Wireless Pers Commun
DOI 10.1007/s11277-010-0134-1

IEEE 802.11 and 802.16 Cooperation Within Multi-Radio Stations

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Abstract In this paper we consider a multi-radio wireless network client that is capable of simultaneous operation in IEEE 802.16 and IEEE 802.11 telecommunication networks. In order to enable the cooperative functioning of both networks we introduce the media access control coordination concept. A set of coordination algorithms is then presented together with a simple approach to their performance analysis. Our performance evaluation shows that the saturation goodput of the proposed coordination algorithm is at least 50% higher than that of the existing coordination algorithms. Moreover, it allows for the considerable reduction in the data packet delay.

1 Introduction and Previous Work

Wireless technology becomes more widespread as new telecommunication protocols emerge, which enable higher data rates. The parallel evolution of personal, local and metropolitan area networks provides the mobile clients with a wide choice of which infrastructure to use for a given application. Recent advances in the area introduce wireless systems that exploit multiple radios in a collaborative manner. The use of such *multi-radio* devices was shown to dramatically improve the overall system performance and functionality over the traditional single-radio wireless systems.

The first works on multi-radio performance considered IEEE 802.11 (WiFi) [1] telecommunication protocol in the wireless mesh mode. Equipping the mesh routers with multiple radios tuned to non-overlapping channels was studied by many authors. In [2] some common

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Published online: 01 September 2010

problems in wireless networking were revisited in the multi-radio context, including energy management, capacity enhancement, mobility management, channel failure recovery and last-hop packet scheduling. A novel link layer protocol for multihop community wireless mesh network, where cost of the radios and battery consumption are not limiting factors, was presented and analyzed in [3].

A new metric for routing in multi-radio multihop wireless networks was given by [4]. The authors focused on wireless networks with stationary nodes, such as community wireless networks. The goal of the metric was to choose a high-throughput path between a source and a destination. The authors of [5] mathematically formulated the joint channel assignment and routing problem, taking into account the interference constraints, the number of channels in a network and the number of radios available at each mesh router. They strictly proved that equipping wireless routers with multiple radios improves the capacity by transmitting over multiple radios simultaneously using orthogonal channels.

In [6] specific mechanisms were defined that can transform partially overlapped channels into an advantage, instead of a peril in a wireless network. The work [7] emphasized that the channel assignment presents a challenge because co-located wireless networks are likely to be tuned to the same channels. The resulting increase in interference can adversely affect performance. Therefore, the authors presented an interference-aware channel assignment algorithm for multi-radio wireless mesh networks that addresses this interference problem. The proposed solution intelligently assigned channels to radios to minimize the interference within the mesh network and between the mesh network and co-located wireless networks.

Finally, the design and experimental study of a distributed, self-stabilizing mechanism was conducted by [8] to assign channels to multi-radio nodes in wireless mesh networks. However, with the introduction and further development of IEEE 802.16 (WiMAX) [9] protocol the concept of a multi-radio station was extended to also cover the interworking of several wireless technologies. The multi-radio station may thus operate in several telecommunication networks at the same time in accordance with the inbuilt protocols.

The problems caused by the multi-protocol operation at the *media access control* (MAC) layer has yet received much attention in the scientific literature. The primary focus of [10] is set on the co-existence scenarios between 802.11 and 802.16 in which 802.11 hotspots are inside a 802.16 cell and share the same frequency band. The authors propose new schemes that can control transmit frequency, power, and time of transmission. Three basic schemes are thus proposed: dynamic frequency selection, power control and time agility.

In [11] the above research is continued with the formulation of common spectrum coordination channel etiquette protocol. This protocol is used to exchange control information on transmitter and receiver parameters and hence to cooperatively adapt key variables such as frequency or power. However, the approach of [11] assumes that a common spectrum coordination channel at the edge of available spectrum bands is allocated for announcement of radio parameters. The use of a dedicated channel limits the practical applicability of this research.

Another option to enable 802.16 and 802.11 cooperation is demonstrated in [12] where the capability of 802.11 reuse by 802.16 in the mesh mode is studied. In [13] a general co-existence evaluation approach is shown and [14], particularly, addresses 802.11e and 802.16 interworking, where a concept of the Base Station Hybrid Coordinator is introduced. The use of such a coordinator is possible, when the base station of 802.16 and the hybrid coordinator of 802.11e are co-located. As an alternative, the authors describe some software upgrades to the MAC of the 802.16 base station in [15]. These updates ensure reliable operation of 802.16 when sharing unlicensed spectrum with 802.11.

Some works (see, for example, [16,17] and [18]) also cover IEEE 802.15.1 (Bluetooth) and 802.11 co-existence issues. In this paper we address the practical case of cooperation between 802.11 and 802.16 standards. But by contrast to the approach of [14] and [15] we consider a more realistic scenario without any modification of the central coordinating node in the telecommunication system. Instead, we discuss the problem of the MAC coordination within a client multi-radio station itself, thus avoiding any restriction on the network topology.

The rest of the text is structured as follows. In Section 2 we provide a deeper insight into the separate functioning of 802.11 and 802.16. Section 3 introduces the concept of the MAC coordination and presents a set of coordination algorithms. Section 4 analytically evaluates the performance of these algorithms from the MAC goodput viewpoint. In Section 5 the simulation results are presented and Section 6 concludes the paper.

2 Non-Cooperative Network Functioning

2.1 IEEE 802.11 Standard

From the MAC layer point of view, the contemporary IEEE 802.11 standard provides both distributed and centralized multiple-access protocols to the shared communications channel. 802.11 supports several operation modes, including the most common *infrastructure* mode, in which an *access point* (AP) becomes the central network node. The AP arbitrates all communication between the stations (STAs) and is mandated to use a contention-based channel access protocol, that is built on top of the truncated binary exponential backoff collision resolution algorithm [19]. The channel access protocol itself is termed carrier sense multiple access with collision avoidance (CSMA/CA). It is fully defined by three parameters: the *arbitration inter-frame space* (AIFS) interval, which each station waits prior to the channel contention and the pair of the minimum (W_{min}) and the maximum (W_{max}) contention windows, that regulate the uniform sampling of random numbers and enable the collision avoidance feature of the protocol.

Starting from 802.11e version [1] the standard introduces quality of service (QoS) enhancements and adopts the concept of a *transmission opportunity* (TXOP), which is illustrated in Fig. 1. A TXOP may be regarded as a bounded time interval during which a sequence of packets encapsulated into frames is transmitted by a source station, while only service messages are received. A TXOP is only obtained if both channel state detection functions of a station indicate that the channel is idle. They are the *clear channel assessment* (CCA) algorithm at the physical (PHY) layer and the *network allocation vector* (NAV) value at the MAC layer. As discussed above, a TXOP is precluded by the deterministic AIFS interval and then by a random number of slots.

Commonly, a source station initiates a frame transaction with a *request to send* (RTS) frame, which is responded by the destination station with a *clear to send* (CTS) frame after a *short inter-frame space* (SIFS) interval. The source station then transmits aggregated data packet (DATA) with a single PHY layer preamble, which is subject to the acknowledgment by a *block acknowledgment* (BA) frame. If some unused TXOP time remains, the source station may release it by a *contention-free end* (CFE) frame.

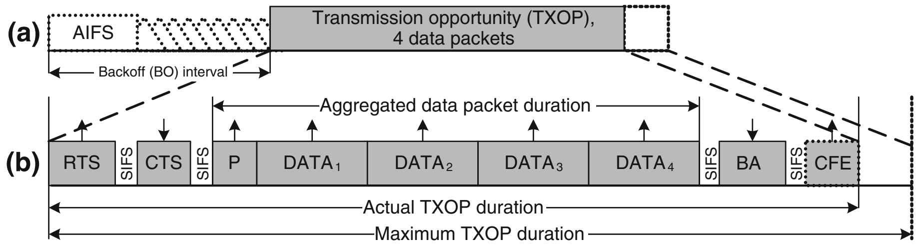

Fig. 1 IEEE 802.11 TXOP: **a** example frame transaction, **b** typical time structure

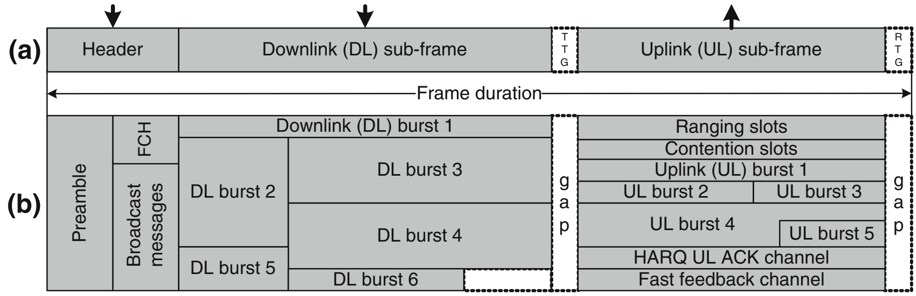

Fig. 2 IEEE 802.16 frame: **a** simplified structure, **b** detailed OFDMA frame time-frequency structure

2.2 IEEE 802.16 Standard

IEEE 802.16 MAC layer adopts a schedule-based protocol, commonly operating in the mandatory infrastructure mode. A *base station* (BS) arbitrates all activity within the network and broadcasts both service messages and useful data to its *subscribed stations* (SSs) in the *downlink* (DL) sub-frame. The DL sub-frame is composed of a 802.16 MAC header and DL bursts, directed at the SSs (see Fig. 2). In the *uplink* (UL) sub-frame the SSs transmit scheduled UL bursts as well as service messages. 802.16 supports several PHY layer modes, of which the most practical is the *orthogonal frequency division multiple access* (OFDMA) scheme (see Fig. 2).

IEEE 802.16 was specifically designed to support a variety of traffic types. It should be efficient for high data rate applications (video streaming) as well as for low data rate applications (web surfing). IEEE 802.16 effectiveness should not degrade in case of bursty traffic and delay-critical applications (voice over IP (VoIP), audio). The main challenge in ensuring QoS requirements in 802.16 is that all the traffic types with respective characteristics should be serviced at the same time. For this purpose the standard defines five QoS classes, which are described below.

1. Unsolicited Grant Service (UGS) is oriented at the real-time traffic where fixed-size data packets are generated periodically (CBR input source).
2. Real-Time Polling Service (rtPS) is oriented at the real-time traffic where variable-size data packets are generated periodically (VBR input source).
3. Non Real-Time Polling Service (nrtPS) is similar to rtPS, but data packet generation is not necessarily periodic.
4. Best Effort (BE) is suitable for applications, where no throughput or delay guarantee is provided.

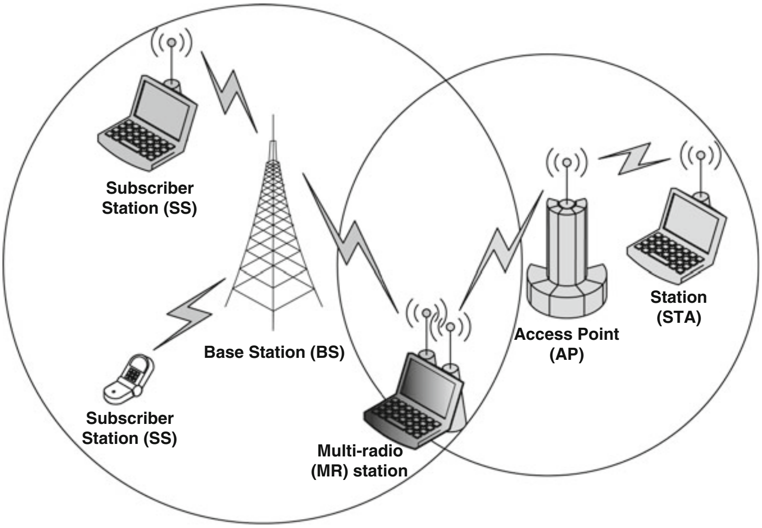

Fig. 3 General cooperative network example

5. Extended Real-Time Variable Rate (ERT-VR) is similar to rtPS, but with more strict delay requirement (guaranteed jitter) to support real-time applications like VoIP with silence suppression. This class is defined only in the recent IEEE 802.16e [9] standard and is often referred to as Extended Real-Time Polling Service (ertPS).

The MAC layer also supports a variety of bandwidth reservation mechanisms, each of which is assigned to a particular service flow. The mechanisms are based upon unicast, multicast or broadcast polling techniques. However, the standard specifies neither scheduling algorithm nor admission control mechanism.

3 Cooperative Network Functioning

3.1 MAC Coordination Concept

Currently IEEE 802.11 and 802.16 standards operate in non-overlapping frequency bands [20]. Therefore, the respective telecommunication networks may coexist simultaneously without any significant performance degradation. However, this is the case only when each client station supports the functionality of exactly one protocol. When the functionalities of two or more standards are co-located within a single multi-radio (MR) station (see Fig. 3) the network performance degrades dramatically, even if the simultaneous operation is technically possible. This is explained by the fact that the radio parts of a MR station are close enough and the ongoing transmission in one network prohibits the reception in another one.

Coexistence enhancement research summarized in [21] states that co-located transmissions or receptions via different standards generally do not deteriorate each other. However, when a station receives data, an overlapping transmission of the co-located technology prevents the successful reception. This effect is elaborated on further in [22]. It is shown that 802.11 and 802.16 radio-to-radio interference severely degrades the performance and requires isolation of at least 55 dB. Increasing isolation is costly, large in size and highly platform

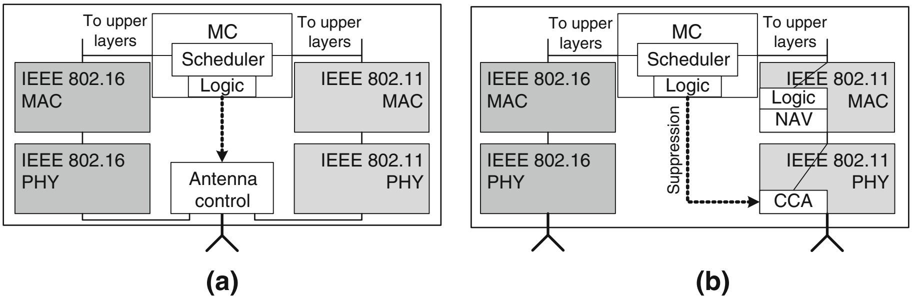

Fig. 4 MR station structure with: **a** shared antenna, **b** separate antennas

Table 1 MR station technical limitations

IEEE 802.11-802.16	Shared antenna	Separate antennas
Rx-Rx	Denied	Allowed
Rx-Tx	Denied	Denied
Tx-Rx	Denied	Denied
Tx-Tx	Denied	Allowed

dependent. An alternative solution may be pursued in the time domain. In order to mitigate the indicated effect a special module on top of the respective MAC layers may be implemented for the purposes of the *MAC coordination* (MC). This solution is known to be universal, effective and media independent.

The MC module controls scheduling of both network activities within a MR station and thus enables the simultaneous operation of 802.11 and 802.16. As 802.16 is schedule-based, the MC module only monitors its transmit (Tx) and receive (Rx) activity and allows/denies the channel access of 802.11 part depending on the 802.16 schedule.

Two principally different options exist for the MC module implementation within a MR station (see Fig. 4). One of them uses one reconfigurable antenna [23], which becomes *shared* in terms of the channel access. Clearly, this design prohibits the simultaneous operation of two standards (see Table 1). Another possibility is to use two *separate* antennas: one for each of the cooperating standards. As discussed above, the simultaneous Tx-Rx and Rx-Tx operations should be excluded to avoid radio-to-radio interference.

Coordination algorithms restrict the operation of a MR station such that its technical limitations (see Table 1) are accounted for. For the sake of clarity, the below coordination algorithms are demonstrated for the case of only uplink traffic in both networks, that is, 802.11 and 802.16 transmit useful data, while receive only service messages.

3.2 Basic Coordination Algorithm

Here we present the simplest coordination algorithm, which is referred to as *Basic* in what follows (see Algorithm 1). This algorithm operates under both shared and separate antennas technical limitations (see Table 1) and its main idea is to allow 802.11 utilize only the gaps in 802.16 activity (see Fig. 5).

Considering the operation of any coordination algorithm we introduce the notion of an *atomic operation* (AO). The AO may be defined as a time interval for a MR station frame transaction such that IEEE 802.11 TXOP the station obtains does not exceed the AO. Thus,

1: Call CCA PHY layer function.
2: **if** CCA indicates busy channel **then**
3: Go to step 1.
4: Call NAV MAC layer function.
5: **if** NAV indicates busy channel **then**
6: Go to step 1.
7: Obtain current parameters of backoff procedure.
8: **if** backoff interval is not over **then**
9: Go to step 1.
10: Set maximum IEEE 802.11 TXOP duration T_{mTXOP} as atomic operation duration.
11: Call MC module parametrized by atomic operation duration.
12: Calculate remaining time until closest forthcoming IEEE 802.16 activity.
13: **if** duration of remaining interval is *not less* than atomic operation duration **then**
14: Send pending data packets during time interval, not exceeding atomic operation duration.
15: Begin new backoff interval with minimum contention window value W_{min}.
16: Go to step 1.

Algorithm 1: Basic coordination algorithm

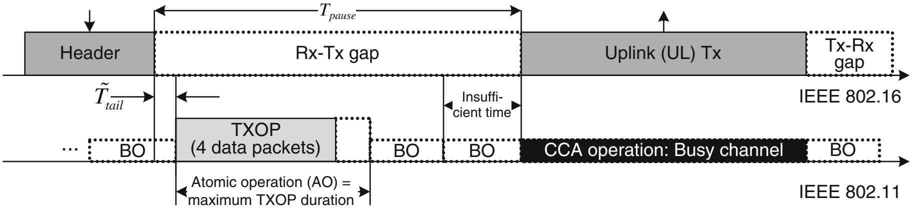

Fig. 5 Basic coordination algorithm operation

AO is the time unit of a MC module and may potentially vary during the coordination algorithm operation. The simplest Basic algorithm, however, utilizes a static AO, which may be reasonably set to the maximum TXOP duration. Therefore, as actual TXOP duration is always less than its maximum, some operation time is unavoidably wasted. This necessarily leads to the less effective performance.

The implementation of the Basic algorithm is straightforward and involves an additional function call to the MC module. More specifically, once both CCA and NAV of 802.11 indicate that the channel is idle, AIFS interval duration (T_{AIFS}) is spent and backoff time left is 0 the MAC layer requests the time necessary for performing the AO from the MC module. Analyzing the 802.16 schedule, the MC module decides whether there is enough time remaining before the forthcoming 802.16 activity. Further, 802.11 MAC either sends pending TXOP immediately, or initiates a new random backoff with the minimum value of the contention window.

We may therefore formulate the following properties of the Basic coordination algorithm:
+ Simple implementation.
+ Workability in case of both shared and separate antennas.
− Constant atomic operation, resource waste.
− Usage of activity gaps only, non-maximum performance.

3.3 Enhanced Coordination Algorithm

In order to improve the performance of the Basic coordination algorithm, the *Enhanced* algorithm may be introduced (see Algorithm 2). Its idea is similar to the coexistence-aware TXOP

1: Call CCA PHY layer function.
2: **if** CCA indicates busy channel **then**
3: Go to step 1.
4: Call NAV MAC layer function.
5: **if** NAV indicates busy channel **then**
6: Go to step 1.
7: Obtain current parameters of backoff procedure.
8: **if** backoff interval is not over **then**
9: Go to step 1.
10: Calculate maximum number of data packets K within maximum IEEE 802.11 TXOP duration T_{mTXOP}.
11: **while** $K > 0$ **do**
12: Set actual IEEE 802.11 TXOP duration, which contains exactly K data packets, as atomic operation duration.
13: Call MC module parametrized by atomic operation duration.
14: Calculate remaining time until closest forthcoming IEEE 802.16 activity.
15: **if** duration of remaining interval is *not less* than atomic operation duration **then**
16: Send K pending data packets.
17: $K = 0$.
18: **else**
19: $K = K - 1$.
20: Begin new backoff interval with minimum contention window value W_{min}.
21: Go to step 1.

Algorithm 2: Enhanced coordination algorithm

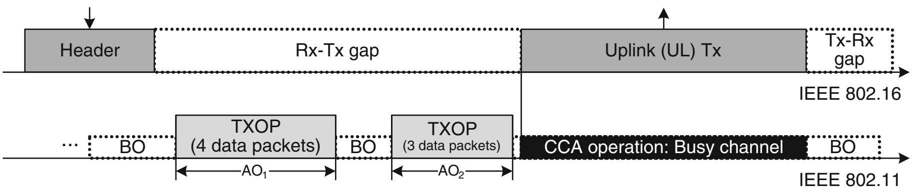

Fig. 6 Enhanced coordination algorithm operation

adaptation approach from [16]. It also may operate under both types of technical limitations (see Table 1) and utilizes only gaps in 802.16 activity. However, the Enhanced algorithm varies its atomic operation to adjust to the remaining operation time (see Fig. 6).

The Enhanced coordination algorithm is more complex than its Basic version. In particular, MC module performs more intensive computations of the actual TXOP duration T_{TXOP} with K packets.

We may therefore formulate the following properties of the Enhanced coordination algorithm:

+ Dynamic atomic operation, enhanced performance.
+ Workability in case of both shared and separate antennas.
− Higher computational and implementation complexity.
− Usage of activity gaps only, non-maximum performance.

3.4 Suppressing Enhanced Coordination Algorithm

We emphasize, that the previously discussed coordination algorithms utilize only the gaps in 802.16 activity. By relaxing this restriction, higher performance could be achieved. However, enabling simultaneous Tx-Tx and Rx-Rx operation is only possible under the separate

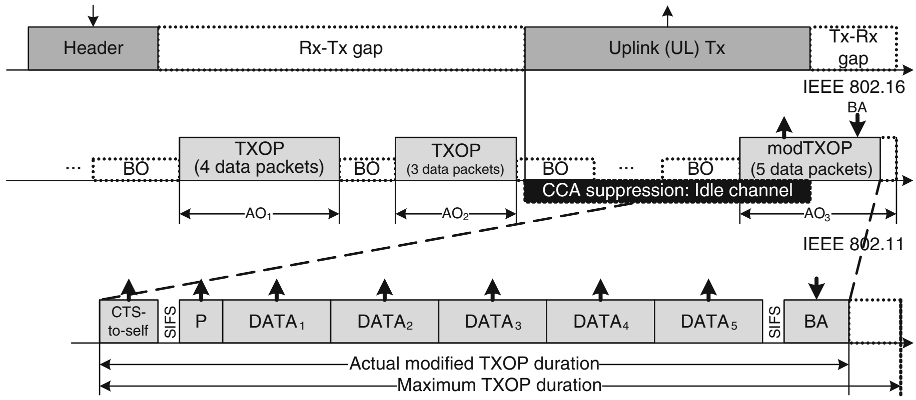

Fig. 7 Suppressing enhanced coordination algorithm operation

antennas technical limitations (see Table 1). We refer to the corresponding coordination algorithm as to *Suppressing* enhanced algorithm in what follows (see Fig. 7 and Algorithm 3).

We assume, that the channel is sensed busy by 802.11 CCA function of a MR station during any 802.16 Tx activity. We propose the temporary suppression of the CCA signal to enable the simultaneous Tx-Tx operation. This step, however, may decrease the robustness of 802.11 busy channel detection mechanism and may lead to the increase in the number of 802.11 collisions.

Require: IEEE 802.11 CCA signal suppression is enabled during any ongoing Tx via IEEE 802.16.
Ensure: Steps 11 and 13 account for IEEE 802.11 TXOP structure change depending on whether CCA signal suppression is enabled.
1: **if** CCA signal suppression is *disabled* **then**
2: Call CCA PHY layer function.
3: **if** CCA indicates busy channel **then**
4: Go to step 1.
5: Call NAV MAC layer function.
6: **if** NAV indicates busy channel **then**
7: Go to step 1.
8: Obtain current parameters of backoff procedure.
9: **if** backoff interval is not over **then**
10: Go to step 1.
11: Calculate maximum number of data packets K within maximum IEEE 802.11 TXOP duration T_{mTXOP}.
12: **while** $K > 0$ **do**
13: Set actual IEEE 802.11 TXOP duration, which contains exactly K data packets, as atomic operation duration.
14: Call MC module parametrized by atomic operation duration.
15: Calculate remaining time until closest forthcoming IEEE 802.16 activity.
16: **if** duration of remaining interval is *not less* than atomic operation duration **then**
17: Send K pending data packets.
18: $K = 0$.
19: **else**
20: $K = K - 1$.
21: Begin new backoff interval with minimum contention window value W_{min}.
22: Go to step 1.

Algorithm 3: Suppressing enhanced coordination algorithm

The Suppressing enhanced algorithm may be regarded as an extension of the Enhanced algorithm for separate antennas (see Fig. 7). Thus, its operation during 802.16 activity gaps remains unchanged. In order to enable the simultaneous operation, the TXOP start time should be scheduled in a way that its Tx part coincides with that of 802.16 (or a gap) and its Rx part— with that of 802.16 (or a gap). Otherwise, according to Table 1 a violation of the technical limitations occurs.

A typical TXOP contains the transmission of RTS, DATA and, optionally, CFE frames, together with the reception of CTS and BA frames (see Fig. 1). In order to simplify Tx/Rx TXOP separation we use a modified TXOP, which consists of CTS-to-self and DATA frames in the Tx part and BA frame in the Rx part (see Fig. 7). Clearly, the complexity of the Suppressing enhanced coordination algorithm is only slightly higher than that of the Enhanced algorithm.

We may therefore formulate the following properties of the Suppressing enhanced coordination algorithm:
+ Simultaneous operation in both networks, better resource utilization.
+ Dynamic atomic operation, enhanced performance.
− Workability in case of separate antennas only.
− CCA signal suppression, highest computational and implementation complexity.

4 Performance Analysis of Coordination Algorithms

4.1 System Model Description

Here we introduce a set of the simplifying restrictions in order to enable the further performance analysis of the described coordination algorithms.

Restriction 1 IEEE 802.16 transmission schedule remains unchanged during the system operation.
Remember, that the MC module operation does not influence the schedule of IEEE 802.16 directly. We, therefore, define the MAC *goodput* of a MR station as the portion of 802.11 PHY layer data rate available for the data transmission at the MAC layer.
Restriction 2 There is only one client station in the system, which is the MR station. It transmits useful data in both 802.11 and 802.16 networks and receives service messages.
Restriction 3 As 802.16 part of the MR station operates in the OFDMA mode, it is assumed to transmit without interruption for the entire UL sub-frame duration, whereas there is no activity in the DL sub-frame except for the header reception.
Restriction 4 802.11 part of the MR station transmits constant-size data packets and is observed under *saturation conditions* [19], that is, it always has a packet ready for transmission.
Restriction 5 The communications channel is noise-free and since no other 802.11 station is present in the system, the MR station always initiates backoff procedure with the minimum contention window size of W_{min} (see description of IEEE 802.11 standard above).

Clearly, MAC goodput under the introduced restrictions is the achievable maximum. For convenience we summarize the principal performance analysis parameters in Table 2.[1]

[1] As standard abbreviation (AIFS, TXOP, BO, etc.) is used as lower index of the considered variables, we capitalize the letters and mark random variables with a tilde.

Table 2 Principal performance analysis parameters

Parameter	Description
T_{frame}	IEEE 802.16 frame duration (see Fig. 2)
T_{pause}	Rx-Tx gap duration in IEEE 802.16 schedule (see Fig. 5)
T_{slot}	IEEE 802.11 slot duration (see Fig. 1)
T_{AIFS}	IEEE 802.11 arbitration inter-frame space (AIFS) duration (see Fig. 1)
T_{TXOP}	Actual IEEE 802.11 transmission opportunity (TXOP) duration with maximum number of packets (see Fig. 6)
T_{mTXOP}	Maximum IEEE 802.11 TXOP duration (see Fig. 5)
W_{min}	Minimum contention window value
W_{max}	Maximum contention window value
Q_{max}	Maximum number of packets within IEEE 802.11 TXOP (see Fig. 5)
Q_{mod}	Maximum number of packets within modified IEEE 802.11 TXOP (see Fig. 7)
L	IEEE 802.11 data packet length
$\tilde{T}_{tail}$	IEEE 802.11 tagged backoff interval duration that avoids coincidence with IEEE 802.16 header (see Fig. 5)
$\tilde{T}_{BO}$	IEEE 802.11 backoff interval duration. (see Fig. 1)
$\tilde{W}_{mark}$	Number of slots in tagged backoff interval
$\tilde{Q}_{last}$	Number of packets within last IEEE 802.11 TXOP per IEEE 802.16 frame (see Fig. 6)

4.2 Single TXOP Per Frame Case

Consider the behavior of the Basic coordination algorithm. Practically, the number of 802.11 TXOPs a MR station obtains per 802.16 frame varies due to the random backoff time. At the same time backoff interval is on average sufficiently shorter than the TXOP duration. One may show that the difference between the maximum number of TXOPs per frame and the respective minimum number is not more than 1. Here we concentrate on the case, when either 0 or 1 TXOP is possible per 802.16 Rx-Tx gap and derive the corresponding goodput value $\left(G_1^B\right)$.

Proposition 1 *MAC goodput of the Basic coordination algorithm in case of single TXOP per frame* G_1^B *may be calculated as:*

$$G_1^B = \frac{L Q_{max}}{T_{frame}} \cdot \Pr\left\{\tilde{T}_{tail} \leq T\right\}, \tag{1}$$

where L *is the* 802.11 *data packet length;* Q_{max} *is the maximum number of packets within* 802.11 *TXOP;* T_{frame} *is the* 802.16 *frame duration.*

Proof In Fig. 5 we observe that MC module reservation is only possible, when after the first *tagged* backoff in the Rx-Tx gap the remaining time is not less than the maximum TXOP duration (T_{mTXOP}). However, of the tagged backoff interval only the remainder should be accounted for, that does not coincide with the header of 802.16 (denoted by $\tilde{T}_{tail}$ in Fig. 5).

Generally, the backoff time $\left(\tilde{T}_{BO}\right)$ is a concatenation of a deterministic AIFS interval and a random number of slots, that is, $\tilde{T}_{BO} = T_{AIFS} + \tilde{W} T_{slot}$, where $\tilde{W} \in \{0, 1, \ldots, W_{min}\}$. We firstly compute the probability that the number of slots in the tagged backoff $\left(\tilde{W}_{mark}\right)$ equals to the exact value of $j\left(\Pr\left\{\tilde{W}_{mark} = j\right\}\right)$. We introduce several assumptions that allow for the further simplification of the analysis.

Assumption 1 Assume that the number of consecutive backoff intervals before the tagged one is sufficiently large and regard it as an infinite sequence of the backoff intervals one of which is tagged randomly.

Therefore, accounting for the regeneration properties [24] of the backoff process we obtain the following expression for the sought probability $\Pr\left\{\tilde{W}_{mark} = j\right\}$ as:

$$\Pr\left\{\tilde{W}_{mark} = j\right\} = \frac{T_{AIFS} + jT_{slot}}{\sum_{i=0}^{W_{min}} T_{AIFS} + iT_{slot}}, \tag{2}$$

where $j \in \{0, 1, \ldots, W_{min}\}$.

Assumption 2 Assume that the interval $\tilde{T}_{tail}$ is discrete. As a discretization unit we select the interval of 1 μs duration, which divides all the standardized intervals (T_{slot}, T_{AIFS}, T_{mTXOP}, etc.).

Assumption 3 Assume that the starting point of the $\tilde{T}_{tail}$ interval is randomly placed at the tagged backoff interval according to the uniform distribution.

Therefore,

$$\begin{aligned} &\Pr\left\{\tilde{T}_{tail} = i | \tilde{W}_{mark} = j\right\} \\ &= \begin{cases} (T_{AIFS} + jT_{slot})^{-1}, & \text{if } i \in \{1, 2, \ldots, T_{AIFS} + jT_{slot}\}, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \tag{3}$$

By averaging over the possible values of j we obtain the respective unconditional probability as:

$$\Pr\left\{\tilde{T}_{tail} = i\right\} = \sum_{j=0}^{W_{min}} \Pr\left\{\tilde{T}_{tail} = i | \tilde{W}_{mark} = j\right\} \cdot \Pr\left\{\tilde{W}_{mark} = j\right\}, \tag{4}$$

where $i \in \{1, 2, \ldots, T_{AIFS} + W_{min} T_{slot}\}$.

Let T represent the threshold value of the backoff interval remainder duration $\tilde{T}_{tail}$ that still results in one TXOP per frame. This value is given by:

$$T = T_{pause} - T_{mTXOP}, \tag{5}$$

where T_{pause} is the Rx-Tx gap duration in 802.16 schedule (see Fig. 5). Then, the probability that $\tilde{T}_{tail}$ does not exceed T is readily obtained as:

$$\Pr\left\{\tilde{T}_{tail} \le T\right\} = \begin{cases} 0, & \text{if } T < 1, \\ 1, & \text{if } T > T_{AIFS} + W_{min} T_{slot}, \\ \sum_{i=1}^{T} \Pr\left\{\tilde{T}_{tail} = i\right\}, & \text{otherwise,} \end{cases} \tag{6}$$

which immediately implies (1). □

4.3 Several TXOPs Per Frame Case

Here we concentrate on the more general case, when the minimum number of TXOPs per frame is k and the maximum number is $k+1$. Due to the space limitations we consider only the value of $k = 1$ below. The calculations for any natural value $k > 1$ are made similarly.

Proposition 2 *MAC goodput of the Basic coordination algorithm in case of not more than two TXOPs per frame G_2^B may be calculated as:*

$$G_2^B = \frac{LQ_{max}}{T_{frame}} \cdot \left(1 + \Pr\left\{\tilde{T}_{tail} + \tilde{T}_{BO} \leq T\right\}\right). \tag{7}$$

Proof As before, we derive the threshold value of the random backoff interval duration (T) that now results in two TXOPs per frame. However, this time the random backoff comprises two intervals: the remainder $\tilde{T}_{tail}$ and the full backoff interval $\tilde{T}_{BO}$ between two consecutive TXOPs. The indicated threshold is thus equal to:

$$T = T_{pause} - (T_{TXOP} + T_{mTXOP}), \tag{8}$$

where T_{TXOP} is the actual 802.11 TXOP duration with maximum number of packets. Further, we calculate the probability, that $\tilde{T}_{BO}$ is equal to the exact value of i:

$$\Pr\left\{\tilde{T}_{BO} = i\right\} = \begin{cases} (W_{min}+1)^{-1}, & \text{if } i = T_{AIFS} + jT_{slot}, \\ 0, & \text{otherwise,} \end{cases} \tag{9}$$

where $j \in \{0, 1, \ldots, W_{min}\}$.

The probability that the sum of $\tilde{T}_{tail}$ and $\tilde{T}_{BO}$ is equal to some exact value of j may now be computed as a convolution of the distributions (4) and (9) (see Fig. 8):

$$\Pr\left\{\tilde{T}_{tail} + \tilde{T}_{BO} = j\right\} = \sum_{i=1}^{j} \Pr\left\{\tilde{T}_{tail} = i\right\} \cdot \Pr\left\{\tilde{T}_{BO} = j - i\right\}, \tag{10}$$

where $j \in \{2, 3, \ldots, 2 \cdot (T_{AIFS} + W_{min}T_{slot})\}$.

The value of $\Pr\left\{\tilde{T}_{tail} + \tilde{T}_{BO} \leq T\right\}$ is obtained similarly to (6) and may be used to derive the final expression (7). □

4.4 Enhanced Coordination Algorithm

MAC goodput of the Enhanced algorithm may be established after an extension of the above approach. Again, a general problem may be formulated for minimum k and maximum $k+1$ number of TXOPs, which we solve below for $k = 1$.

Proposition 3 *MAC goodput of the Enhanced coordination algorithm in case of not more than two TXOPs per frame G_2^E may be calculated as:*

$$G_2^E = \frac{L}{T_{frame}} \cdot \left(Q_{max} + E\left[\tilde{Q}_{last}\right]\right), \tag{11}$$

where $\tilde{Q}_{last}$ is the number of packets within the last 802.11 *TXOP per* 802.16 *frame.*

Proof We notice, that under the saturation conditions only the duration of the last 802.11 TXOP of those obtained per 802.16 frame may vary, subject to the remaining time in the

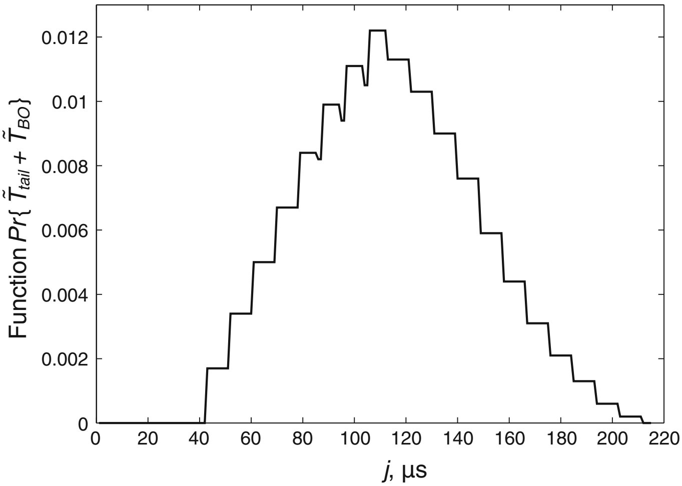

Fig. 8 Example probability function from Eq. (10): $T_{AIFS} = 43\,\mu$ s, $W_{min} = 7$ and $T_{slot} = 9\,\mu$s

Rx-Tx gap. We firstly compute a set of thresholds $T(i)$ that result in obtaining the second TXOP, containing exactly i data packets:

$$T(i) = T_{pause} - (T_{TXOP} + T_{TXOP}(i)), \tag{12}$$

where $T_{TXOP}(i)$ is the actual 802.11 TXOP duration, which contains exactly i packets. Once the thresholds are computed, we consider the event E_i that a TXOP contains i packets, conditioning on the fact that $i + 1$ packets may not be transmitted. Further, we establish the probabilities $\Pr\{E_i\}$ using (10), (6) and the corresponding thresholds $T(i)$. Denote the random number of packets in the last TXOP by $\tilde{Q}_{last}$. The respective mean value is thus given by:

$$E\left[\tilde{Q}_{last}\right] = \sum_{i=1}^{Q_{max}} i \cdot \Pr\{E_i\}, \tag{13}$$

which, in turn, results in (11). □

4.5 Suppressing Enhanced Coordination Algorithm

Proposition 4 *MAC goodput of the Suppressing enhanced coordination algorithm in case of not more than three TXOPs per frame G_3^S may be calculated as:*

$$G_3^S = \frac{L}{T_{frame}} \cdot \left(Q_{max} + E\left[\tilde{Q}_{last}\right] + Q_{mod}\right) = G_2^E + \frac{LQ_{mod}}{T_{frame}}, \tag{14}$$

where Q_{mod} is the maximum number of packets within the modified 802.11 *TXOP.*

Proof In order to derive the MAC goodput of the Suppressing enhanced algorithm, we should add to the Enhanced algorithm MAC goodput the term corresponding to one modified TXOP per frame (see Fig. 7). As the system operates in the saturation conditions, the modified TXOP contains the maximum number of packets (Q_{mod}), which immediately yields (14).

□

Table 3 Principal simulation parameters

IEEE 802.16 parameter	Value
DL:UL ratio	60:40
PHY type	OFDMA
Frame duration (T_{frame})	5 ms
Rx-Tx gap duration (T_{pause})	2.5 ms
IEEE 802.11 parameter	**Value**
Maximum IEEE 802.11 TXOP duration (T_{mTXOP})	1.3 ms
Contention window values: W_{min}/W_{max}	7/15
Arbitration inter-frame space (AIFS) duration (T_{AIFS})	43 µs
Slot duration (T_{slot})	9 µs
Data packet length (L)	12,000 bits

5 Numerical Results

5.1 Saturation Scenario Summary

In order to verify the assumptions of the above coordination algorithms performance analysis, an event-driven simulator was developed, that accounts for the necessary details of the considered system model. The simulator is based on the notorious OPNET Modeler [25] and extends its functionality to the MAC coordination purposes. In particular, to saturate the IEEE 802.16e UL sub-frame, the constant DVD flow of 9.8 Mbps is transmitted. IEEE 802.11n+e part of the MR station also transmits data packets and is observed under the saturation conditions. Each simulation run lasts for 10 s, while the principal simulation parameters are summarized in Table 3.

5.2 Algorithms Saturation Performance Comparison

We plot both analytical and simulated MAC saturation goodputs for the available set of PHY data rates in Fig. 9. Lines demonstrate the obtained analytical results, while dots represent simulation results. Firstly, we observe that the introduced theoretical approach shows very good accordance with the simulation.

Notice also, that, as expected, the MAC goodput of the Basic coordination algorithm is the lowest comparing with the other algorithms, mainly due to its simplicity. The function for the Enhanced coordination algorithm is almost linear, which is explained by the fact that the dynamic 802.11 TXOP size makes it independent of the variable system parameters. Finally, the Suppressing enhanced coordination algorithm outperforms its competitors for the cost of a more difficult implementation. Additionally, we observe that its effectiveness grows with the increasing data rate, as more data packets fit the additional TXOP per frame.

5.3 Number of MR Stations Analysis

We continue with the analysis of the presented algorithms with respect to the coexistence issues between MR stations. Remember, that IEEE 802.16 is a schedule-based protocol. Therefore, all the MR stations in the system share the UL sub-frame. As no DL activity is assumed, the 802.16 behavior remains unchanged with the increase in the number of MR stations. By contrast, the MR stations contend for the shared IEEE 802.11 channel. Whenever

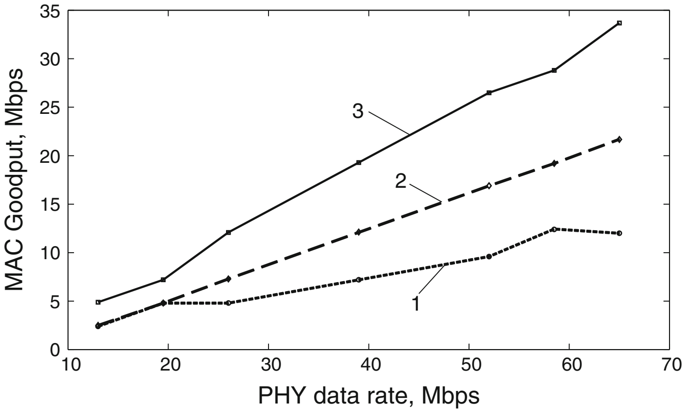

Fig. 9 Coordination algorithms performance comparison: *1* Basic algorithm, *2* Enhanced algorithm, *3* Suppressing enhanced algorithm

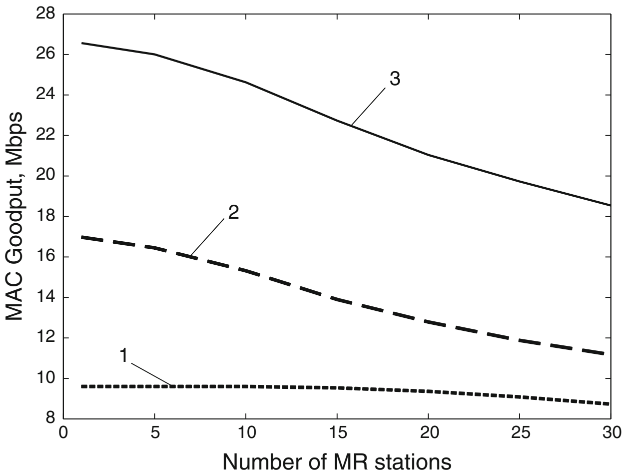

Fig. 10 Saturation goodput vs. number of MR stations for: *1* Basic algorithm, *2* Enhanced algorithm, *3* Suppressing enhanced algorithm

two or more stations start their transmissions simultaneously, a collision occurs that degrades 802.11 performance. Clearly, with the increasing number of MR stations the collision probability also grows. Consequently, the overall saturation goodput of the 802.11 network drops. The simulation analysis of the indicated problem is shown in Fig. 10 for the fixed PHY data rate of 52 Mbps.

We emphasize the fact that for the Basic coordination algorithm the saturation goodput degradation is almost negligible when the number of MR stations is sufficiently small. This is due to the simplified operation of the Basic algorithm, which leaves extra gaps before the forthcoming 802.16 activity. Packet collisions that are short due to the RTS-CTS mechanism do not change this behavior much. By contrast, Enhanced and Suppressing enhanced algorithms utilize the available 802.16 gaps better due to the dynamic atomic operation. Therefore, their performance is more vulnerable to the number of collisions.

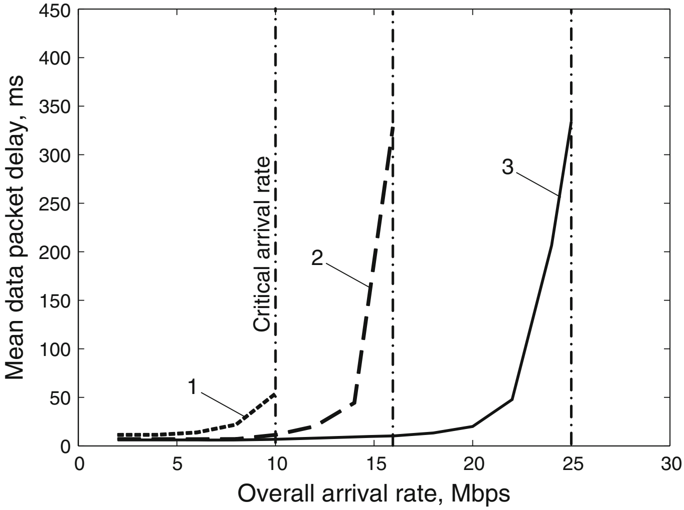

Fig. 11 Mean data packet delay vs. overall arrival rate for: *1* Basic algorithm, *2* Enhanced algorithm, *3* Suppressing enhanced algorithm

5.4 Mean Delay Analysis

Even though the saturation goodput is the main performance metric of a wireless network, data packet delay analysis is also important to ensure the client QoS requirements are satisfied. For this purpose we extend our simulator with the capability of changing the arrival flow of new packets into the client queue. We compare the delay behavior of the presented coordination algorithms in Fig. 11 for 10 MR station in the system.

Figure 11 indicates the clear superiority of the Suppressing enhanced coordination algorithm, for which the overall critical arrival rate was established to be 24.5 Mbps in Fig. 10. The Enhanced algorithm is the second best and saturates the system at about 15.5 Mbps. Finally, the Basic algorithm shows the worst mean delay performance having the critical rate of less than 10 Mbps.

6 Conclusion

We presented an approach to enable the simultaneous operation of IEEE 802.11 and IEEE 802.16 telecommunication standards within a multi-radio client station. The MAC coordination concept was introduced and three various coordination algorithms were discussed that demonstrate the performance-complexity trade-off. In particular, we developed a novel Suppressing enhanced coordination algorithm, which increases the MAC goodput of a MR station for more than 50% in comparison to the other algorithms. A simple analytical approach to the performance evaluation of the coordination algorithms was proposed.

The analysis regarding the coexistence with other MR client stations was also performed, as well as the mean data packet delay evaluation. The performance of the considered coordination algorithms was estimated analytically in the framework of the simplified system model, which could be extended further to account for the imperfect channel conditions. It may be shown, that in the noisy channel an appropriate rate adaptation strategy sufficiently improves network performance. The development of coexistence-aware rate adaptation algorithms is thus the prominent research direction.

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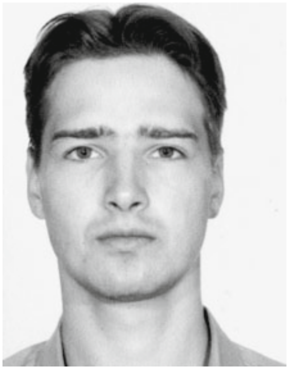

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