STA 1b), (mesh STA 4 → mesh STA 2) ∥ (AP 2 → STA 2c), (AP 1 → STA 1c)}. Each step in this sequence is limited by the slowest transmission. Under the assumption of the No-Acknowledgment (ACK) policy, data frames are separated by a Short Interframe Space (SIFS) period. With six streams coming from the central Internet gateway to each end station the total throughput is calculated according to Section 4.7
8.3 Maximum throughput in an example scenario

Figure 8.2: Mesh STA 4 is a portal (connection to the Internet). It provides access to mesh APs 1 and 2. STAs 1a, 1b and, 1c receive frames via AP 1 arriving on the route via mesh STA 3. STAs 2a, 2b, and 2c receive frames via AP 2 that is in single hop distance to the portal.

Total Throughput

\[
\text{Total Throughput} = \frac{6 \cdot 80B}{\text{Duration}(6 \cdot 80B@QPSK^{3/4} + 2 \cdot 80B@64-QAM^{3/4})} = \frac{6 \cdot 80B}{6 \cdot (72\mu s + \text{SIFS}) + 2 \cdot (40\mu s + \text{SIFS})} = \frac{6 \cdot 80B}{6 \cdot 88\mu s + 2 \cdot 56\mu s} = 5.3 \text{Mb/s}
\]

Under the assumption of a fully synchronized network, the MSDU receiving devices may simultaneously reply with an ACK frame. With acknowledgments an additional SIFS provides time for Transceiver (TRX) turnaround. Thus the achievable throughput is
Because of the small MSDU size of 80 B the system throughput without frame acknowledgements (8.2) is 1.6 times higher than with acknowledgements (8.3).

\[
\frac{6 \cdot 80 \text{B}}{640 \mu s + 8 \cdot (\text{SIFS+ACK@BPSK}^{1/2})} = \frac{6 \cdot 80 \text{B}}{640 \mu s + 8 \cdot (16 \mu s + 44 \mu s)} = 3.4 \text{Mb/s}
\] (8.3)

8.4 Example string topology — IEEE 802.11

Frame transmissions in an IEEE 802.11 WLAN synchronize STAs to a common reference. At the end of each transmission, STAs start to independently contend on the WM. However, there is one exception. Once a STA performed the post-backoff that follows each frame exchange sequence, it transmits immediately on a frame arrival if the WM has been idle for at least a Distributed Coordination Function Interframe Space (DIFS)/Arbitration Interframe Space (AIFS) period. Therefore, frame transmissions in an IEEE 802.11 WLAN occur at arbitrary times. Without synchronized medium access, STAs rely on the Carrier Sense (CS) to detect the status of the WM. However, Physical Carrier Sense (P-CS) is of limited range. STAs cannot detect the status of the WM at their intended communication partner’s location. Fig. 8.3 provides an example scenario. Five STAs are placed in a line. Only neighboring STAs are assumed to be able to sense each other. The first STA \( n \) transmits MSDUs that are forwarded along the string topology. Although STA \( n \) is the only traffic source in the example, collisions occur owing to hidden STAs.

Since a Request To Send/Clear To Send (RTS/CTS) handshake sets the Network Allocation Vector (NAV) at surrounding STAs only, the handshake cannot prevent that frame collisions occur in a mesh topology. Furthermore, a STA cannot detect if the absence of an expected frame occurs due to interference with another transmission or due to experiencing bad channel conditions. Accordingly, studies show that usage of RTS/CTS has almost no impact on the network performance [75]. Especially in a WMN it only adds to the overhead [9, 76]. The example in Fig. 8.3 does not change with respect to collisions if RTS/CTS handshakes are omitted. Neither with, nor without RTS/CTS the CS medium access of IEEE 802.11 cannot detect the conditions on the WM at the receiver side and therefore Collision Avoidance (CA) cannot be achieved. Facing that fact, standard IEEE 802.11s has
Figure 8.3: A single STA sends MSDUs along a string topology. It is assumed that CS is limited to neighboring STAs.
been finalized following the assumption that later amendments will con-tribute to improve throughput capacity by introducing improved Medium Access Control (MAC) protocols.

8.5 IEEE 802.11s — Standard for WLAN Mesh

The author contributed to the IEEE 802.11s standard since 2003. He served as Vice Chairman of this Task Group (TG) from 2010 until its ratification in September 2011 [306]. During the course of standardization, the author's proposal to IEEE 802.11s was modified and incorporated into the final document. Besides the WiMedia Alliance (WiMedia) IEEE 802.11s is the second standard that makes use of Distributed Reservation Protocol (DRP) and reservation announcements in beacon frames as invented by the author. In the following, the author briefly outlines the development of IEEE 802.11s and his contributions to its standardization in chronological order.

8.5.1 Standard development

In 2004, Task Group “S” began to develop an amendment to the IEEE 802.11 standard for multi-hop communication. In January 2005, IEEE 802.11s called for proposal submissions. Following the Call for Proposals (CFP), 34 proposal submission intents were announced until March 2005. Out of those, seven full and eight partial proposals were presented during the IEEE 802 meeting in July 2005. The author and colleagues formed a consortium and developed a proposal named Mesh Networks Alliance (MNA). This proposal ranked third during the IEEE 802.11s down selection process. In January 2006, it merged into the proposal of the Wi-Mesh Alliance (WiMA). Neither WiMA nor the competing SEE-Mesh consortium received a majority of 75% of the IEEE 802.11 voting members that would have been needed to select a proposal as the IEEE 802.11s baseline document. Therefore in January 2006, the consortia decided to merge their proposals. In the following the author presents and analyzes the MNA protocol in Chapter 9. Chapter 10 describes the final IEEE 802.11s standard and the new Coordination Function (CF) that it introduces. The author compares the performance of the new CF to the MNA protocol that it is based on. During the process of standardization, terminology in IEEE 802.11s changed several times. In following chapters, the most recent terminology introduced with [271] is used.
The joint research of the Department of Communication Networks, RWTH Aachen University (ComNets) and Philips Research, Eindhoven, led to the formation of the Mesh Networks Alliance (MNA) consortium. Encouraged by the good performance of the Distributed Reservation Protocol (DRP), the author proposed a medium access protocol introducing DRP and its reservation concept to IEEE 802.11s. The author's proposal [157, 158] extended DRP for usage with multi-hop communication. This thesis describes the improvements needed to apply DRP for
Figure 9.1: Depending on path loss coefficient $\gamma$ and ED threshold, a device transmitting at 100 mW (20 dBm) may block other devices over large distances.

dense spatial frequency reuse in Wireless Mesh Networks (WMNs). The author presents in this thesis simulation results that prove DRP to have the best performance among all proposals submitted to IEEE 802.11s.

### 9.1 Introduction

MNA’s proposal to IEEE 802.11s aimed at a scalable solution for the Consumer Electronic (CE) and Small Office Home Office (SOHO) markets. For low cost devices, good performance with a single radio is key. Therefore, MNA proposed to operate the IEEE 802.11 Access Points (APs) and the IEEE 802.11s service on the same carrier frequency. Thus, backbone (relayed) and local (BSS) traffic share the Wireless Medium (WM). Depending on the attenuation factor $\gamma$ (Eq. 2.9), the IEEE 802.11 Clear Channel Assessment (CCA) mechanism blocks large areas covered by the WMN from reusing the WM, however. As an example, IEEE 802.11a devices consider the WM busy if

- the Energy Detection (ED) exceeds a threshold of -62 dBm, or
- a valid preamble can be decoded at $\geq -82$ dBm.

Fig. 9.1 presents the impact of $\gamma$ on the busy channel detection condition. To provide sufficient capacity for the Basic Service Set (BSS) and the WMN traffic, the MNA protocol aims at a close spatial frequency reuse.

In the following the author describes the MNA protocol as published in [30, 77, 78, 157, 159, 160]. Section 9.2 outlines the structure of the MNA superframe. Section 9.3 presents the details of the protocol proposed for MNA. In Section 9.9 the author provides a simulation based analysis of the MNA protocol.
9.2 Superframe structure

The MNA protocol divides time into a Mesh Contention Free Period (MCFP) and a BSS Period. The MCFP operates during the Contention Free Period (CFP) of the IEEE 802.11 protocol. The BSS Period operates during the Contention Period (CP) of the IEEE 802.11 standard. Together both periods form a periodic superframe, Fig. 9.2.

APs signal the start and duration of the CFP in their beacons. During the CFP, non-AP Stations (STAs) cannot access the WM. Therefore, the CFP can be used exclusively by compliant mesh devices. To allow for spatial frequency reuse, medium access during the Mesh Traffic Period (MTP) incorporates principles known from the Medium Access Control (MAC) protocol standardized by WiMedia, see Chapter 7 and the Wireless Channel oriented Ad hoc mobile Broadband (W-CHAMB) protocol [31, 323].

During the CP, STAs use either Distributed Coordination Function (DCF) or Enhanced Distributed Channel Access (EDCA) as Coordination Function (CF), where APs transmit frames to or receive frames from their associated STAs.

9.3 Mesh Contention Free Period

With non-mesh STAs refraining from channel access during the IEEE 802.11 CFP, the MNA protocol uses the latter to form a MCFP. The MCFP consists of \( k \) Mesh Transmission Opportunities (MTXOPs) of equal duration. \( n \) MTXOPs form the Beacon Period (BP) and \( k - n \) MTXOPs form the MTP as shown in Fig. 9.3.

Similar to the concepts described in Section 7.4.3.1, the BP comprises Beacon Transmission Slots (BTSs). With the help of its beacon frame, devices use the DRP described in Section 7.4.3.2.2 to reserve MTXOPs during the MTP. The author describes the organization of the BP and MTP in Section 9.3.1 and Section 9.3.3 respectively.
Chapter 9 – *The Mesh Networks Alliance Proposal to IEEE 802.11s*

**Figure 9.3:** The MNA protocol reserves the IEEE 802.11 CFP for mesh operation.

### 9.3.1 Beacon Period

Each of the $n$ MTXOPs that establish the BP is subdivided into BP-SlotsPerMTXOP BTS. Every mesh STA reserves one or more BTS to transmit its beacon frames. All beacons together announce an IEEE 802.11 CFP that begins at the same Target Beacon Transmission Time (TBTT). As described in Section 4.5.3.3, non-mesh STAs preset their Network Allocation Vector (NAV) to TBTT and to the duration of the CFP. Thereby, an MCFP is established.

The Beacon Period Access Protocol (BPAP) organizes the sequence of beacon frame transmissions. Fig. 9.4 presents an example.

Shadowing and attenuation by obstacles provide spatial separation of mesh STAs. Fig. 9.5 presents an example where mesh STA C cannot receive transmissions of both mesh STAs A and E. However, mesh STA C is in reception range of mesh STAs B and D. Since all mesh STAs transmit a BTS occupancy map, mesh STA C learns from mesh STA B’s beacon frame that mesh STA A occupies BTS 2. Because BPAP guarantees collision-free occupation of the BTSs, mesh STAs measure the received signal strength for each BTS. Although mesh STA C cannot decode the beacon frame of...
mesh STA A in BTS 2, the signal strength received from STA A during the BTS informs mesh STA C about the approximate interference separation between A and C.

Table 9.1 presents the Beacon Period Occupancy Information Element (BPOIE) that is transmitted by a mesh STA in its beacon. All mesh STAs maintain the BPOIE to communicate their current observation of each BTS occupation. When the mesh STA sets the BPOIE bits to 10, the mesh STA includes the Device ID of the mesh STA that occupies the BTS and the Received Channel Power Indicator (RCPI) that it measured during this BTS. For a BTS whose beacon frame the mesh STA cannot decode, the mesh STA sets the BPOIE to 11. The mesh STA learns about the Device ID for this BTS from beacon frames successfully received from its neighbor mesh STAs.

Fig. 9.6 presents the proposed beacon frame format containing both, Information Elements (IEs) that non-mesh IEEE 802.11 STAs decode and IEs that help to organize the MCFP.
Table 9.1: The BTS occupancy bits indicate a mesh STA’s observation of the status of the BP.

<table>
<thead>
<tr>
<th>Value (b1 b0)</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>Free BTS The mesh STA consider this BTS as free.</td>
</tr>
<tr>
<td>01</td>
<td>Occupied by transmitter The mesh STA occupies this BTS.</td>
</tr>
<tr>
<td>10</td>
<td>Occupied by neighbor mesh STA During this BTS, the mesh STA successfully received a beacon frame by the indicated mesh STA.</td>
</tr>
<tr>
<td>11</td>
<td>Occupied by neighbors’ neighbor mesh STA X The mesh STA has learned by neighboring mesh STA that this BTS is reserved by mesh STA X.</td>
</tr>
</tbody>
</table>

Figure 9.6: Proposed beacon frame format.

The example in Fig. 9.5 is translated into RCPI measurement values of mesh STA C as presented in Fig. 9.7. Accordingly, mesh STA C may build a BTS occupancy map as presented in Table 9.2.

A mesh STA learns about a beacon collision similar to Section 7.4.3.1. It considers its beacon frames as collision free when all beacon frames of neighboring mesh STAs announce its Device ID for the BTSs that it occupies. In case of a beacon collision, the mesh STA randomly selects an empty BTS and observes its neighbors’ beacon frame announcements.

When a mesh STA cannot carry all information in a single BTS it needs to transmit another beacon in an additional BTS. Via BP extension and
Figure 9.7: Mesh STA C measures the received signal strength during all BTSs. It is able to receive beacon frames from mesh STAs B and D. Owing to the attenuation of the wall the beacon frames of mesh STAs A and E cannot be received by C.

Table 9.2: Neighborhood as seen by mesh STA C.

<table>
<thead>
<tr>
<th>Mesh STA</th>
<th>A</th>
<th>B</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCPI (dBm)</td>
<td>-86</td>
<td>-76</td>
<td>-78</td>
<td>-92</td>
</tr>
<tr>
<td>Beacon received</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Mesh STAs announced in Beacon</td>
<td>A, C, D, E</td>
<td>B, C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Also known through</td>
<td>B</td>
<td>D</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>BTS occupancy bits for the mesh STA</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

contraction (see Section 7.4.3.1) the beacon transmission order can reorganized and a mesh STA may occupy consecutive BTSs. Fig. 9.8 presents the BTS occupation for the example in Fig. 9.5. Here, mesh STAs C and E due have an increased beacon payload. Thus, they occupy two BTSs while all other mesh STAs occupy one BTS.

Figure 9.8: Example beacon distribution.
Similar to WiMedia Alliance (WiMedia) [304], the MNA protocol describes mechanisms for the extension and the contraction of the BP. Furthermore, methods to group multiple beacon frames of the same device into consecutive BTSs are specified.

9.3.2 Device ID

The standard IEEE 802 MAC has 48 b length. To reduce the payload size in a mesh STA’s beacon frame the MNA protocol introduces Device IDs similar to Section 7.4.1.1. During its initialization phase, a mesh STA listens to the beacon frames received in its neighborhood. Before joining a mesh network, the mesh STA selects a random Device ID that is not in use by any other mesh STA.

9.3.3 Mesh Traffic Period

The MNA protocol uses the DRP presented in Section 7.4.3.2.2 to organize frame transmissions during the MTP. Whereas standard ISO/IEC 26907 considers a Wireless Personal Area Network (WPAN) scenario, the MNA protocol extends the DRP to exploit spatial frequency reuse. Spatially separated mesh STAs transmit concurrently on the same frequency channel.

In Fig. 9.9 mesh STA A has negotiated with mesh STA B on the reservation of several MTXOPs. Their neighbors include the reservation information in their own beacon frames. Thereby, surrounding mesh STAs learn of the medium reservation and refrain from channel access.

Fig. 9.10a presents an example scenario with mesh STAs A–E being in mutual reception range. Without any spatial separation, concurrent trans-
missions lead to frame collisions. Therefore, frame exchanges must occur sequentially.

In Fig. 9.10b, a wall partitions the WM into different areas. E.g., the wall shadows mesh STAs A, B, and E from mesh STAs D. Because of spatial separation, mesh STA B can transmit data to mesh STA A concurrently to a frame transmission of mesh STA C to mesh STA D. To allow for concurrent transmissions, two conditions to be met are key:

1. A Transceiver (TRX) turnaround shall not occur during a single reservation. Thus, via DRP reservations surrounding mesh STAs learn about the radio transmission source in advance. Only the MTXOP owner transmits during the MTXOP. Therefore, separate reservations in reverse direction must be used to transmit acknowledgments. As a consequence, delayed acknowledgments replace immediate acknowledgments.

2. Mesh STAs need to know the radio channel environment. Owing to the RCPI measurements during the BP, mesh STAs learn about the interference separation between them and their neighbors. Together with the MTXOP occupancy learned from its neighbor mesh STAs, a mesh STA can predict the potential interference that a concurrent MTXOP usage may cause. This approach extends the concept of the Digital Enhanced Cordless Telecommunications (DECT) [10] stan-
standard where devices use measurements to identify the least interfered time slot for use. With the MNA protocol, a mesh STA identifies the appropriate Modulation and Coding Scheme (MCS) that fits the expected SINR communicated in the BP. Fig. 9.11 presents an example of the “world model” that each mesh STA develops. The combined knowledge about the situation on the radio channel enables spatial frequency reuse.

Fig. 9.12 presents an example of concurrent transmissions according to the example in Fig. 9.10b enabled through the MNA protocol. Mesh STAs B and C transmit frames to mesh STAs A and D, respectively. Because of the spatial separation B and C use MTXOPs $n$ and $n + 1$ at the same time. Shadowed by the wall neither C interferes with A nor B interferes with D.

To select an appropriate MTXOP (which may result in a concurrent transmission) a mesh STA estimates the Signal to Interference plus Noise Ratio (SINR) that it expects at the receiver and the impact of its transmission on other reservations. In the example of Fig. 9.12, it is assumed that mesh STA B has a reservation in place when mesh STA C searches for an MTXOP for its transmission to mesh STA D. To transmit (concurrently) to mesh STA B, mesh STA C needs to consider the two cases:
Figure 9.12: The MNA protocol enables mesh STAs B and C to transmit concurrently.

1. Mesh STA C must select an MCS that operates well with an SINR that mesh STA D will experience when transmitting concurrently to mesh STA B. With \( n \in (B) \) in Eq. 2.11 mesh STA D has SINR\(_D(C)\) when mesh STA C transmits:

\[
\text{SINR}_D(C) = \frac{P_D(C) \cdot \left(\frac{c}{4\pi f}\right)^2}{P_{D,\text{Noise thermal}} + \frac{P_D(B)}{d_{D,B}} \cdot \left(\frac{c}{4\pi f}\right)^2}
\]  
(9.1)

2. Further, mesh STA C must consider the impact of its transmission on any established reservation. In the present example, mesh STA C’s transmission would reduce SINR of mesh STA A while receiving data from mesh STA B:

\[
\text{SINR}_A(B) = \frac{P_A(B) \cdot \left(\frac{c}{4\pi f}\right)^2}{P_{A,\text{Noise thermal}} + \frac{P_A(C)}{d_{A,C}} \cdot \left(\frac{c}{4\pi f}\right)^2}
\]  
(9.2)

Because of differences in implementation, manufacturing, ambient and actual temperature at the location of the device etc. \( P_{X,\text{Noise thermal}} \) is different for every device. According to [32–36, 79, 80], however, Eq. 9.3 provides an estimate for this case (\( \Delta f = 20 \text{ MHz} \)):

\[-90 \text{ dBm} \leq P_{\text{Noise thermal}} \leq -95 \text{ dBm}\]  
(9.3)
### Chapter 9 – The Mesh Networks Alliance Proposal to IEEE 802.11s

<table>
<thead>
<tr>
<th>Element ID</th>
<th>Length</th>
<th>Transmitter</th>
<th>Receiver</th>
<th>SignalStrength</th>
<th>Time Stamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 b</td>
<td>8 b</td>
<td>DevIdBits</td>
<td>DevIdBits</td>
<td>6 b</td>
<td>6 b</td>
</tr>
</tbody>
</table>

Figure 9.13: The IE indicates the RCPI of neighbor mesh STA transmissions.

![Mesh Network Diagram](image)

Figure 9.14: A full RCPI graph as observed by mesh STA C.

Since the attenuation coefficient $\gamma$ in Eq. 2.9 represents several effects, it cannot be easily estimated. However, mesh STAs measure the RCPI level of their neighbors’ beacon frame transmissions during each BTS. While the direct line distance between two devices is symmetric $d_{\gamma}^{Y} = d_{\gamma}^{C,D}$, devices may transmit at different power levels — $P_{D}(C) \neq P_{C}(D)$. Furthermore, different radio designs may lead to different receiver sensitivity. Therefore, not all wireless links may behave in a symmetric way, see [320]. To increase accuracy, the MNA protocol adapts the extensions of IEEE 802.11k [307] to disseminate each mesh STA’s RCPI level measurements. Fig. 9.13 presents the IE that mesh STAs use to broadcast their measurement results.

The aforementioned mechanisms enable mesh STA C to assess the power level at which mesh STA D will receive its transmission — $P_{D}(C)$. Furthermore, the RCPI level list helps to estimate $P_{D}(B)$. Consequently, mesh STA C has all information necessary to estimate $\text{SINR}_{D}(C)$ according to Eq. 9.1.

To assess Eq. 9.2, mesh STA C needs estimates of $P_{A}(C)$ and $P_{A}(B)$. Again the propagation of the RCPI level measurements help to acquire the necessary information. Finally, mesh STA C may maintain a signal strength graph as presented in Fig. 9.14 enabling it to determine the best MCS for transmitting to mesh STA D in taking the impact of the frame reception at mesh STA A into account.
Extensions to the MNA protocol foresee to signal also the MCS that a reservation intends to apply. With the current protocol, mesh STAs assume a MCS based on the predicted SINR. With explicit signaling of this MCS, performance can be further enhanced.

## 9.4 Modulation and Coding Scheme adaptation

MNA compliant devices need criteria to decide when to establish a concurrent reservation. Under consideration of [32–36, 79, 80], a typical IEEE 802.11a receiver has a noise figure $N_f$ of 5 dB. Owing to the channel bandwidth $\Delta f = 20$ MHz in IEEE 802.11a, the MNA protocol assumes $P_{\text{Noise}_\text{thermal}} = -95$ dBm. IEEE 802.11 [280] mandates a minimum receiver sensitivity with a Packet Error Rate (PER) of $10^{-1}$ for a 1000 B frame. With Eq. 2.4 and $P_{\text{Noise}_\text{thermal}}$ the SNR for each MCS can be calculated. With concurrent transmissions the Signal to Noise Ratio (SNR) extends to the SINR. To allow for a safety margin, the MNA protocol requires SINR values that allow for PERs of $10^{-3}$ of a 1500 B frame. Hence, the MNA protocol adopts minimal SINR values that conform to the Wireless Access Radio Protocol 2 (WARP2) settings and the findings in [79]. Consequently, the minimum RCPI and SINR values presented in Table 9.3 present conservative settings that do not risk established reservations to be impacted by upcoming concurrent transmissions.

## 9.5 Received signal strength estimation

Owing to the time varying nature of the WM, the results of RCPI measurements fluctuate. Since the MNA protocol relies on interference prediction to select the optimal MTXOP and MCS for data exchanges, accurate RCPI estimation becomes important. Accordingly, the author proposes that mesh STAs filter their measurements of the signal strength of beacon frames transmitted by their neighbor mesh STAs. Therefore, a Kalman filter [37] is introduced. Fig. 9.15 presents an example.

The Kalman filter is described by

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1} \quad (9.4)$$

with

$$x \in \mathbb{R}^n \quad (9.5)$$

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Table 9.3: Assumed minimum RCPI and SINR with IEEE 802.11 MCSs.

<table>
<thead>
<tr>
<th>MCS</th>
<th>Coding rate</th>
<th>Minimum RCPI (dBm)</th>
<th>Minimum SINR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary Phase Shift Keying (BPSK)</td>
<td>1/2</td>
<td>-82</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>-81</td>
<td>9</td>
</tr>
<tr>
<td>Quarternary Phase Shift</td>
<td>1/2</td>
<td>-79</td>
<td>9</td>
</tr>
<tr>
<td>Keying (QPSK)</td>
<td>3/4</td>
<td>-77</td>
<td>12</td>
</tr>
<tr>
<td>16-Quadrature Amplitude Modulation (QAM)</td>
<td>1/2</td>
<td>-74</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>-70</td>
<td>19</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>-66</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>-65</td>
<td>25</td>
</tr>
</tbody>
</table>

Figure 9.15: Example measurements and filtered values.
Let $z \in \mathbb{R}^m$ denote the received signal strength that a mesh STA observes

$$z_k = H x_k + v_k$$  \hspace{1cm} (9.6)

The measurement noise $v_k$ occurs at the receiver side. The process noise $w_k$ reflects the random changes on the WM. It is assumed that $w_k$ and $v_k$ are uncorrelated. Their probability distribution relates to a Gaussian noise process:

$$p(w) \sim \mathcal{N}(\mu_w, \sigma^2_w)$$  \hspace{1cm} (9.7)

$$p(v) \sim \mathcal{N}(\mu_v, \sigma^2_v)$$  \hspace{1cm} (9.8)

Since their expected values ($\mathbb{E}(p(w)), \mathbb{E}(p(v))$) are assumed to be zero, $\mu_w = 0$ and $\mu_v = 0$. Let $Q = \sigma^2_w$ denote the process variance and $R = \sigma^2_v$ the measurement variance. It is assumed that $B = 0$ since the receiver side takes no control in this application. Fig. 9.16 presents the impact of the variance of the process noise $Q$ onto the one-dimensional estimation. Since mesh STAs do not vary the transmit power for beacon frames, $A = 1$. Because of the stationary scenario, it is assumed that $H = 1$. The measurement variance is set $R = 0.04$.

Fig. 9.16 shows that an elevated value of $Q$ increases the responsiveness of the Kalman filter. However, the variance of the estimation of $x_k$ also increases.

Figure 9.16: The factor $Q$ impacts the responsiveness of the Kalman filter.
With

\[ x_k = \begin{bmatrix} x_{1,k} \\ x_{2,k} \end{bmatrix} \quad (9.9) \]

the Kalman filter extends into two dimensions. Let \( x_1 \) denote the current signal strength and \( x_2 \) denote the estimation of the linear curve progression. Then, \( A \) is defined as

\[ A = \begin{bmatrix} 1 & 1 \\ 0 & \beta \end{bmatrix} \quad (9.10) \]

and

\[ H = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (9.11) \]

Therefore, Eq. 9.4 becomes

\[ x_{1,k} = x_{1,k-1} + x_{2,k-1} + w_{1,k-1} \quad (9.12) \]

\[ x_{2,k} = \beta x_{2,k-1} + w_{2,k-1} \quad (9.13) \]

with \( \beta \) denoting the slope weighing factor. Accordingly, Eq. 9.6 becomes

\[ z_k = x_{1,k} + v_k \quad (9.14) \]

\( Q \) describes the process noise's covariance matrix that consists of the variances \( q_1 \) and \( q_2 \)

\[ Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix} \quad (9.15) \]

Fig. 9.17 compares the result of one- and two-dimensional Kalman filters in different scenarios. In Fig. 9.17a, the input signal continually increases. The two dimensional Kalman filter follows the trend without any delay. In contrast, the estimation error of the one-dimensional Kalman filter increases. In Fig. 9.17b, the two-dimensional Kalman filter follows an abrupt state transition with minor delay. The one-dimensional Kalman filter, however, adapts much more slowly.
9.5 Received signal strength estimation

![Graph A: Linear adaptation with $\beta = 1$.](image1)

![Graph B: Abrupt state transition, $\beta = 0.9$.](image2)

Figure 9.17: Kalman filtering with one- and two-dimensional state variables.

Table 9.4: Default values of the proposed two-dimensional Kalman filter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_1$</td>
<td>$5 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$q_2$</td>
<td>$5 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.85</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.89</td>
</tr>
</tbody>
</table>

9.5.1 Parameter adaptation

Optimal assumptions on the parameters $R$, $q_1$, and $q_2$ allow for improved filter operation. According to the design goals of the MNA protocol indoor conditions are assumed. In a fading environment the variance $R$ of the measurement noise $v_k$ is not static. $R$ is derived from the true measurement variance. Therefore, $R = \sigma_k^2$. $\sigma_k^2$ can be estimated by Eq. 9.16.

$$\sigma_k^2 = \alpha \sigma_{k-1}^2 + (1 - \alpha) \cdot (\mu_k - z_k)^2, \alpha \in (0, 1)$$  (9.16)

The true measurement’s expected value $\mu_k$ is derived through an exponentially weighted moving average

$$\mu_k = \alpha \mu_{k-1} + (1 - \alpha) \cdot z_k$$  (9.17)

Based on simulations, the empirical values presented in Table 9.4 are derived.
Although the RCPI IE defined in [307] signals RCPI values in multiples of 0.5 dBm, the MNA protocol quantizes in multiples of 1 dBm. To quantize, a sliding window of length $L = 15$ and threshold $M = 5$ is used. If $M$ measurements in the window are above or below the current value, the RCPI value is updated. Fig. 9.18 presents the results of a WARP2 simulation. A small scale fading process leads to 5 dB fluctuation of the beacon frame signal strength measurement. The Kalman filter shows only minor fluctuations. The mapped RCPI value remains constant.

Fig. 9.19a and Fig. 9.19b compare the mapped values of the two-dimensional Kalman filter and the exponentially weighted moving average filter. In comparison to the exponentially weighted moving average filter, the Kalman filter presents less fluctuating RCPI values. Since the estimated RCPI values can be signalled to neighboring mesh STAs during the BP only, the propagation of the measured values is delayed for the duration of the superframe. Thus, Kalman filtering is preferable as it indicates the general trend of the RCPI estimation and does not cause too frequent updates as the exponentially weighted moving average filter does.

Fig. 9.20 presents the signal levels in a scenario where an interference source similar to a Bluetooth (BT) device emits bursts that collide with the beacon frame signal strength measurements. Being close to the receiver side, the interference bursts lead to up to 25 dB higher signal strength measurements. Whereas the Kalman filter shows minimal impact by the interference source, the exponentially weighted moving average filter is heavily affected. Since the interference source is uncorrelated to the frame
exchanges in the WMN, the RCPI estimation of the exponentially weighted moving average filter leads to false neighborhood estimations. This can severely impact identification of spatial frequency reuse opportunities. Frequent transmission schedule rearrangements are the consequence. On the contrary, the Kalman filter estimates the uninterfered RCPI levels and thus helps to accurately identify a mesh STA’s neighborhood. Since the latter is needed for the identification of spatial frequency reuse opportunities Kalman filtered RCPI measurements are beneficial.

9.6 Multi Channel DRP

Frequency channel switching allows single radio devices to benefit from spectrum unused otherwise. Thus, the MNA protocol is extended to support transmissions in multiple frequency channels with a single radio. Fig. 9.21 presents an example of three mesh STAs transmitting in three different frequency channels. In addition to the single frequency channel DRP, the modified beacon frames extend the reservation information with frequency channel announcements. Thus, mesh STAs are able to transmit concurrently in different frequency channels. However, the BP remains a common resource during which all mesh STAs must be tuned to the frequency channel where the BP is transmitted.

An AP transmits its beacon frames on the frequency channel that its BSS operates on. Since STAs are not frequency agile, they remain on the
Figure 9.20: Beacon frames collide with a BT like interference source. In contrast to the Kalman filter, the exponentially weighted moving average of the beacon signal strength measurements is heavily affected.

Figure 9.21: Frequency channel information in the beacon frame allows for multi-frequency DRP.
frequency channel of the BSS that they are associated with. When all APs transmit their beacon frames in the same frequency channel, all BSSs operate on a single frequency channel. With overlapping BSSs as presented in Fig. 9.22 the mutual interference limits the performance of each BSS. Thus, a single frequency channel BP causes the CP to become a bottleneck.

Fig. 9.23 presents the concept of beacon hopping. Mesh STAs use a common Channel Hop Sequence (CHS) to distribute their beacon frames over different frequency channels. For each BTS, mesh STAs tune their radio to the next frequency channel. Mesh STA E in Fig. 9.23 scans the WM for several superframes. It learns of the CHS from beacon frames that it receives. Once it has followed a full BP, mesh STA E selects an empty BTS in the frequency channel that the collocated AP and its associated STAs use. By transmitting a beacon frame in this BTS, mesh STA E joins the mesh network.

The extended DRP provides additional frequency channel information to identify MTXOPs for reservation. Fig. 9.24 provides an example where multiple mesh STAs transmit concurrently in different frequency channels.

### 9.7 Congestion Avoidance

When mesh STAs send traffic to the intended destination, intermediate relay mesh STAs store and forward the traffic. While a mesh STA at the edge of a WMN may detect several idle MTXOPs, a mesh STA in the center of the
Figure 9.23: A common frequency hopping pattern allows for the transmissions of beacon frames in different frequency channels.

Figure 9.24: Multiple frequency channels increase the number of concurrent transmissions.

network may find only few idle MTXOPs. Without knowledge about the traffic capacity along the mesh path chosen, an edge mesh STA may easily congest intermediate relay mesh STAs. A congested mesh STA, however, drops traffic. Since the dropped frames have been forwarded already, the frame dropping wastes radio resources and leads to inefficient usage of the WM. Until higher layer protocols like TCP detect the congestion and start to throttle, the packet flow of the connection, MAC Service Data Units (MSDUs) are forwarded in the WMN without reaching their destination.

To prevent frame dropping, the MNA protocol introduces a back pressure algorithm for congestion avoidance. When a mesh STA detects that it cannot forward the amount of traffic that it receives, the congested mesh
9.8 Performance enhancements

The MNA protocol applies “Frame Aggregation” and “Cumulative Acknowledgments” to further enhance throughput performance as described in Section 9.8.1 and Section 9.8.2.

9.8.1 Frame Aggregation

Frame aggregation helps to overcome the IEEE 802.11 Interframe Spaces (IFSs) between consecutive frame transmissions and to save Acknowledgment (ACK) frames. Because of the absence of a TRX turnaround during a single MTXOP, mesh STAs may transmit without interruption.
While IEEE 802.11n offers MAC Protocol Data Unit (MPDU) and MSDU aggregation, the MNA protocol applies the former one only. Fig. 9.27 presents an example. The aggregation header is prepended to the subframes. Each subframe can be directed to a different mesh STA. Therefore, each subframe may be transmitted with a different MCS.

Fig. 9.28 presents the structure of the aggregation header. The aggregation header announces the number of subframes that follow, Device Identifier (DevId) of each subframe receiver, the length of each subframe measured in OFDM symbols, and the MCS used to transmit the subframe. A Cyclic Redundancy Check (CRC) ends the aggregation header.

A subframe consists of one or more MPDUs, MAC Management Protocol Data Unit (MMPDU) or ACK frames. In the following, the author subsumes them as MPDU. Fig. 9.29 presents the subframe structure. The subframe header signals the number of MPDUs and the length of each MPDU measured in B.

Fig. 9.30 presents the structure of the MPDU. The MPDU contains all elements of standard IEEE 802.11 [276] besides the Duration/ID field (see
Section 4.4.2). The latter is unimportant as the MNA protocol implements Virtual Carrier Sense (V-CS) through its reservation protocol instead of the NAV specified in IEEE 802.11. Since this changes the structure of the IEEE 802.11 frame, the Frame Check Sequence (FCS) becomes invalid and needs to be recalculated. Consequently, a CRC follows at the end of the MPDU.

### 9.8.2 Cumulative and Selective Acknowledgments

Acknowledgments indicate the successful reception of a data frame. Since the MNA protocol prohibits TRX turnarounds within an MTXOP, immediate acknowledgements cannot be send. Instead, a receiving mesh STA must reserve an MTXOP in reverse direction to transmit its acknowledgments or piggyback it to data that is sent in reverse direction. Owing to the frame aggregation scheme of the MNA protocol, several acknowledgements may accumulate at a receiving mesh STA. To allow for flexible operation, the MNA protocol offers a cumulative and selective ACK. With the cumulative ACK a mesh STA indicates the sequence number of the next MSDU that it expects. All MSDUs up to the sequence number indicated have been successfully received.

The selective ACK is implemented by means of a bitmap. It contains the sequence number of the next MSDU that the mesh STA expects and indicates success or failure of reception of all MSDUs with sequence numbers smaller than the one indicated.

### 9.9 Simulation based analysis

To survey the performance of the MNA protocol the WARP2 simulation environment is used. The MNA protocol has been implemented in WARP2 by [324, 330, 331]. The simulation results are based on the author's IEEE 802.11s proposal presented in [157, 159, 160]. Unless stated otherwise, all simulation studies assume the following values:

- The attenuation factor Eq. 2.9 is $\gamma = 3.5$.
- Devices transmit at 20 dBm output power.
• Both, the CFP and CP are set to 32 TXOPs.
• Each Transmission Opportunity (TXOP) takes 256 µs.
• The maximum buffer size of a mesh STA is 256 kB.

9.9.1 Single transmitter, single receiver

The IEEE 802.11s Task Group (TG) intensively debated about the performance of collocated non-mesh (legacy) BSSs that have to coexist with WMN applying the MNA protocol. As a consequence of this discussion TGs asked for simulation results that consider limited usage of the CFP. Thus, in the scenario in Section 9.9.1 the superframe is assumed to be split evenly into CFP and CP. Mesh STA A transmits MSDUs of varying size to mesh STA B. Without any non-mesh STA present, the CP remains unused. Thus, frame transmissions occur during 50% of the time only. Fig. 9.32 presents the throughput achieved for all MCS available with IEEE 802.11a.

![Figure 9.31: A transmits to B using DRP.](image)

During the CFP the MNA protocol carries 23.1 Mb/s using the 64-QAM\(\frac{3}{4}\), 9.9 Mb/s using the 16-QAM\(\frac{1}{2}\), and 3.7 Mb/s using the BPSK\(\frac{3}{4}\) MCS with MSDUs of 1500 B size. Assuming that Block Acknowledgment mechanism (BA) is used and its buffer size is 64, Section 4.7 shows that a single IEEE 802.11e STA achieves a maximum throughput of 43 Mb/s using the 64-QAM\(\frac{3}{4}\), 20.6 Mb/s using the 16-QAM\(\frac{1}{2}\), and 8 Mb/s using the BPSK\(\frac{3}{4}\) MCS. In an MNA controlled WMN such client STAs are active during the CP only. According to the assumption of an equal duration of the CFP and CP, the MNA protocol is capable to carry the traffic that an associated IEEE 802.11e BSS generates. This reveals the remarkable efficiency of the MNA protocol since it uses the CFP not only for frame transmissions (MTP) but also for beacon frame transmissions (BP). With MSDU sizes smaller than 1500 B, the MNA protocol clearly carries more traffic than associated BSSs may generate, see Section 4.7. Furthermore, frame collisions, that are inevitable in a BSS, further reduce the achievable throughput of IEEE 802.11. Thus, the MNA protocol is well suited to serve attached BSSs and their associated STAs.
9.9 Simulation based analysis

![Figure 9.32: The MNA proposed protocol is active during the MTP (<50% of the time) only.]

9.9.2 AP backhaul with single building

The following scenario is presented in Fig. 8.2. The walls of the building are assumed to attenuate transmissions by 6 dB. Inside the building free space propagation is assumed. Thus, there is a total attenuation of

\[ A_{(\text{total})} = 2 \cdot 6 \text{dB} + A(\sqrt{2} \cdot 25 \text{m}) = 113 \text{dB} \]

between mesh STAs at opposite corners. APs transmit MSDUs of 80 B size to their associated STAs using DCF. They use MCS 64-QAM\(^{3/4}\) for frame delivery. Within the WMN QPSK\(^{3/4}\) is used. 50% of the superframe is assigned to the CFP and 50% to the CP.

During the CP APs always use the IEEE 802.11 DCF to transmit to their associated STAs. Fig. 9.33 and Fig. 9.34 compare the simulation results when mesh STAs also apply the IEEE 802.11 during the CFP and when mesh STAs apply the MNA protocol, respectively. Fig. 9.33a presents throughput versus offered traffic per route when all STAs apply the IEEE 802.11 protocol. The system carries a maximum traffic of 200 kb/s per route. Once the system saturates the traffic of routes with less hops (mesh STA 4 to STAs 2a, 2b, and 2c) dominates that of routes with more hops (mesh STA 4 to STAs 1a, 1b, and 1c). Fig. 9.33b presents the cumulative throughput versus the offered traffic per route when mesh STAs apply the MNA protocol. With the MNA protocol the system carries up to 400 kb/s per route, which is twice that of the IEEE 802.11 protocol. Under the present assumptions (\(\gamma = 3.5, 20 \text{ dBm transmit power, } d = 25 \text{ m}\)) APs 1 and 2 mutually receive
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Figure 9.33: Throughput without and with the MNA protocol applied.

throughput [kb/s]
offered traffic [kb/s]
Route 2c
Route 2b
Route 2a
Route 1c
Route 1b
Route 1a

(a) Throughput versus offered traffic per route. All STAs use the IEEE 802.11 protocol.

(b) Throughput versus offered traffic per route. During the CFP, mesh STAs apply the MNA protocol.

their transmissions at a level of -76 dBm. This exceeds the CCA threshold of -82 dBm for 20 MHz channels in the 5 GHz band. Consequently, the APs may sense the WM as busy and need to transmit sequentially to their associated STAs. Therefore, the IEEE 802.11 BSSs limit system throughput to 70% of the theoretical performance (3.4 Mb/s) of a fully synchronized system that was calculated in Eq. 8.3. Thus, the MNA protocol meets the expectations while the IEEE 802.11 BSSs form a bottleneck in this scenario.

Fig. 9.34a presents the CCDF of the end-to-end delay at 200 kb/s offered traffic per route. When all STAs apply the IEEE 802.11 protocol the system is saturated. MSDUs on both routes experience a small delay. Fig. 9.34b presents the CCDF of the end-to-end delay when mesh STAs apply the MNA protocol. Since mesh STAs forward MSDUs during the CFP only, the MNA protocol causes a larger delay than the IEEE 802.11 protocol.

Fig. 9.34c and Fig. 9.34d present the simulation results at 400 kb/s offered traffic per route. The CCDF of the end-to-end delay reveal that the MNA protocol is able even in a saturated system to limit the delay while the totally overloaded IEEE 802.11 gives preference to routes 2a-c on cost of routes 1a-c.

9.9.3 WMN as AP backhaul with string topology

For the remainder of this chapter, the default simulation setup values is modified as follows:

- IEEE 802.11 STAs use EDCA for medium access.
9.9 Simulation based analysis

(a) CCDF of the MSDU end-to-end delay at 200 kb/s offered traffic per route. All STAs use the IEEE 802.11 protocol.

(b) CCDF of the MSDU end-to-end delay at 200 kb/s offered traffic per route. Mesh STAs use the MNA protocol.

(c) CCDF of the MSDU end-to-end delay at 400 kb/s offered traffic per route. All STAs use the IEEE 802.11 protocol.

(d) CCDF of the MSDU end-to-end delay at 400 kb/s offered traffic per route. Mesh STAs use the MNA protocol.

Figure 9.34: Comparison of the CCDF of the MSDU delay without and with the MNA protocol applied.

- All STAs apply the EDCA default parameter set (see Section 4.5.3.4.1) of [265] except for the TXOP Limit that is set to 2048 µs (according to 64 slots of 32 µs duration).

- STAs support a BA buffer size of eight.

In Fig. 9.35 a single IEEE 802.11 STA connects with an AP that is collocated with a mesh STA. The mesh STA connects via two intermediary mesh STAs to a central Internet gateway. The IEEE 802.11 STA sends to and receives from its AP during the CP. All STAs use the QPSK1/2 MCS for transmission. Traffic is sent in up- and downlink direction. Route 1 denotes the downlink traffic. Route 2 denotes the uplink traffic.
Figure 9.35: An IEEE 802.11 STA associates with an AP that is collocated with a mesh STA. The mesh STA connects to a central Internet gateway.

The simulation results presented in Fig. 9.36 compare the performance when mesh STAs implement EDCA with mesh STAs implementing the MNA protocol. When all STAs implement EDCA they may be active any time during the superframe. When mesh STAs implement the MNA protocol they exchange frames during the CFP only. The CP is reserved for the BSS traffic then.

With MSDUs of 80 B size the EDCA (Access Category Best Effort (AC_BE)) enabled WMN carries 400 kb/s and the MNA protocol WMN carries 1 Mb/s, see Fig. 9.36a. Fig. 9.36b and Fig. 9.36c show that the MNA protocol carries roughly 3.2 Mb/s and EDCA AC_BE carries around 1.2 Mb/s for MSDUs of 512 B and 1500 B length. As presented in Fig. 9.36d, similar results can be achieved with the traffic source presented in Fig. 3.4 that generates MSDUs of different length between 80 B and 1500 B.

The performance advantage of the MNA protocol is remarkably, since in this WMN mesh STAs forward frames during the CFP (50% of the superframe) only. The scheduled medium access and the efficient spatial frequency reuse of the MNA protocol more than compensate for the limited transmission time. Since only immediately neighboring STAs are inside mutual sensing range, the EDCA enabled STAs start transmitting irrespective even of their neighbor STA receiving frames. Thus, their independent medium access causes frame collisions as presented in Fig. 8.3. In WMN that uses the MNA protocol, however, mesh STAs know about the neighbors’ frame exchange schedules and collisions can be avoided, therefore. Additionally the scheduled medium access of the MNA protocol enables concurrent transmissions that help to benefit from spatial frequency reuse, see Fig. 8.1. This further increases the performance of the WMN in contrast to EDCA based medium access.

Furthermore, the simulation results reveal that EDCA Access Category Voice (AC_VO) suffers from its aggressive EDCA parameter settings. With
9.9 Simulation based analysis

any MSDU size, this EDCA Access Category (AC) achieves at most 400\( \text{kb/s} \) in the WMN. Although a AC_VO backoff entity draws random numbers from [0, 7], this interval is too small even in this scenario where a STA has at most two neighbors. The consequence are frequent frame collisions in this scenario.

Fig. 9.37a presents the CCDF of the MSDU end-to-end delay when mesh STAs use EDCA AC_BE for frame forwarding. With 80 B MSDU size, the system hardly carries 300\( \text{kb/s} \) traffic offered in each direction. In contrast Fig. 9.37b presents the CCDF of the MSDU end-to-end delay when mesh STAs implement the MNA protocol. The end-to-end delay stays below 25 ms.
Chapter 9 – The Mesh Networks Alliance Proposal to IEEE 802.11s

0 20 40 60 80 100
10
−3
10
−2
10
−1
10
0
delay [ms]
probability (delay > x) (CCDF)
Route 1
Route 2
(a) Mesh STAs use EDCA with AC_BE for medium access.

(b) Mesh STAs use the MNA protocol for medium access.

Figure 9.37: CCDF of the MSDU end-to-end delay of EDCA and MNA in a string topology scenario. Offered traffic is 300 kb/s in each direction.

9.9.4 Multi frequency WMN backhaul in an open office building

Fig. 9.38 presents usage model six of [161] that is implemented in this scenario. Two Internet gateways at opposite sides of an office building connect with mesh STAs, each collocates with an AP. STAs located in office cubicles associate with the APs. The Internet gateways transmit MSDUs of 80 B size over two single-hop routes, four two-hop routes, and two three-hop routes to the STAs.

Figure 9.38: Office scenario as specified in the IEEE 802.11s usage models description.
Fig. 9.39 presents the simulation results when mesh STAs implement the MNA protocol. Mesh STAs implement the multi-frequency channel extensions to the MNA protocol described in Section 9.6. All STAs use the 64-QAM 3/4 MCS for frame transmissions. Fig. 9.39a, Fig. 9.39b, Fig. 9.39c, and Fig. 9.39d present the cumulative throughput versus the offered traffic with one, two, three, and eight frequency channels available. Throughput increases linearly from 2.4 Mb/s for a single frequency channel to 7.2 Mb/s for three frequency channels. With eight frequency channels, each route carries 1.7 Mb/s resulting in a total throughput of 13.6 Mb/s. Fig. 9.40 presents the throughput versus the frequency channels available under overload conditions. Up to four frequency channels, the system scales linearly.
Chapter 9 – *The Mesh Networks Alliance Proposal to IEEE 802.11s*

On the last hop, APs use EDCA to deliver the MSDUs to their associated STAs and therefore, the throughput per route is EDCA limited. According to Section 4.7, with MSDUs of 80 B size, standard EDCA parameters for AC_BE, 64-QAM\(^{3/4}\) MCS for data, and BPSK\(^{1/2}\) for control frames (ACK), the maximum throughput under EDCA is calculated as \(\sim 3.2 \text{ Mb/s}\). Under the same assumptions a TXOP Limit of 2048 \(\mu\)s is sufficient to fill the assumed BA buffer size of eight frames. A maximum throughput of \(\sim 5.4 \text{ Mb/s}\) is possible then. Since it is assumed that CFP and CP have equal duration, during the CP an AP may transmit a maximum of \(2.7 \text{ Mb/s}\). This approximately conforms with the findings for up to four different frequency channels resulting in a total of \(\sim 10 \text{ Mb/s}\).

With eight frequency channels in the present scenario, each AP may use one frequency channel exclusively for its BSS. In this case no interference can occur among the BSSs. Then, the system saturates at roughly \(15 \text{ Mb/s}\). With CPs that are active during 50% of the time, eight independent BSSs would be able to carry a total of \(\sim 20 \text{ Mb/s}\) traffic. However, the CFP used by the MNA enabled mesh network is too short to carry the total BSS traffic.

Fig. 9.41 presents the CCDF of the MSDU end-to-end delay that decreases with an increasing number of frequency channels. Fig. 9.41d reveals that ca. 50% of all frames on the one-hop route are transmitted immediately, because of the exclusive frequency channel that each AP uses in this case. Frame forwarding during the CFP appears to occur nearly...
9.9 Simulation based analysis

Figure 9.41: CCDF of the MSDU end-to-end delay. Offered traffic is 200 kb/s per route.

without access delay. Accordingly, frame transmission on the two- and three-hop routes experience almost similar delay.

9.9.5 Multi frequency WMN backhaul with multiple buildings

In the scenario presented in Fig. 9.42 all STAs transmit using the QPSK3/4 MCS. It is assumed that each wall adds 11 dB to the total path loss. STAs connect over one, two, and three hops with the Internet gateway in the middle. Up- and downlink are evaluated separately.

Fig. 9.43 presents the simulation results in a downlink scenario. In this scenario, the Internet gateway is the only source of traffic. Fig. 9.43a and Fig. 9.43b present the results when mesh STA use EDCA to forward MSDUs of 80 B and 1500 B size, respectively. With MSDUs of 80 B size the system
Figure 9.42: Eleven IEEE 802.11 STA associate with APs that connect to a mesh network. STAs transmit and receive frames over one, two, and three hops.

Table 9.5: Optimal number of TXOPs with different MSDU sizes and frequency channels.

<table>
<thead>
<tr>
<th>MSDU size</th>
<th>One</th>
<th>Three</th>
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<tbody>
<tr>
<td>MNA 80 B</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>1500 B</td>
<td>14</td>
<td>7</td>
</tr>
</tbody>
</table>

saturates when each route carries 100\text{ kb}/s. Each route carries up to 500\text{ kb}/s when the MSDU size is 1500 B.

When mesh STAs operate the MNA protocol, the CP has a duration as presented in Table 9.5. The duration of the CFP remains as before (32 TXOPs). Fig. 9.43c reveals that with MSDUs of 80 B size the MNA enabled WMN carries four times the traffic of an EDCA enabled network. With
Simulation based analysis

(a) Mesh STAs implement EDCA. MSDU size is 80 B.

(b) Mesh STAs implement EDCA. MSDU size is 1500 B.

(c) Mesh STAs implement the MNA protocol and operate on one frequency channel. MSDU size is 80 B.

(d) Mesh STAs implement the MNA protocol and operate on one frequency channel. MSDU size is 1500 B.

Figure 9.43: Cumulative downlink throughput as a function of traffic offered per route. Mesh STAs implement either EDCA or the MNA protocol.

MSDUs of 1500 B size the performance increase of the MNA protocol is less. In this case, each route carries 700 kb/s until the system saturates.

Fig. 9.44 provides the simulation results when the MNA enabled network operates in three different frequency channels. With MSDUs of 80 B size each route carries 500 kb/s, see Fig. 9.44a. Fig. 9.44b shows that the system saturates with MSDUs of 1500 B when each route carries 800 kb/s. Since the buildings in this scenario provide a high degree of shading, the MNA protocol is able to identify several opportunities for concurrent transmissions. Accordingly, additional frequency channels only help to improve the performance marginally.
Fig. 9.45 presents simulation results when STA transmit MSDUs to the central Internet gateway. While in the previous scenario there was a single source of traffic, there are eleven traffic sources in this scenario. Table 9.6 presents the settings that are applied for the CP duration when mesh STAs use the MNA protocol. With EDCA, each route carries 100 \( \text{kb/s} \) of traffic when the MSDUs size is 80 B, see Fig. 9.45a. With an increasing amount of traffic offered, the single hop route close to the central Internet gateway begins to starve all other routes. This behavior is similar when MSDU size is 1500 B. Then, the system saturates at 300 \( \text{kb/s} \) traffic per route, see Fig. 9.45b. This is less than in the Downlink (DL) scenario since in the Uplink (UL) scenario eleven independent traffic sources are competing on access to the WM. Their independent medium access leads to a higher degree of collisions.
Mesh STAs implement EDCA. MSDU size is 80 B.

Mesh STAs implement EDCA. MSDU size is 1500 B.

Mesh STAs implement the MNA protocol and operate on one frequency channel. MSDU size is 80 B.

Mesh STAs implement the MNA protocol and operate on one frequency channel. MSDU size is 1500 B.

Figure 9.45: Comparison of EDCA and MNA throughput versus offered traffic per route in an uplink scenario.

When mesh STAs implement the MNA protocol, the scheduled access increases throughput to 400 kb/s (Fig. 9.45c) and 700 kb/s (Fig. 9.45d) with MSDUs of 80 B and 1500 B size, respectively. Remarkably, with the MNA protocol saturation throughput is the same in the DL and UL case. This indicates that the MNA protocol identifies opportunities for concurrent transmissions independent of the direction of the traffic flow.

Similar to the downlink scenario, the MNA protocol benefits only marginally when three frequency channels are available. Fig. 9.46a presents the results when MSDU size is 80 B and Fig. 9.46b presents the results when MSDU size is 1500 B. Also with three frequency channels, the saturation throughput per route is exactly the same as for the DL scenario. Thus, the
Figure 9.46: Throughput versus offered traffic per route. Mesh STAs implement the MNA protocol and operate on three frequency channels.

Performance of the MNA protocol is independent of direction of the traffic flow.
The only new Medium Access Control (MAC) protocol finally included in the IEEE 802.11s standard bases on the Mesh Networks Alliance (MNA) protocol of the author as described in Chapter 9. This chapter outlines the evolution of the MNA protocol during the standardization process. Simulation results for the evolved optional MAC protocol of IEEE 802.11s are presented and compared with results for the basic MAC protocol Enhanced Distributed Channel Access (EDCA).

10.1 Introduction

On behalf of Philips, the author negotiated the inclusion of the concepts of the MNA protocol into the baseline document of IEEE 802.11s. As a consequence, the author’s inventions of the Distributed Reservation Protocol (DRP) and of the reservation information propagation now form an optional medium access protocol of standard IEEE 802.11s.

From January until November 2006, the two consortia Wi-Mesh Alliance (WiMA) and SEE-Mesh prepared six revisions of the IEEE 802.11s baseline document. They included the combined contributions of 38 companies. The latest revision [308] of the joint WiMA and SEE-Mesh proposal became the first draft [309] that was forwarded to a Working Group (WG) (letter) ballot.

The XO-1 laptop of the One Laptop Per Child (OLPC) project [350] includes the first publicly available implementation of this initial draft.
2010 two million of the so called $ 100 laptop have been shipped [351]. Measurement results of a testbed of twelve XOs can be found in [38]. Based on its experiences when developing the XO code, the engineering and consulting company Cozybit [352] initiated the open80211s project [353]. The latter introduces IEEE 802.11s capability to the Linux kernel. open80211s is an inherent part of the Linux code since the kernel’s revision 2.6.26 [354].

In July 2010, the IEEE 802.11s Task Group (TG) published the first draft [310] to be reviewed during an IEEE Standards Association (SA) sponsor ballot. Until July 2011, five recirculation sponsor ballots occurred. In September 2011, the final standard [306] was published.

### 10.2 MCF Coordinated Channel Access

Similar to the Hybrid Coordination Function (HCF) introduced with IEEE 802.11e [279], IEEE 802.11s defines the Mesh Coordination Function (MCF) that consists of EDCA and MCF coordinated channel access (MCCA)\(^1\). It is mandatory for an IEEE 802.11s compliant device to implement the EDCA. Distributed Coordination Function (DCF) and HCF Controlled Channel Access (HCCA), in contrast, must not be used in a Mesh Basic Service Set (MBSS). Implementation of the MCCA is optional. A mesh Station (STA) may use EDCA and MCCA concurrently. However, a device that uses MCCA adheres to certain transmission rules that may limit its EDCA usage.

MCCA has been derived from the MNA protocol. Compared to MNA, MCCA does not rely on the IEEE 802.11 Contention Free Period (CFP). However, MCCA borrows the concept of advanced medium reservation from the MNA protocol. With MCCA, the time between consecutive Delivery Traffic Indication Message (DTIM) beacon frames (Mesh DTIM interval) is divided into slots of 32\(\mu\)s length, see Fig. 10.1. Mesh STAs exchange management frames of type “action” to reserve the Wireless Medium (WM) for MCF coordinated channel access opportunities (MCCAOPs). The mesh STA that intends to set-up an MCCAOP, includes an MCCAOP Setup request Information Element (IE) in its action frame. The Setup request IE includes

- the MCCAOP reservation Identification (ID) (1 B length),
- the MCCAOP duration (1 B length),
- the MCCAOP periodicity (1 B length), and

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\(^1\) Prior to revision 3.0 [311] of IEEE 802.11s MCCA was termed Mesh Deterministic Access (MDA).
10.2 MCF Coordinated Channel Access

Figure 10.1: Two consecutive DTIM beacons form a Mesh DTIM interval. MCCA divides the interval in slots of 32 µs duration.

- the MCCAOP offset (3 B length).

Accordingly, an MCCAOP has a maximum duration of 4096 µs. The MCCAOP periodicity indicates the amount of subintervals during the Mesh DTIM interval. The MCCAOP offset defines the beginning of the MCCAOP relative to the start of the Mesh DTIM interval, see Fig. 10.2.

The mesh STA that receives the MCCAOP Setup request message checks the included IE. If the intended MCCAOP does not conflict with other MCCAOPs the receiver is involved in, or with MCCAOPs of neighboring mesh STAs it is aware of, the mesh STA may accept the MCCAOP Setup. From then on, both the MCCAOP initiator and the intended receiver inform their neighborhood about the MCCAOP Setup. Mesh STAs perform the MCCAOP advertisement with the help of management unicast (action) or broadcast (beacon) messages. In the TX-RX times report, a mesh STA includes

- all MCCAOPs it is involved in as receiver or transmitter,
- its own or expected neighboring beacon transmissions, and
- any other periods that are unavailable.

Furthermore, mesh STAs send an Interfering times report. The latter is a copy of a mesh STA’s neighbors’ TX-RX times report. Thus, the MCCAOP reservation information spreads out in the direct and indirect neighborhood. Thereby, MCCA avoids interference from stations outside the carrier sensing range. In addition, the information provided in the MCCAOP advertisement helps MCCA capable mesh STAs to identify unused time slots and to proactively arrange their MCCAOP schedules.

When a mesh STA has more MCCAOPs to report than what would fit into a single beacon or management frame, the mesh STA may send updates with subsequent frames. Furthermore, MCCA capable mesh STAs may request their neighbors reservation reports through individually addressed frames.
Figure 10.2: Besides non-periodic, single MCCAOP reservations, an MCCAOP setup may allow for periodic medium reservation. Here, the MCCAOP periodicity divides the Mesh DTIM interval into four subintervals. The MCCAOP offset defines the start time of each MCCAOP relative to the beginning of the subinterval.

At the beginning of an MCCAOP, the owner access the WM with highest priority. Therefore, MCCA introduces the concept of the Resource Allocation Vector (RAV) in addition to the physical and virtual Carrier Sense (CS) mechanism of IEEE 802.11 Section 4.5.2. An MCCA capable mesh STA sets the RAV at the beginning of each MCCAOP in its Interfering Times Report. Upon receipt of a frame from either the MCCAOP owner or responder, the mesh STA resets the RAV. From then on, physical and virtual CS mechanisms hinder neighboring mesh STAs from accessing the WM. For frames received from any other STA the mesh STA does not reset the RAV.

While all other devices perform a random backoff, the MCCAOP owner uses MCCA minimal values for Arbitration IFS Number (AIFSN), $CW_{min}$, and $CW_{max}$. If the WM is idle, these EDCA parameter values help the MCCAOP owner to grab the channel immediately. However, if the WM is busy due to non-MCCA capable devices that do not respect the reservation settings, the MDA Opportunity (MDAOP) owner needs to defer until the WM becomes idle again. Its MCCAOP is shortened then, since it cannot be extended beyond the original schedule as this would affect other mesh STAs’ schedules.

To consider concerns about excessive medium usage by MCCA capable mesh STAs, the Mesh wide MDA Access Fraction (MAF) threshold limits the maximum percentage capacity of the superframe occupied by the Mesh DTIM interval that each mesh STA may be using under MCCA operation for MCCAOPs as a receiver or transmitter. The lower the MAF, the more frame exchanges must use EDCA for medium access. If a mesh STA’s total duration of all MCCAOPs it is involved in exceeds the MAF, it cannot accept or set-up further MCCAOPs.
10.3 Simulation based analysis

The author compares the performance of IEEE 802.11s including its optional medium access protocol MCCA and the MNA concept proposed by him. The simulation results that were presented earlier in [30] assume the following settings:

- The path loss coefficient Eq. 2.9 is $\gamma = 3.5$.
- Devices transmit at 20 dBm output power.
- A Transmission Opportunity (TXOP) takes 256 $\mu$s.

To provide a worst-case assumption where the MAC overhead has the largest possible impact on system performance, each MAC Service Data Unit (MSDU) is assumed to have 80 B size. EDCA access parameters are set to IEEE 802.11 default parameters [265]. MNA is assumed to operate during the CFP that takes 50% of the superframe. MCCA is assumed to operate up to 67% of the superframe duration. During the Contention Period (CP), STAs and Access Points (APs) communicate by means of the EDCA protocol.

10.3.1 AP backhaul with single building

Fig. 10.3 provides a scenario where two STAs are separated by a building. It provides sufficient shadowing (100 dB) that separates both sides. The selected Modulation and Coding Scheme (MCS) allows for the transmission at 12 Mb/s data rate. While route 1 comprises three hops, route 2 consists of two hops. STAs 1 and 2 send uplink traffic to the gateway.

According to Fig. 10.4 the system capacity under EDCA is about 800 kb/s at 500 kb/s offered traffic. The highest EDCA priority achieves a little lower capacity than the best effort category due to its small contention window size. With an MAF of 67%, MCCA carries up to 0.7 Mb/s offered traffic per route where the system saturates with 1.3 Mb/s capacity. As the offered traffic increases, MCCA suffers more and more from the legacy STAs that do not respect MCCA reservations. Thus, the capacity drops. With MNA a system capacity of 2.5 Mb/s is achieved, however, the saturation traffic per route appears to be similar to MCCA at 700 kb/s, since the system throughput does not increase linearly beyond the offered traffic. From there on, some frames are lost and need to retransmitted twice or more.

Apparently, the main difference between the MNA and MCCA access protocols is that the system beyond saturation behaves very “cooperative”
Figure 10.3: On both sides of a building, APs provide network access to STAs. A WMN connects the APs with an Internet gateway.

Figure 10.4: System throughput versus offered traffic per route.
in the sense that most of the offered traffic is carried, until the saturation
offered traffic per route is reached $1.7\,\text{Mb}/\text{s}$ and a capacity of $2.6\,\text{Mb}/\text{s}$ is
achieved.

### 10.3.2 Multi frequency AP backhaul in the home

This scenario implements usage model two of [162], see Fig. 10.5. In a
residential environment, four IEEE 802.11 STAs associate with three differ-
ent APs. The STAs transmit frames to a central Internet gateway. The APs
collocate with mesh STAs that form a WMN. All STAs use the 64-Quadra-
ture Amplitude Modulation (QAM)$^{3/4}$ MCS for frame transmissions. Walls
are assumed to provide 10 dB and doors are assumed to provide 3.5 dB
attenuation.

As shown in Fig. 10.6 the system saturates at $350\,\text{kb}/\text{s}$ per route when
all STAs use either DCF or EDCA. With MCCA and an MAF of 45% each
route carries up to $400\,\text{kb}/\text{s}$. The MAF limits MCCA from achieving higher
throughput.

When mesh STAs use the MNA protocol it is assumed that the Mesh
Contention Free Period (MCFP) has a duration of 35 Mesh Transmission
Opportunities (MTXOPs) and the CP has a duration of 52 MTXOPs. In
this case, the system saturates at $500\,\text{kb}/\text{s}$ when operating on one or three
frequency channels. In contrast to the other protocols MNA has room to
carry more traffic. However, beyond the saturation point frames are lost.
As shown previously in Fig. 9.36a, a single mesh STA carries roughly two
streams of $500\,\text{kb}/\text{s}$ each with similar settings. Thus, the first hop of routes 3
and 4 forms the bottleneck in this scenario. As Fig. 10.6 indicates, a higher
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throughput would be possible but the DCF protocol that is used on the first hop from the STAs to the AP limits the system.

10.3.3 AP backhaul in office building

Fig. 10.7 depicts an office scenario. Walls are assumed to provide 13 dB of shadowing. A central gateway delivers frames to eight STAs via 2 and 3 hops, respectively. Considering the route arrangement, no hidden nodes are present in this scenario. When using MCS 64-QAM$^{3/4}$ (54 Mb/s) MCS, EDCA and MCCA show exactly the same system throughput vs. offered traffic results. With the MNA protocol, distinct transmission areas can be organized by the MAC protocol, enabling concurrent transmissions. The system capacity is close to 9 Mb/s at the saturation of the system (1.1 Mb/s offered traffic per route); see Fig. 10.8. Clearly the MNA protocol that was not accepted as an option to the standard is substantially better compared to both EDCA and MCCA that are contained in the standard.
10.3 Simulation based analysis

Figure 10.7: In an office environment, a central gateway delivers downlink traffic to the network.

Figure 10.8: System throughput versus offered traffic offered per route. The MNA protocol achieves four times as much throughput.
Conclusions

Current IEEE 802.11 products implement Distributed Coordination Function (DCF) or Enhanced Distributed Channel Access (EDCA) to access the Wireless Medium (WM). Both protocols rely on Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). However, the competition based medium access has limited efficiency. To increase efficiency this thesis introduces the Distributed Reservation Protocol (DRP). DRP has become the default medium access protocol of the Ultrawideband (UWB) Wireless Personal Area Network (WPAN) standard ISO/IEC 26907 and the 60 GHz WPAN standard ISO/IEC 13156. Stochastic, event-driven simulations reveal the performance advantage of DRP.

With IEEE 802.11s Wireless Local Area Networks (WLANs) emerge from a wireless single-hop to wireless multi-hop networks. However, the current medium access protocols in IEEE 802.11 are not well suited for multi-hop communication. With DCF or EDCA competition on accessing the WM occurs with every hop along the path of an MSDU’s source to its destination. Frame collisions reduce efficiency and the IEEE 802.11 Clear Channel Assessment (CCA) blocks neighboring Stations (STAs) from transmitting concurrently. To overcome these limitations, this thesis introduces the Mesh Networks Alliance (MNA) protocol that applies DRP in Wireless Mesh Networks (WMNs). To allow for spatial frequency reuse, the MNA protocol introduces a measurement scheme that allows for Signal to Interference plus Noise Ratio (SINR) estimation when multiple STAs transmit concurrently. Simulation results indicate that the MNA protocol outperforms EDCA in IEEE 802.11s scenarios. Due to its beacon period the MNA protocol introduces more overhead than EDCA. However, this is more than compensated for by MNA’s efficient usage of the WM. The increase in efficiency depends on the usage scenario. The more shadowing is provided by obstacles in a scenario, the more likely the MNA protocol detects and exploits spatial frequency reuse, thereby increasing system capacity. Furthermore, MNA allows for simultaneous operation in multiple frequency channels with a single radio. This helps to further increase performance.
In its original form, the MNA has not been accepted by IEEE 802.11s. However, the protocol builds the foundation of a compromise solution that was accepted as a Coordination Function (CF) in the final IEEE 802.11s standard. This solution is denoted as MCF coordinated channel access (MCCA) and provides a tradeoff between the MNA and the simpler EDCA protocol. Owing to the MCCA reservation scheme, contention among mesh STAs reduces. Furthermore, MCCA seamlessly coexists with legacy STAs. Compared to the MNA protocol MCCA has less strict requirements on synchronization and spatial frequency reuse is not possible, therefore. However, MCCA provides a valid compromise solution and clearly outperforms EDCA operation.

DRP has proven useful in different standards for WLAN and WPAN. To exploit the capacity of the WM new standards like IEEE 802.11ad [312] apply the DRP principle of distributed medium reservation and thereby overcome the limitations of random channel access.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>5C</td>
<td>Five Criteria</td>
</tr>
<tr>
<td>AC</td>
<td>Access Category</td>
</tr>
<tr>
<td>ACK</td>
<td>Acknowledgment</td>
</tr>
</tbody>
</table>
| AC_BE        | Access Category
Best Effort |
| AC_BK        | Access Category
Background |
| AC_VI        | Access Category
Video |
| AC_VO        | Access Category
Voice |
| ADDBA        | Add Block
Acknowledgment |
| AIFS         | Arbitration
Interframe Space |
| AIFSN        | Arbitration IFS
Number |
| AP           | Access Point |
| BA           | Block
Acknowledgment
mechanism |
| BlockAck     | Block
Acknowledgment |
| BlockAckReq  | Block
Acknowledgment
Request |
| BP           | Beacon Period |
| BPAP         | Beacon Period
Access Protocol |
| BPOIE        | Beacon Period
Occupancy
Information
Element |
| BPSK         | Binary Phase Shift
Keying |
| BS           | Base Station |
| BSS          | Basic Service Set |
| BSSID        | Basic Service Set
Identification |
| BT           | Bluetooth |
| BTS          | Beacon
Transmission Slot |
| CA           | Collision
Avoidance |
| CAP          | Controlled Access
Phase |
| CBR          | Constant Bit Rate |
| CCA          | Clear Channel
Assessment |
<table>
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<th>Abbreviation</th>
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<tbody>
<tr>
<td>CCDF</td>
<td>Complementary Cumulative Distribution Function</td>
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<td>CD</td>
<td>Collision Detection</td>
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<td>CE</td>
<td>Consumer Electronic</td>
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<td>CF</td>
<td>Coordination Function</td>
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<td>CFP</td>
<td>Call for Proposals</td>
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<td>CFP</td>
<td>Contention Free Period</td>
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<td>Channel Hop Sequence</td>
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<td>CRC</td>
<td>Cyclic Redundancy Check</td>
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<td>Carrier Sense</td>
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<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access / Collision Avoidance</td>
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<td>CTS</td>
<td>Clear To Send</td>
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<td>CW</td>
<td>Contention Window</td>
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<td>DA</td>
<td>Destination Address</td>
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<tr>
<td>DCF</td>
<td>Distributed Coordination Function</td>
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<tr>
<td>DCM</td>
<td>Dual Carrier Modulation</td>
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<td>DECT</td>
<td>Digital Enhanced Cordless Telecommunications</td>
</tr>
<tr>
<td>DevId</td>
<td>Device Identifier</td>
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<tr>
<td>DIFS</td>
<td>Distributed Coordination Function Interframe Space</td>
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<td>DL</td>
<td>Downlink</td>
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<td>Digital Living Network Alliance</td>
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<td>DLS</td>
<td>Direct-Link Setup</td>
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<tr>
<td>DRP</td>
<td>Distributed Reservation Protocol</td>
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<tr>
<td>DRPIE</td>
<td>DRP Information Element</td>
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<tr>
<td>DS</td>
<td>Direct Sequence</td>
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<td>DSM</td>
<td>Distribution System Medium</td>
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<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
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<td>DTIM</td>
<td>Delivery Traffic Indication Message</td>
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<td>Ecma International — European association for standardizing information and communication systems</td>
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<td>Enhanced Distributed Channel Access</td>
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<td>EIFS</td>
<td>Extended Interframe Space</td>
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<td>ESS</td>
<td>Extended Service Set</td>
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<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FCC</td>
<td>Federal Communication Commission</td>
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<td>FCS</td>
<td>Frame Check Sequence</td>
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<td>FEC</td>
<td>Forward Error Correction</td>
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<tr>
<td>FFI</td>
<td>Fixed Frequency Interleaving</td>
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<tr>
<td>FHSS</td>
<td>Frequency Hopping Spread Spectrum</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>HC</td>
<td>Hybrid Coordinator</td>
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<tr>
<td>HCCA</td>
<td>HCF Controlled Channel Access</td>
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<tr>
<td>HCF</td>
<td>Hybrid Coordination Function</td>
</tr>
<tr>
<td>HDMI</td>
<td>High Definition Multimedia Interface</td>
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<tr>
<td>HDTV</td>
<td>High Definition Television</td>
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<td>HiperLAN/2</td>
<td>High Performance Local Area Network 2</td>
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<td>HR</td>
<td>High Rate</td>
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<td>HT</td>
<td>High Throughput</td>
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<tr>
<td>IBSS</td>
<td>Independent Basic Service Set</td>
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<tr>
<td>ID</td>
<td>Identification</td>
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<tr>
<td>IE</td>
<td>Information Element</td>
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<tr>
<td>IEC</td>
<td>International Engineering Consortium</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>Description</td>
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<tr>
<td>IETF</td>
<td>Internet Engineering Task Force</td>
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<td>IFS</td>
<td>Interframe Space</td>
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<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<tr>
<td>LBT</td>
<td>Listen Before Talk</td>
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<td>LOS</td>
<td>Line Of Sight</td>
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<tr>
<td>LRC</td>
<td>Long Retry Count</td>
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<td>LRE</td>
<td>Limited Relative Error</td>
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<td>MAC</td>
<td>Medium Access Control</td>
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<td>MAF</td>
<td>MDA Access Fraction</td>
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<td>MANET</td>
<td>Mobile Ad-hoc Networks</td>
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<td>Medium Access Slot</td>
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<td>MBOA</td>
<td>Multiband OFDM Alliance</td>
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<tr>
<td>MBSS</td>
<td>Mesh Basic Service Set</td>
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<tr>
<td>MCCA</td>
<td>MCF coordinated channel access</td>
</tr>
<tr>
<td>MCCAOP</td>
<td>MCF coordinated channel access opportunity</td>
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<td>MCF</td>
<td>Mesh Coordination Function</td>
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<td>MCFP</td>
<td>Mesh Contention Free Period</td>
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<td>MCS</td>
<td>Modulation and Coding Scheme</td>
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<td>MDA</td>
<td>Mesh Deterministic Access</td>
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<td>MDAOP</td>
<td>MDA Opportunity</td>
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<tr>
<td>MIB</td>
<td>Management Information Base</td>
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<td>MIFS</td>
<td>Minimum Interframe Spacing</td>
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<td>MIMO</td>
<td>Multiple Input/Multiple Output</td>
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<td>MLME</td>
<td>MAC sublayer Management Entity</td>
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<td>MMPDU</td>
<td>MAC Management Protocol Data Unit</td>
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<td>MPDU</td>
<td>MAC Protocol Data Unit</td>
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<tr>
<td>MRD</td>
<td>Market Requirements Document</td>
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<td>MSB</td>
<td>Most Significant Bit</td>
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<td>Description</td>
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<td>MSDU</td>
<td>MAC Service Data Unit</td>
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<td>MTP</td>
<td>Mesh Traffic Period</td>
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<td>MTXOP</td>
<td>Mesh Transmission Opportunity</td>
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<td>NAV</td>
<td>Network Allocation Vector</td>
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<td>NesCom</td>
<td>New Standards Committee</td>
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<td>non-LOS</td>
<td>non Line Of Sight</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>OLPC</td>
<td>One Laptop Per Child</td>
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<td>OSI</td>
<td>Open System Interconnection</td>
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<td>P-CS</td>
<td>Physical Carrier Sense</td>
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<td>PAL</td>
<td>Protocol Adaptation Layer</td>
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<td>PAR</td>
<td>Project Authorization Request</td>
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<td>PCA</td>
<td>Prioritized Contention Access</td>
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<td>PCF</td>
<td>Point Coordination Function</td>
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<td>PC</td>
<td>Personal Computer</td>
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<td>PC</td>
<td>Point Coordinator</td>
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<td>PDA</td>
<td>Personal Digital Assistant</td>
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<td>PER</td>
<td>Packet Error Rate</td>
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<td>PHY</td>
<td>Physical Layer</td>
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<td>Point (Coordination Function) Interframe Space</td>
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<td>PLCP</td>
<td>Physical Layer Convergence Protocol</td>
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<td>Piconet Controller</td>
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<td>PS</td>
<td>Power Save</td>
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<td>PSDU</td>
<td>PLCP Service Data Unit</td>
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<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<td>Quality of Service</td>
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<td>QPSK</td>
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<td>QoS Station</td>
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<td>RA</td>
<td>Receiver Address</td>
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<td>RAV</td>
<td>Resource Allocation Vector</td>
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<td>RCPI</td>
<td>Received Channel Power Indicator</td>
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<td>RD</td>
<td>Reverse Direction</td>
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<td>RIFS</td>
<td>Reduced Interframe Space</td>
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## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
<th>Abbreviation</th>
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<tr>
<td>rt</td>
<td>real time</td>
<td>STA</td>
<td>Station</td>
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<td>RTS</td>
<td>Request To Send</td>
<td>TA</td>
<td>Transmitter Address</td>
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<td>RTS/CTS</td>
<td>Request To Send/Clear To Send</td>
<td>TBTT</td>
<td>Target Beacon Transmission Time</td>
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<td>SA</td>
<td>Source Address</td>
<td>TC</td>
<td>Traffic Category</td>
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<td>Standards Association</td>
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<td>Transmission Control Protocol</td>
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<td>Service Access Point</td>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<td>Specification and Description Language</td>
<td>TFC</td>
<td>Time-Frequency Code</td>
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<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
<td>TRX</td>
<td>Transceiver</td>
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<td>Signal to Interference Ratio</td>
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<td>Station Management Entity</td>
<td>TSPEC</td>
<td>Traffic Specification</td>
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<td>Signal to Noise Ratio</td>
<td>TVWS</td>
<td>TV white spaces</td>
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<td>SOHO</td>
<td>Small Office Home Office</td>
<td>TXOP</td>
<td>Transmission Opportunity</td>
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<td>Short Retry Count</td>
<td>UDA</td>
<td>Unused DRP reservation announcement</td>
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<td>Service Set Identifier</td>
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<td>UDR</td>
<td>Unused DRP reservation response</td>
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<td>UL</td>
<td>Uplink</td>
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<td>UP</td>
<td>User Priority</td>
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<td>US</td>
<td>United States</td>
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<td>USB</td>
<td>Universal Serial Bus</td>
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<td>UWB</td>
<td>Ultrawideband</td>
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<td>V-CS</td>
<td>Virtual Carrier Sense</td>
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<td>VoIP</td>
<td>Voice over IP</td>
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<td>W-CHAMB</td>
<td>Wireless Channel oriented Ad hoc mobile Broadband</td>
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<td>WARP2</td>
<td>Wireless Access Radio Protocol 2</td>
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<td>WFA</td>
<td>Wi-Fi Alliance</td>
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<td>Wireless Fidelity</td>
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<td>WiMA</td>
<td>Wi-Mesh Alliance</td>
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<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
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<td>WiMedia Alliance</td>
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<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<td>Wireless Medium</td>
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<td>Wireless Mesh Network</td>
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<td>WPAN</td>
<td>Wireless Personal Area Network</td>
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<td>WFA</td>
<td>Wireless USB</td>
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Draft Supplement to STANDARD FOR Information Technology — Telecommunications and Information Exchange Between Systems —


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Techreports


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**Ph.D. Theses**


Diploma and Masters Theses


Networks, Faculty 6, RWTH Aachen University, Germany, Jul. 2005, Supervisor: G. R. Hiertz, Y. Zang, and L. Stibor.


---

**Miscellaneous**


Bibliography
From 2002 to 2009 I had the honor to be a member of the research and teaching staff at ComNets Aachen, the Department of Communication Networks at RWTH Aachen University. ComNets Aachen is led by Prof. Dr.-Ing. Bernhard Walke and my doctoral work was under his guidance. My utmost gratitude goes to him for his thorough reviews, feedback, and advice to this thesis as well as his trust in my work and me. Prof. Walke provided me with a remarkable freedom in research, allowed me from the very beginning to engage into an incredibly successful cooperation with Philips Research, and offered me the outstanding opportunity to be part of eight challenging research projects at ComNets Aachen. I very much appreciate to have learned from his research expertise and I am extremely grateful for his suggestions to my work. Furthermore I thank Prof. Walke for the scientific supervision and the consistent encouragement that I received over the many years.

As head of ComNets Bremen, the Department of Communication Networks of University Bremen, Prof. Dr. rer. nat. Camelita Görg supported my research activities in ComNets Aachen’s and ComNets Bremen’s joined research projects CoCoNet I – III. I sincerely thanks her for her guidance during these years and her careful review of this thesis as second examiner.

My sincere appreciation goes to Philips Research Aachen and Philips Research Eindhoven with whom I cooperated in research and standardization from 2001 to 2011. Philips provided me with the unique opportunity to represent this truly global player in IEEE 802.11s, IEEE 802.15.5, the Wi-Fi Alliance, and the WiMedia Alliance. I am deeply grateful to Dee Denteneer for supporting my activities in the process of standardizing IEEE 802.11s and for being allowed to serve as vice chairman to the latter. I especially thank Dee Denteneer for his personal advise, fruitful discussions, and deep personal friendship. Furthermore, I would like to thank the Philips members Hans-Jürgen Reumerman, Jörg Habetha, Maurice Draijer, and Ruud van Bockhorst for their friendly support and assistance. They always made me feel part of the fantastic Philips research community.

Furthermore I thank all IEEE members that serve in the IEEE 802.11 and IEEE 802.15 working group. I am delighted that I was allowed to be part of this fine community. Working there provided me with invaluable
Acknowledgment

experiences and the confidence that good standards truly have an impact on our daily life. Among so many, I especially highlight Osama Aboul-Magd, Michael Bahr, Javier Cardona, Dan Harkins, Jarkko Kneckt, Kazuyuki Sakoda, and Juan Carlos Zúñiga for trustful and intense cooperation.

I very much enjoyed working with Bahman Badali, Rajesh Bagul, Dirk Eisold, Markus Frewel, Bing Han, Bancha Hiransri, Daniel Kuppe, Kamil Kurowski, Raffaele Leone, Hong Ma, Vladimir Marchenko, Maciej Mühlleisen, Harald Radke, Holger Rosier, Nima Shambayati, Hamza Şirin, Zheng Xie, Mengrong Yu, and Mehmet Göksel Zeybek who served either as student assistant or developed their student, master’s, or diploma theses under the supervision of the author. In particular I highly appreciate working with the diploma thesis students Thomas Junge, Sebastian Max, and Lothar Stibor who provided outstanding ideas, inspiration, and contributions to this thesis.

A special word of appreciation goes to my colleagues in the team of system and network administrators at ComNets. I always enjoyed being part of an enthusiastic group that constantly aimed at developing sophisticated solutions enhancing our IT environment, computing cluster, and simulation framework.

ComNets would not have been a beacon within the wireless networking research landscape without its fantastic employees. The wide variety of research fields and the passionate research members have been a reliable source of motivation. I especially thank my research fellows Lars Berlemann, Daniel Bültmann, Ingo Forkel, Stefan Göbbels, Ian Herwono, Christian Hoymann, Tim Irnich, Ralf Jennen, Andreas Kemper, Karsten Klagges, Ole Klein, Dirk Kuypers, Matthias Malkowski, Sebastian Max, Maciej Mühlleisen, Georgios Orfanos, Arif Otyakmaz, Ralf Pabst, Holger Rosier, Klaus Sambale, Marc Schinnenburg, Matthias Siebert, Peter Sievering, Lothar Stibor, Zheng Xie, and Rui Zhao for enlightening debates and unforgettable collegiality.

I am very grateful to my former colleague Stefan Mangold for supervising my diploma thesis and recommending me to Prof. Walke. In addition I thank Stefan for his friendship and for handing me over the simulation tool WARP2 that I enhanced and extended to develop this thesis.

While doctoral candidates have a limited timeframe for their studies at ComNets, I am very thankful to ComNets’ permanent staff. Especially Norbert Konkol, Doro Pawelzick, Heinz Rochhausen, Anne Schröder, Rosalia Söhnen, and Karin von Czapiewski carried the department’s wonderful spirit over so many years.

Since 2003 I have the honor of collaborating with Yunpeng Zang. Yunpeng is a fantastic discussion partner and a remarkable source of expe-
rience and knowledge. Without his inspiration and support many joint patent applications and papers would not have been possible. Therefore, I am especially pleased that we continue to be colleagues in our new position after ComNets.

My deep appreciation goes to Dr. Alfred Kuhlmann for recommending me for scholarship of the Benedikt und Helene Schmittmann-Wahlen foundation.

Last but not the least, I like to deeply thank my friends and family. This thesis would not exist without my parent's loving support and their sponsorship of my initial academic degree. Special thanks go to my sister Regina and my brother Martin for being there whenever I needed them. During all these years Markus Grade, Matthias Bäcker, Thomas Boosmann, Bernd Reichenberg, and Yunpeng Zang have proven to provide true and reliable friendship. Above all, I sincerely thank my wife Sonja for her continuous support, great patience, never ending love, and for being the center of our family. Without her, this thesis would not have become reality.
Acknowledgment