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UNLICENSED OPERATION OF IEEE 802.16: COEXISTENCE WITH 802.11(A) IN SHARED FREQUENCY BANDS

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ABSTRACT

The coexistence of IEEE 802.16 (WiMAX) and IEEE 802.11 (WiFi) in shared radio spectrum is an acute problem. In license-exempt frequency bands, the frame-based medium access of 802.16 requires rigorous protection against interference from wireless local area networks in order to operate properly when sharing spectrum. We focus here on the unlicensed U-NII frequency band at 5 GHz and consider therefore the distributed medium access of 802.11(a) as competitor for spectrum utilization. We expect 802.16 systems to be available in laptops soon and then to provide wireless VoIP services that 802.11 cannot support satisfactorily well. Therefore, this paper describes approaches for enabling a reliable operation of 802.16 when sharing unlicensed spectrum with 802.11. We propose software upgrades to the medium access control of the 802.16 BS. Thereby, no 802.11 frame transmissions are required by an 802.16 system. Coexistence between 802.16 and 802.11 is enabled without any data exchange between both standards. Our solution of the described coexistence problem implies the possibility to guarantee Quality-of-Service within the 802.16 system although operating in unlicensed frequencies.

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 802.11a [2].

A. Related Work

WLANs of the 802.11 standard are able to coexist [3], i.e., operate at the same time and location without harmful interference in using *Dynamic Frequency Selection* (DFS) and *Transmit Power Control* (TPC). 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 [4, 5]. With interworking, wireless networks are able to coordinate spectrum usage among each other. A central coordinating device that combines the central *Base Station* (BS) of 802.16 with the *Hybrid Coordinator* (HC) of 802.11e is proposed in [6]. This central device requires an operation in both protocol modes, 802.16 and 802.11(e), in order to realize interworking and coexistence.

Contrary, we propose in this paper software upgrades to the *Medium Access Control* (MAC) of the 802.16 BS. Coexistence between 802.16 and 802.11 is enabled (without any data exchange) between both standards. Thereby, no 802.11 frame transmissions are required by an 802.16 system. We expect 802.16 systems to be available in laptops soon and then to provide wireless VoIP services that 802.11 cannot support satisfactorily well. As shown in this paper, 802.16 is able to control access to a radio channel such that competing 802.11 systems only get access when permitted by an 802.16 BS. It is even possible for an 802.16 BS to push away any 802.11 system from a frequency channel at 5 GHz, if necessary.

B. Regulatory Restrictions for Unlicensed Operation at 5 GHz

The frequency band at 5 GHz is often referred to as Unlicensed National Information Infrastructure (U-NII) band. While the regulatory restrictions for unlicensed operation in the Industrial, Scientific and Medical (ISM) bands from 2400-2483.5 MHz are similar in the world, spectrum regulation of unlicensed operation in the 5 GHz band differs essentially when comparing Europe, US and Japan as depicted in Fig. 1.

In Europe, the operation in the 5 GHz frequency bands is mainly regulated in [7]: The 5150-5350 MHz band is designated for indoor usage with a mean Equivalent Isotropic Radiated Power (EIRP) of 200 mW and DFS together with TPC are additionally required above 5250 MHz. The frequencies from 5470-5725 MHz may be used indoors as well as outdoors and the mean EIRP is limited in this band to

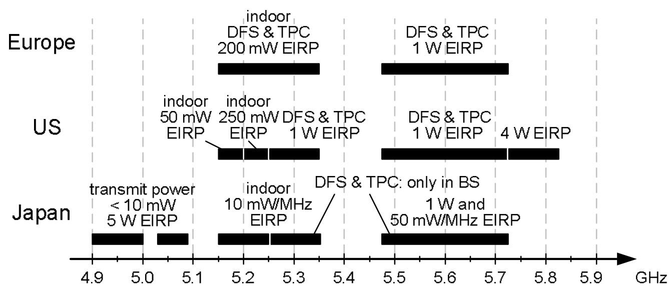

Figure 1: Frequency bands and regulatory restrictions of unlicensed operation at 5 GHz.

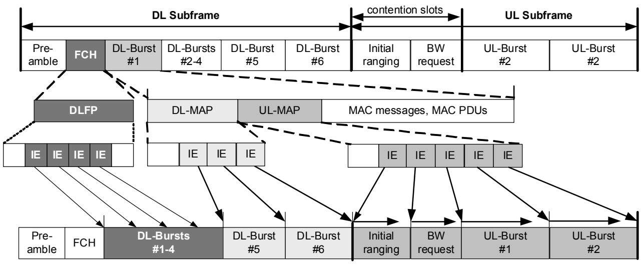

Figure 2: IEEE 802.16 references of MAC management messages for composition of the MAC frame [9].

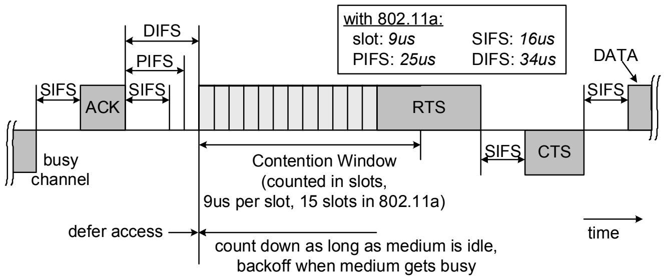

Figure 3: Decentralized medium access in 802.11 with the help of the Distributed Coordination Function. The contention based medium access with backoff procedure is initiated after an idle time of DIFS (with 802.11a: after 34us) [11].

1 W. The usage of DFS and TPC is mandatory. In the US, the regulator reserved in 1997 300 MHz and in 2003 255 MHz at 5 GHz for unlicensed operation and regulates also limited coexistence capabilities like DFS and TPC [8]. In Japan, frequencies below 5.1 GHz are also available for unlicensed operation with a mean EIRP of 5 W and a transmit power below 10 mW.

C. *Outline*

This paper is outlined as follows: A short overview of the medium access in 802.16 is given in Section II while the basic principles of the distributed medium access of 802.11 are summarized in Section III. Concepts for enabling the operation of 802.16 in spectrum shared with 802.11 (here the unlicensed frequency bands at 5 GHz) are discussed in Section IV. The coexistence of multiple 802.16 systems is addressed in Section V and this paper ends with a conclusion in Section VI.

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 Fig. 2. 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 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* (SDMA) operation of IEEE 802.16 benefits from this. For a description and detailed evaluation of 802.16 with the help of a stochastic event-driven simulator see [9] or [10].

III. IEEE 802.11(A)

The 802.11 MAC protocol is built with the help of two coordination functions, i.e., the *Distributed Coordination Function* (DCF) for traffic without QoS and the Point Coordination Function for traffic with QoS requirements. Today’s mass market 802.11 devices (*Access Points* (APs) and stations (STAs)) only use the contention based medium access of the DCF. An AP forms together with a number of associated stations an infrastructure based *Basic Service Set*. The DCF works based on the listen-before-talk scheme, based on the *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA). Stations deliver *MAC Service Data Units* (MSDUs) of arbitrary lengths after detecting that there is no other transmission in progress on the radio channel. The DCF of 802.11 implies a backoff procedure before starting a transmission as depicted in Fig. 3. A station that has an MSDU to deliver has to keep sensing the channel for an additional random time duration after detecting the channel as being idle for the minimum duration DIFS, which is 34 µs for 802.11a. Only if the channel remains idle for this additional random time duration, the station is allowed to initiate its transmission.

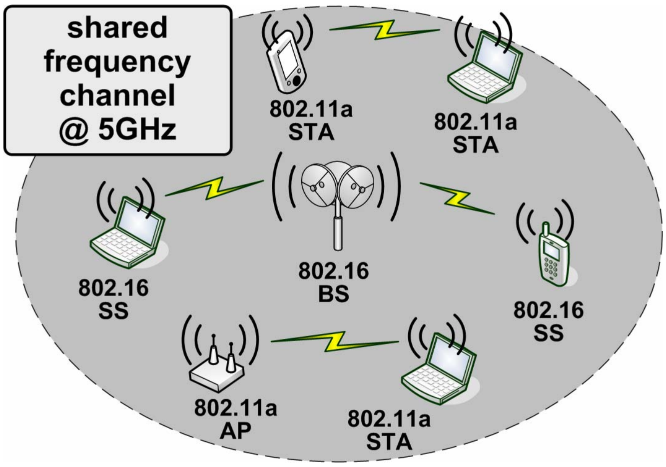

Figure 4: Coexistence scenario of 802.16 and 802.11a sharing the same frequency channel in the 5 GHz band.

IV. Coexistence of 802.16 and 802.11 at 5 GHz

A. Coexistence Scenario

Approaches for enabling the coexistence of a single 802.16 system with multiple 802.11 APs and STAs using the DCF for medium access are introduced in the following. The basic idea is to prevent medium access of 802.11 before and during the MAC frame transmission of 802.16. The proposed solution targets at the avoidance of an idle medium with a duration equal or longer than the *Distributed Interframe Space* (DIFS) of 802.11. Thus, APs and STAs sense a busy channel and do not transmit according to the listen-before-talk principle of their medium access.

The coexistence scenario considered in this section is illustrated in Fig. 4: One BS and controlled SSs are depicted. They are operating at a frequency channel at 5 GHz that is shared with multiple 802.11a APs/STAs. We assume that the 802.16 system has selected this frequency channel in using DFS according to the regulatory restrictions. In the following, three risk points are identified that imply a danger for the transmission of the 802.16 MAC frame. These dangers and their handling are illustrated in the timing diagram of Fig. 5 and are marked with ①, ② and ③ respectively. Note that no multi-mode device capable of operating according to 802.16 and 802.11 is required. A manipulation of the 802.11 devices' NAVs in order to prevent unwanted allocation attempts requires for instance such a multi-mode device. This and similar concepts are discussed and evaluated in [6].

The MAC frame duration of 802.16 can be varied between 2.5 to 20 ms, while the beacon interval (often referred to as superframe) of 802.11 typically has a value of 100 ms. Thus, multiple 802.16 MAC frames are nested into one 802.11a superframe. We assume in the following, that the 802.16 system allocates only a fraction of the shared frequency channel for its own operation depending on its current traffic load. The time interval between two consecutive 802.16 MAC frames is accessed by the coexisting 802.11a APs/STAs in using the DCF, as also illustrated in Fig. 5. We further assume that TTG and RTG are shorter than the DIFS duration interval of 802.11a. The minimum transceiver turnaround time and the round trip delay, which varies with the cell size, determine the duration of TTG and RTG. The unlicensed operation of 802.16 will most likely be limited to short/medium range communication implying small cell sizes and thus short TTG/RTG durations. Nevertheless, in case of a scenario where TTG/RTG are longer than DIFS the BSHC can transmit a blocking signal to prevent medium access of 802.11a.

B. Protecting the Beginning of 802.16 MAC Frame

Contrary to 802.11, 802.16 is not able to tolerate a delayed beginning of its MAC frame. Therefore, no 802.11a transmission is allowed to be ongoing when the 802.16 MAC frame begins (with a Preamble and the FCH). Therefore, the BS blocks the medium before the intended frame start in order to prevent an access from 802.11a. The medium has to be blocked as soon as the time instance of the next 802.16 MAC frame is closer than the maximum duration of an 802.11a transmission. With the most robust PHY mode and the largest data packet size (2346 byte) the maximum duration of an 802.11a transmission is approx. 2 ms. Thus, the blocked time interval has a duration of this 2 ms in the worst case. An interruption of an ongoing 802.11a transmission that reaches into this blocking interval is not required. Only a new allocation attempt after this transmission has to be prevented. Consequently, the effective duration of the blocked time interval may differ from one MAC frame to the next one, which is also illustrated in Fig. 5 (①). As the actual beginning of the blocking may vary, the blocked time interval cannot be used for 802.16 transmissions.

In our scenario, which has a frame duration of 10 ms, 20 percent of the transmission time/capacity is wasted in the worst case for guaranteeing a timely beginning of the MAC frame. This can be seen as cost or effort for operating 802.16 in unlicensed frequency bands.

C. Protecting the 802.16 UL Subframe

Table 1: Basic OFDM parameters and resulting time values.

IEEE 802.16 vs. 802.11a

802.11a + 802.16 - Frequency Band	@ 5 GHz
802.11a + 802.16 - Bandwidth	20 MHz
802.16 - OFDM Symbol Duration	13.89 µs
802.16 - Contention Slot Duration for BW Requests	2 OFDM Symbols = 27.78 µs
802.16 - Contention Slot Duration for Initial Ranging	10 OFDM Symbols = 138.9 µs
802.11a - DCF access after idle time of DIFS with a duration of	34 µs

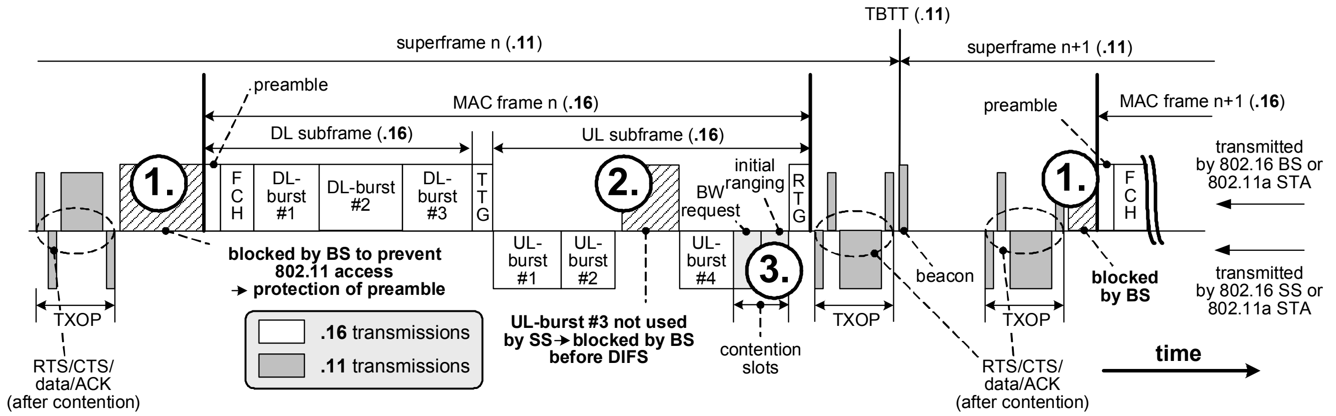

Figure 5: Timing diagram of an 802.16 MAC frame transmitted on a shared frequency channel. The 802.16 BS protects the beginning of the MAC frame (①) and prevents idle times longer than DIFS during the MAC frame (② and ③). In this way, 802.11 devices are blocked out and an interference free 802.16 MAC frame transmission can be guaranteed.

The 802.16 transmissions in the DL subframe are transmitted by the BS without any gaps so that no 802.11 device has the opportunity to access the medium: The medium is never idle for a duration equal or longer than DIFS. In the UL subframe this is not the case: A SS may not allocate an assigned UL-burst and the medium becomes idle. In this case, the BS has to block the unused UL-burst with an own transmission before an idle time duration of DIFS, as depicted in Fig. 5 (②). This is done to prevent a medium access of 802.11 and to protect the following UL-bursts of the on-going UL subframe.

D. *Shifting the Contention Slots*

The The contention slots of 802.16 are another weak point in the 802.16 MAC frame when considering the 802.11a medium access. These slots are used for initial ranging and bandwidth requests. The random access to these slots follows the slotted ALOHA principle. Unallocated 802.16 contention slots may lead to an idle medium with a duration equal or longer than DIFS. In this case, 802.11 APs/STAs might access the frequency channel and interfere the following UL bursts scheduled for data transmission. The duration of contention slots in 802.16 depend on the used frequency band and on the expected round trip delay. In our scenario at 5 GHz with a bandwidth of 20 MHz, the contention slots used for bandwidth requests have a duration of 27.78 us. The slots used for initial ranging are essentially longer and have a duration of 138.9 µs as summarized in Tab. 1. Consequently, the medium access of the 802.11a DCF after 34 µs implies a danger for the 802.16 MAC frame.
802.16 allows to schedule the contention slots at the end of the UL subframe. This protects all other UL bursts as depicted in Fig. 5 (③). In this way, UL bursts are not interfered by the 802.11a medium access in the contention phase. The contention slots for bandwidth requests are shorter than DIFS. At least the first two slots may be used for requests by SSs without interference from 802.11a STAs. The contention slots used for initial ranging are essentially longer than DIFS. Thus, an access of 802.11a STAs might only be prevented by the BS in blocking each unallocated contention slot if it is idle, similar to the blocking of unused UL-bursts as described above. Thus, the contention slots are ordered as follows: First the slots for bandwidth requests are scheduled and thereafter the slots for initial ranging as also illustrated in Fig. 5 (③).
Associated SSs do not necessarily need to use contention-based bandwidth requests to change the capacity assigned to them by the BS. This can be done by piggy-backing these requests or by implicit bandwidth request provided by special uplink scheduling services.

V. Coexistence among 802.16 Systems

The coexistence of multiple 802.16 systems, i.e., multiple BSs, is discussed in this section. In the previous section, we proposed mechanisms for solving the coexistence with 802.11a in blocking it out of the shared frequency channel. These mechanisms guarantee an exclusive spectrum usage right to the BS. This exclusiveness is lost in case of multiple BSs that compete for spectrum access. This coexistence problem is similar to the coexistence problem of several 802.11e HCs sharing a single frequency channel in the time domain. Such a scenario is intensively analyzed in the context of cognitive radios in [5]. Spectrum sharing among cognitive radios is discussed in applying and comparing solution concepts derived from information theory on the one hand and from game theory on the other hand. These approaches allow cognitive radios, realized as modified 802.11e HCs, to support and guarantee QoS when sharing spectrum without requiring direct information exchange in observing past spectrum utilization.
Both approaches introduce periodic resource allocations in order to enable a distributed coordination based on past spectrum utilization. An application of these approaches for mitigating the coexistence problem of 802.16 benefits essentially from this introduction of periodicity. Nested MAC frame transmissions of multiple 802.16 BS can be compared

to these decentralized coordinated periodic resource allocations.

A. IEEE 802.16h

The IEEE 802.16h License-Exempt Task Group is developing improved mechanisms for enabling coexistence among license-exempt systems based on IEEE 802.16. The standardization efforts target for instance at medium access control enhancements and policies. A distributed architecture for radio resource management is suggested [12] that enables communication and exchange of parameters between different networks formed by one 802.16 BS and its associated SSs. Each BS has a Distributed Radio Resource Management entity to execute the spectrum sharing policies of 802.16h and to build up a data base for sharing information related to actual and intended future usage of radio spectrum. 802.16h proposes a coexistence protocol to realize all functions required for coexistence as for example detecting the neighbourhood topology, to register to the data base or the negotiation for sharing radio spectrum.

VI. Conclusion

Mechanisms for enabling an operation of IEEE 802.16 in spectrum shared with 802.11(a) have been proposed in this paper. Coexistence is enabled in partly blocking 802.11(a) out of the medium. This enables a guarantee of QoS in 802.16. A drawback of operating 802.16 in unlicensed frequency bands shared with 802.11 is identified: A considerably large portion of the available transmission time is wasted leading to a reduced efficiency of channel/spectrum usage.

The coexistence of multiple 802.16 BSs introduces an additional level of complexity. Its solution requires intelligent algorithms for distributed coordination that imply intensive impacts on the medium access control. Contrary, the solution proposed in this paper requires only minimal modifications of the medium access in the BS.

The practical realization of the proposed solution is challenging but nevertheless feasible related to the required transceiver turnaround times in the 802.16 BS.

From the perspective of 802.11a, the proposed method can be regarded as unfair. Unfortunately, 802.16 requires such a rigorous protection against interference of its MAC frame from other communication systems because of its inability to coexist. A fundamental regulatory recommendation for operation in unlicensed frequencies shared in the time domain can be derived from our proposed solution: A limitation of spectrum access in its duration and the usage of deterministic spectrum allocation patterns allowing a distributed coordination on the basis of spectrum observation. The fulfilment of this recommendation would allow QoS support [5], mitigate the coexistence problem of multiple 802.16 systems and would introduce fairness, when sharing spectrum with dissimilar systems.

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