Coexistence and Interworking of IEEE 802.16 and IEEE 802.11(e)

[1]Lars Berlemann, [1]Christian Hoymann, [1]Guido R. Hiertz, [2]Stefan Mangold
[1]Chair of Communication Networks, Faculty 6, RWTH Aachen University, Germany
{ber|hoy|grh}@comnets.rwth-aachen.de
[2]Swisscom Innovations, Berne, Switzerland
stefan.mangold@swisscom.com

***Abstract*— The coexistence and interworking of IEEE 802.16 and IEEE 802.11 is an acute problem. The frame-based medium access of 802.16 requires rigorous protection against interference from wireless local area networks in order to operate properly. The 802.11e enhancements of the medium access control of 802.11 introduce the capability to support QoS. These enhancements define a central entity as main element: The Hybrid Coordinator. It realizes a contention free, centrally controlled medium access and introduces QoS limitations to the contention based access of 802.11e. In this paper, a central coordinating device combines the central base station of 802.16 with the hybrid coordinator of 802.11e and is thus referred to as Base Station Hybrid Coordinator. The Base Station Hybrid Coordinator is capable to operate in an 802.16 and an 802.11(e) protocol mode in the same frequency band. The realization of the interworking between these two standards is discussed and evaluated in this paper.**

***Keywords*— Base Station Hybrid Coordinator, Coexistence and Interworking; IEEE 802.16; IEEE 802.11(e).**

I. Introduction

Wireless Metropolitan Area Networks (WMANs) of the IEEE 802.16 [1] standard are an upcoming competitor for conventional wired last mile access systems. 802.16 realizes a fixed point-to-multipoint wireless broadband access system. Especially in rural areas, where it is too expensive to deploy fixed networks due to marginal density of population, 802.16 is a promising alternative. Various scenarios will arise, where 802.16 might have to share spectrum with already deployed and operating *Wireless Local Area Networks* (WLANs) of 802.11 like in office or residential deployment scenarios. The U-NII frequency band at 5 GHz is one example for spectrum which might be shared between 802.16 and 802.11. Additionally, 802.16 will be deployed to provide a multi-hop, relay-based wireless backhaul serving 802.11 WLAN hotspots. Multi-mode relays supporting the operation of an 802.16 mode and an 802.11 mode can take advantage from an interworking capability between both standards.

Wireless networks are able to coexist [2], i.e., operate at the same time and location without harmful interference in using Dynamic Frequency Selection and Transmit Power Control. More complex strategies are required, when *Quality-of-Service* (QoS) support is demanded: Successful, deterministic control of access to the radio resource is necessary for all coexisting wireless systems in order to guarantee QoS. The information exchange between spectrum sharing networks enables an interworking but is not required for coexistence. Approaches without information exchange based on the observation of spectrum utilization are discussed in [3, 4]. With interworking, wireless networks are able to coordinate spectrum usage among each other. In order to exchange information, spectrum sharing networks require a common frame structure allowing full control of medium access as discussed in this paper. The enhancements of 802.11e [5] introduce the capability to support QoS to the *Medium Access Control* (MAC) of 802.11. It will be shown that theses extensions simplify the interworking with 802.16, but they are not necessarily required. If not stated different, we will concentrate in the following on 802.11e.

In Section II, this paper provides a short overview on IEEE 802.16. Details can be found for instance in [6]. An interworking concept for integrating the MAC protocol of 802.11 into 802.16 is discussed in Section III. One single communication device, capable of operating in both standards, realizes a centrally organized coordination and interworking between 802.16 and 802.11 when operating at the same frequency channel. An evaluation of this concept is done in Section IV and the paper is concluded in Section IV.

II. IEEE 802.16

IEEE 802.16 [1] is a radio standard for WMANs operating in the frequencies between 2 and 11 GHz often referred to as WiMAX. It specifies four different *PHYsical layers* (PHYs), while in this paper the OFDM layer is considered only. IEEE 802.16 has a centralized architecture provided by a central *Base Station* (BS) with associated *Subscriber Stations* (SS). Typically, a BS is connected either directly or via additional BSs to the core network. 802.16 offers therefore an optional mesh deployment that introduces multi-hop connections via relaying BSs. With its centrally controlled, frame based MAC approach 802.16 offers guaranteed multimedia QoS. 802.16 supports non line-of-sight operation and large coverage areas, which enables a rapidly deployable infrastructure.

The MAC frame structure of IEEE 802.16 allows a variable frame duration of 2.5 to 20 ms. The frame structure of the OFDM PHY layer operating in *Time Division Duplex* (TDD) mode is illustrated in Figure 1. Each frame consists of a *Downlink* (DL) subframe always followed by an *Uplink* (UL) subframe. The DL subframe starts with a long preamble used for synchronization followed by the *Frame Control Header* (FCH). The DL subframe consists of one or multiple DL bursts containing MAC *Packet Data Units* (PDUs) scheduled for DL transmission. The UL subframe starts with contention intervals scheduled for initial

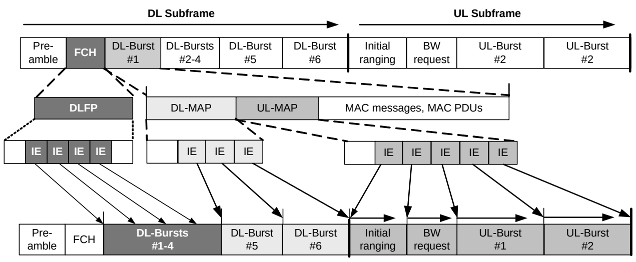


Figure 1: IEEE 802.16 references of MAC management messages for composition of the MAC frame [6].

ranging and bandwidth request purposes. Thereafter, one or multiple UL-bursts follow, each transmitted from a different SS. An UL-burst is initiated with a short preamble and contains one or several MAC PDUs. DL and UL subframe are separated by the *Receive/transmit Transition Gap* (RTG) and the *Transmit/receive Transition Gap* (TTG).

An (optional) extension of the DL-MAP with the duration of a burst enables the BS to flexibly arrange concurrent DL bursts. The knowledge of start time and the duration overcomes the restriction of the sequential nature of bursts. A *Space Division Multiple Access* operation of IEEE 802.16 benefits from this [7]. For a description and detailed evaluation of 802.16 with the help of a stochastic event-driven simulator see [6, 8].

III. INTERWORKING CONTROL OF 802.16 AND 802.11(E)

The integration of 802.11 into 802.16 is described in this section. It aims at the realization of an interworking between these two standards. A common framework is introduced, that allows the operation of 802.11 and 802.16 at the same frequency. The protocols of 802.16 and 802.11 have fundamental differences in their MAC layers: While 802.16 has a frame-based, centrally coordinated MAC protocol, 802.11 allows distributed control and a contention-based medium access. In addition, 802.11 also realizes a contention free, centrally controlled access to the channel. 802.16 and 802.11 have a similar OFDM-based transmission scheme and channelization which facilitates their interworking.

In taking the requirements of 802.16 into account, the concept described in the following realizes a centrally coordinating device. The integration of 802.16 and 802.11 implies the interworking between similar and different types of devices in a common protocol. The central coordinating device combines the central BS of 802.16 with the *Hybrid Coordinator* (HC) of 802.11e (or the *Point Coordination Function* (PCF) of 802.11) and is thus referred to as *Base Station Hybrid Coordinator* (BSHC). The BSHC is capable to operate in both, an 802.16 and an 802.11 mode. The interworking is based on an integration of 802.11 transmission sequences into the MAC frame structure of 802.16. Additionally, an optional period for contention-based access may be placed between two consecutive 802.16 MAC frames. The BSHC comprises an 802.16 as well as an 802.11 physical layer. From the perspective of an 802.16 SS, the BSHC is a normal BS, while *QoS supporting 802.11e Stations* (QSTAs) regard the same BSHC as an ordinary HC.

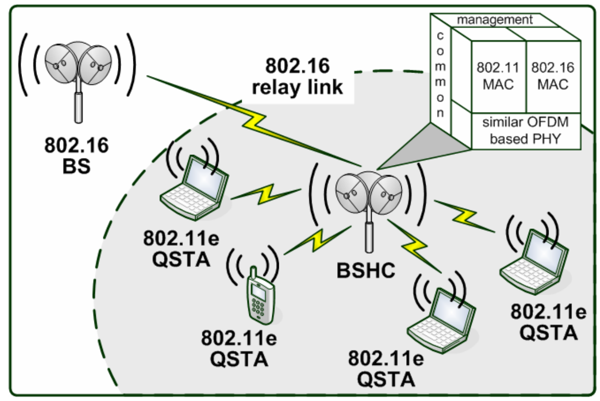


Figure 2: Interworking scenario of a BSHC serving 802.11e QSTAs via an 802.16 relay link on a common frequency channel. The BSHC supports a parallel operation of both standards.

A. Scenario

The interworking scenario considered in this section is illustrated in Figure 2. One BSHC and controlled stations of 802.11e are depicted. The BSHC is connected for broadband access via a multi-hop, relaying link to an 802.16 BS. Allocated time intervals are regarded by the 802.16 SSs as DL/UL burst and by the 802.11e stations as *Transmission Opportunity* (TXOP) corresponding to the 802.11e protocol.

In the interworking scenario of Figure 2, the BSHC provides broadband access to QSTAs and SS. The service provisioning to SSs is left away in the evaluation scenario of Section IV although communication among the stations of the different standards is also enabled via the BSHC device. In case of a communication between an 802.11(e) and 802.16 stations, the BSHC receives the data within a TXOP from the 802.11(e) station and forwards it in the following 802.16 MAC frame to the 802.16 station and vice versa. The protocol stack of the BSHC combines the different MAC protocols of 802.16 and 802.11(e). It is illustrated in the right upper corner of Figure 2. This multi-mode protocol stack is a simple example for applying the multi-mode protocol reference architecture introduced in [9]. The 802.16/802.11 specific MAC layers have similar OFDM-based PHYs. These PHYs are not able to decode the radio transmission of each other but can be realized out of common functional modules, parameterized differently according to the respective standard.

B. Medium Access Control

In order to coordinate the networks of 802.16 and 802.11, the BSHC operates at one single frequency and has control over all 802.16 SSs and 802.11 STAs. The full control of the BSHC over the channel is required to support QoS. This control is guaranteed in frequently assigning radio resources with predefined durations to the SSs and STAs. Comparable to the polling of stations in 802.11e, the STAs/SSs decide on their own which data to transmit, when they get a resource allocation period assigned from the BSHC. The proposed MAC frame structure of the BSHC is depicted in Figure 3 and Figure 4. The transmissions related to 802.16 are filled white, while the 802.11 transmissions

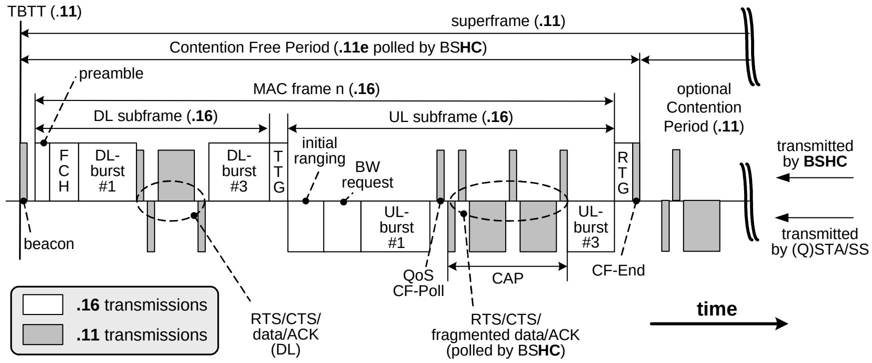


Figure 3: The structure of the BSHC superframe. One 802.11 superframe consists of a contention free period (here) and contention period (Figure 4). The contention free period is regarded by 802.16 as MAC frame. 802.11e TXOPs are scheduled in the DL and UL bursts of 802.16.

are marked grey. The transmissions of the BSHC are depicted above the time line. The stations' transmissions are below the time line.

1) Contention Free Access

An 802.16 MAC frame may not be interfered nor delayed by legacy, non-802.11e, but plain 802.11 stations. Contrary to 802.11, the MAC protocol of 802.16 offers no mechanisms to deal with such delays. The MAC-frame is protected therefore in the BSHC concept against interference from 802.11 STAs in declaring it to a *Contention Free Period* (CFP): The CFP starts with the beacon transmission and ends with a *CF-End* in surrounding the 802.16 MAC frame, as illustrated in Figure 3.

The 802.11 STAs see a superframe bordered through beacons at the *Target Beacon Transmission Time* (TBTT), consisting of the CFP and a here optional *Contention Period* (CP). Information elements in the beacon announce the superframe duration and whether the CFP starts directly after the beacon. Further the *Transmission Opportunity Limit* (*TXOPlimit*) and additional *Enhanced Distributed Coordination Function* (EDCA) parameters are broadcasted by the BSHC via the beacon to control the EDCA's contention-based access. The preamble and FCH are used analogous for 802.16. The 802.11(e) part of the interworking concept in centralized operation is based on the *Hybrid Coordination Function Controlled Channel Access* (HCCA). The BSHC may schedule 802.11e transmissions in the DL/UL in using a DL/UL-burst of the 802.16 DL/UL-subframe. The BSHC may schedule TXOPs in polling associated QSTAs for UL data transmission or may immediately initiate own DL transmissions. This is illustrated in Figure 3 for the DL-burst #2 which is replaced here through an 802.11e DL transmission by the BSHC protected through RTS/CTS. In order to define the DL-burst adequately when composing the 802.16 subframe in the preceding FCH, it is necessary to determine how long the RTS/CTS/data/ACK sequence will take. The 802.16 SSs will fail to decode the 802.11 data transmission. In addressing the DL-burst of 802.11 not to the associated 802.16 SSs, these SSs do not try to encode this burst and a misinterpretation is prevented. The duration of a polled 802.11e TXOP for UL data transmission has to be controlled by the BSHC. A TXOP has a predefined duration and is referred to as CAPs corresponding to the 802.11e access within the CFP. The duration of the CAP is limited through the 802.16 burst duration which is nevertheless under the control of the BSHC. The CAP is polled by the BSHC through *QoS CF-Poll* and its duration may differ from an EDCA TXOP*:* The *QoS CF-Poll* allows setting an individual maximum transmission size.

The polling of 802.11 STAs with the help of *QoS CF-Poll* is illustrated in Figure 3: The UL-burst #2 is replaced with an 802.11 frame transmission sequence of *QoS CF-Poll*/RTS/CTS/data/ACK. Such a data transmission on the UL is regarded by the 802.16 SSs as an UL-burst. Within the CAP the polled 802.11 STAs decide themselves which data to transmit. A RTG is required in case the BSHC switches between reception and transmission. This also refers to the reception of 802.16 UL-bursts and the transmission of *QoS CF-Poll* of 802.11e, as also depicted in Figure 3. The 802.16 UL/DL bursts may be used in the opposite direction for 802.11 data transmission (for instance a polled UL transmission in the DL burst) in order to meet restrictive QoS requirements of applications supported by 802.11. The RTGs and TTGs required for switch between reception and transmission when changing the operation between 802.11 and 802.16 and the other way around are not shown in Figure 3.

2) Limited Contention-based Access

From the perspective of the 802.16 SSs, an 802.16 MAC frame is transmitted periodically with a certain period of time between two consecutive MAC frames, not available for usage by 802.16. The CP depicted in Figure 4 continues the superframe started in Figure 3 with the CFP. After the *CF-end* frame, the CP begins. The CP is designated for access of 802.11. Here, the main problem with the contention-based access is that the 802.16 transmissions may not be delayed. The BSHC therefore has to guarantee, that no 802.11 transmission is ongoing, when an 802.16 transmission is intended to be transmitted. Such a protection is enabled with the means of 802.11e but is almost impossible within 802.11.

The BSHC schedules in advance the time instances where 802.16 MAC frames require access to the wireless medium. In order to protect the timely transmission of the 802.11 beacon and 802.16 preamble/FCH broadcasts the BSHC must allocate the channel when a CP transmission

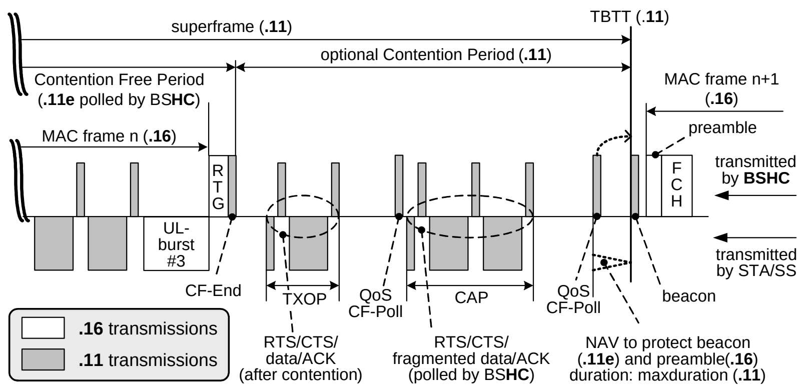


Figure 4: The structure of the BSHC superframe. One 802.11 superframe consists of a contention free period (Figure 3) and contention period (here). The 802.16 is protected against potential interference and delay from contention-based access.

has ended and the next 802.16 allocation is closer than the maximum possible duration of an 802.11 legacy transmission. With an 802.11a PHY, a station may continuously transmit up to 2 ms. Contrary, the QSTAs respect the TBTT and stop TXOP independent from the intended transmission duration. This usage of *QoS CF-Poll* is depicted at the end of the CP in Figure 4. A *QoS CF-Poll* can be used by the BSHC to allocate TXOPs within the CP with high priority (after PIFS idle time). The BSHC can initiate in this way in the CP a frame exchange directly after PIFS with or without RTS/CTS. The STAs may gain control of the channel after contention corresponding to the EDCA and are allowed to transmit with a maximum duration of *TXOPlimit*. Alternatively, *QoS CF-Poll* or CTS transmitted to the BSHC itself can be used to transmit 802.16 MAC frames within the CP in a protected way.

C. BSHC and Legacy 802.11

The mechanisms of 802.11e for the support of QoS are more adequate for an interworking with 802.16 than the ones of 802.11, as the contention-based access needs a well-defined limitation as discussed above. Therefore, the BSHC concept allows the operation of the contention-based medium access as long as the 802.11 stations use the EDCA and not the DCF. The EDCA limits the duration of an allocation and thus can easily be coordinated by the BSHC. Legacy 802.11 stations would violate the *TXOPlimit* leading to fatal interference of the 802.16 MAC frames. 802.11 STAs respect the CFP corresponding to the legacy PCF. Nevertheless they do not respect the TBTT as today's devices can not be polled.

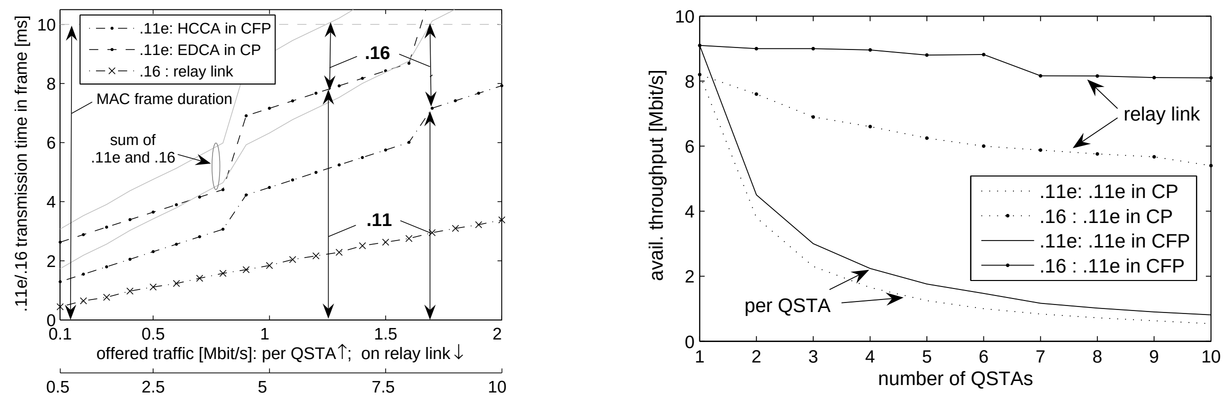
Mangold [10] suggests therefore not to allow legacy 802.11 stations to associate with the BSHC. Furthermore, an exploitation of the *Extended Interframe Space* (EIFS) is proposed that is originally designated for operation under hidden station interference. It allows the BSHC to force legacy 802.11 STAs to defer from medium access for a long time with the duration of EIFS. An incorrect *Frame Check Sequence* (FCS), as part of every 802.11 transmission, indicates an unsuccessful reception. The BHSC can take advantage of this in using identical preambles and headers but different FCSs or PHY modes for the rest of the frame. Legacy STAs that detect such frames from the BSHC will operate with EIFS instead of DIFS. The frequent transmission of preambles and PLCP headers during EIFS duration manipulates the backoff mechanism in resetting the timer in the legacy STAs back to EIFS.

IV. Evaluation

In this section an evaluation of the interworking between 802.11e and 802.16 corresponding to the relaying scenario of Figure 2 is presented. A BSHC is connected via an 802.16 relay link to the core network while serving 802.11e QSTAs on the same frequency channel. The introduced results take the MAC and PHY overhead of the respective protocols into account and define in this way a theoretical limit. The system parameters used in our evaluation are summarized in Table 1 and the results are depicted in Figure 5. Two scenarios are considered: The TXOPs of 802.11e are either allocated with the help of the HCCA in the CFP embedded between the UL/DL bursts of 802.16 or are transmitted with the EDCA in a dedicated CP. The optimal

Table 1: System parameters used for evaluating the interworking scenario from Figure 2 with one IEEE 802.16 relay link and IEEE 802.11e based communication between BSHC and QSTAs

common system parameters			
MAC-frame duration: 10 ms	packet size: 512 Byte	MCS: 16 QAM ½	DL/UL ratio: 50/50
channel bandwidth: 20 MHz	all QSTAs have same traffic loads		
IEEE 802.16		**IEEE 802.11e**	
FCH with one IE for DL burst	UL MAP with one IE for UL burst	802.11a PHY parameters	EDCA in CP: AC_VI
CRC-32 enabled	fragmentation disabled	no RTS/CTS	CWmax = 15
114.58 µs for BW req slots	68.75 µs for ranging slot	with WEP	CWmin = 7
cyclic prefix = 1/32	TTG = RTG = 22.9 µs	retry count: 7	AIFSN = 2
		with Address 4	



(a) frame usage of 802.11e and 802.16 in scenacrio of five 802.11e QSTAs served by one 802.16 relay link

(b) throughput of the 802.16 relay link and for one 802.11e QSTA when each QSTA gets the same throughput

Figure 5: Performance evaluation of interworking between 802.11e/802.16 in scenario of Figure 2. Optimal partitioning of MAC frame between 802.11e/802.16 according to (a) is used in (b) to determine the maximum available throughput per QSTA and on the relay link.

partitioning of the MAC frame between 802.11e and 802.16 is illustrated in Figure 5a. The utilization of a 10 ms MAC frame depending on the offered traffic per QSTA is shown. A scenario of five QSTAs with equal offered traffic loads is evaluated. The relay link of 802.16 carries the traffic of all QSTAs and has therefore five times the offered throughput of one QSTA. The in total required time for transmitting the offered traffic in 802.11e is compared with the transmission time of 802.16. This indicates the lower efficiency of the 802.11e MAC protocol for the analyzed packet data size of 512 Byte. Due to the nature of its distributed medium access the same modulation scheme requires twice the time for transmission of the same amount of user data. The time needed when using the EDCA in the CP is determined with a Markov model of the backoff procedure from [10]. The steps in the 802.11e graphs results from the packet data size limitation: A new polling or RTS/CTS is required in UL and DL direction. The sum of 802.11e's and 802.16's transmission times leads to a maximum value for the system throughput and implies an optimal partitioning of the MAC frame between 802.11e and 802.16 as indicated in Figure 5a.

The maximal available throughput and the optimal partitioning of the MAC frame depend on the number of QSTAs served by the BSHC as shown in Figure 5b. Scenarios similar to Figure 5a with a varied number of QSTAs are summarized and an optimal partitioning is assumed. The throughput of the 802.16 relay link and the available throughput of each QSTA are illustrated. With increasing number of QSTAs decreases the overall system capacity as indicated through the relay link throughput. The contention in the CP increases essentially and thus 802.11e's portion of the MAC frame has to be increased. In the CFP, the increasing MAC overhead for transmitting to multiple QSTAs increases the relative fraction at the MAC frame.

V. Conclusion

The introduced concept allows an interworking between 802.11(e) and 802.16 when these wireless networks operate at the same frequency. It solves the coexistence problem of 802.16 and 802.11. The introduced relay-based deployment of 802.16 as wireless backhaul and 802.11(e) for providing wireless access benefits from the BSHC approach. Nevertheless, the proposed interworking concept requires full control over the radio resource which includes all co-located 802.11(e) and 802.16 wireless networks. It has been shown that interworking influences the medium access of all spectrum sharing wireless networks. Restrictions and requirements of each protocol have to be combined to enable QoS support under coexistence. The adherence of a common frame structure can be regarded as extreme cooperation.

References

[1] IEEE Std 802.16-2004, New York, USA, October 2004.

[2] S. Mangold, J. Habetha, S. Choi, and C. Ngo, "Coexistence and Interworking of IEEE 802.11a and ETSI BRAN HiperLAN/2 in Multi Hop Scenarios," in Proc. of *IEEE 3rd Workshop in Wireless Local Area Networks*, Boston, USA, 27-28 September 2001.

[3] L. Berlemann, S. Mangold, G. R. Hiertz, and B. Walke, "Radio Resource Sharing Games: Enabling QoS Support in Unlicensed Bands," *IEEE Network*,, vol. 19, no. 4, pp. 59-65, July/August 2005.

[4] L. Berlemann, S. Mangold, G. R. Hiertz, and B. H. Walke, "Spectrum Load Smoothing for Cognitive Medium Access in Open Spectrum," in Proc. of *PIMRC 2005*, Berlin, Germany, 11-14 September 2005.

[5] IEEE 802.11e/ D13.0, New York, USA, January 2005.

[6] C. Hoymann, "Analysis and Performance Evaluation of the OFDM-based Metropolitan Area Network IEEE 802.16," *Computer Networks*, vol. 49, no. 3, pp. 341-363, 19 October 2005.

[7] C. Hoymann, A. Ibing, and I. Forkel, "MAC Layer Concepts to Support Space Division Multiple Access in Wireless Metropolitan Area Networks (IEEE 802.16a)," in Proc. of *WWRF10*, New York USA, 27-28 October 2003.

[8] C. Hoymann, "MAC Layer Concepts to Support Space Division Multiple Access in OFDM based IEEE 802.16", Special issue of Wireless Personal Communications, Springer, February 2006

[9] L. Berlemann, R. Pabst, and B. Walke, "Multi-mode Communication Protocols Enabling Reconfigurable Radios," *EURASIP Journal*, vol. 2005, no. 3, pp. 390-400, August 2005.

[10] S. Mangold, "Analysis of IEEE 802.11e and Application of Game Models for Support of Quality-of-Service in Coexisting Wireless Networks," Thesis (PhD), RWTH Aachen University, Aachen Germany: Wissenschaftsverlag Mainz, 2003.