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IEEE 802.11 AND 802.16 COOPERATION WITHIN MULTI-RADIO STATIONS

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ABSTRACT

In this paper we address the problem of the cooperative functioning of two communication standards, namely, IEEE 802.11 and IEEE 802.16, within a single multi-radio station. The concept of the media access control coordination is discussed, which enables the simultaneous operation of the above standards. The design issues of the aforementioned approach are considered, together with a set of different coordination algorithms. These algorithms are compared and a simple approach to estimate their performance is demonstrated. The precision of the introduced estimation is checked with simulation.

I. INTRODUCTION AND PREVIOUS WORK

Wireless technology becomes more widespread as new data communication standards emerge, which enable higher data rates. The parallel evolution of personal, local and metropolitan area networks provides the end users with a choice of which infrastructure to use for a given application. Following the trend for universality, the concept of the multi-radio device (station) was introduced in [1] to allow the simultaneous operation of different networks.

Unfortunately, the problem of the multi-standard operation at the media access control (MAC) layer has yet received much attention in the scientific literature. Some papers (see, for example, [1], [2] and [3]) cover IEEE 802.11 (WiFi) [4] and IEEE 802.15.1 (Bluetooth) co-existence issues.

Another case is IEEE 802.16 (WiMAX) [5] and IEEE 802.11 cooperation. Although these standards adopt drastically different MAC protocols, the capability of 802.11 reuse by 802.16 in the mesh mode was demonstrated in [6]. In [7] the general co-existence evaluation approach was shown and [8], 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, where the base station of 802.16 and the hybrid coordinator of 802.11e are co-located.

In this paper we address the cooperation between 802.11 and 802.16 standards. But by contrast to the approach of [8] we consider the more realistic scenario, where the central coordinating node is absent in the system. Instead, we discuss the problem of the MAC coordination within a multi-radio station itself, thus avoiding any restriction on the network topology.

The rest of the paper is structured as follows. In Section II we provide a deeper insight into the separate functioning of 802.11 and 802.16 standards. Section III introduces the concept of the MAC coordination and presents a set of coordination algorithms. Section IV analytically evaluates the performance of these algorithms from the MAC goodput point of view. In Section V the simulation results are presented and Section VI concludes the paper.

II. NON-COOPERATIVE FUNCTIONING

A. *IEEE 802.11*

From the MAC layer point of view, IEEE 802.11 provides both distributed and centralized multiple access of a group of stations to the shared communications channel. 802.11 supports several modes of operation, including the most common *infrastructure* mode, in which the *access point* (AP) becomes the central network node. The AP is responsible for the communication between the stations and is mandated to use a contention channel access protocol, that is built on top of the truncated binary exponential backoff collision resolution protocol. This protocol is fully determined by three parameters: the *arbitration inter-frame space* (AIFS) interval, which each station waits prior to channel contention and the pair of the minimum (CW_{min}) and the maximum (CW_{max}) contention windows, that regulate the uniform sampling of random numbers.

IEEE 802.11e [4] introduces the quality of service enhancements of the earlier versions of the standard and adopts the concept of the *transmission opportunity* (TXOP), which is illustrated in Fig. 1. The TXOP may be regarded as a sequence of frames during a transaction, with a specified upper limit on duration. Its transmission is only initiated if both channel state detection functions 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. The TXOP transmission is precluded by the AIFS interval and the random number of slots. Commonly, the source station initiates the transaction with a *request to send* (RTS) frame, which is responded with a *clear to send* (CTS) frame after the *short inter-frame space* (SIFS) interval by the destination station. The source station then transmits aggregated data packets (DATA) with a single physical preamble, which is subject to the acknowledgment with the *block acknowledgment* (BA) frame by the destination. In case of unused TXOP time remaining, the source releases this time by a *contention-free end* (CFE) frame.

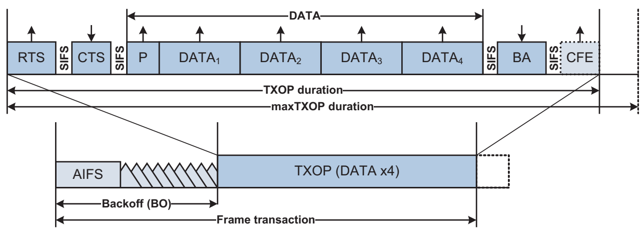

Figure 1: IEEE 802.11 typical TXOP (above) and frame transaction (below) structures.

B. IEEE 802.16

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

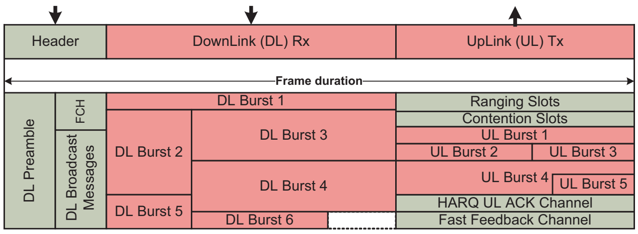

Figure 2: IEEE 802.16 simplified frame (above) and complete OFDMA frame (below) structures.

III. Cooperative Functioning

A. MAC Coordination Concept

To enable the simultaneous operation of 802.11 and 802.16 a special entity on top of the respective MAC layers may be implemented for the purposes of the MAC coordination (MC) [9]. The MC performs the scheduling of both network activities within a multi-radio (MR) station. As 802.16 is schedule-based, the MC only monitors its transmit (Tx) and receive (Rx) activity and allows/denies the channel access of 802.11 part.

For the cooperation of 802.11 and 802.16 within a MR station two principally different implementation possibilities exist (see Fig. 3). One of them uses one reconfigurable antenna [10], which becomes *shared* in terms of the network access. Clearly, this design excludes any simultaneous Tx/Rx operation (see Table 1) by two standards. Another possibility is to use two *separate* antennas: one for each of the cooperating standards. To avoid radio-to-radio interference, Tx-Rx and Rx-Tx operation should be excluded. Otherwise, the ongoing transmission deteriorates any reception by the alternative standard. 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 information.

Table 1: MR station technical limitations.

802.11-802.16	Shared antenna	Separate antennas
Rx-Rx	Denial	Allowance
Rx-Tx	Denial	Denial
Tx-Rx	Denial	Denial
Tx-Tx	Denial	Allowance

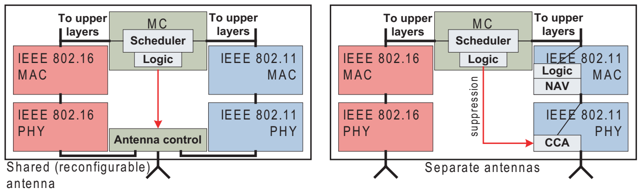

Figure 3: Shared (left) and separate (right) antennas MR station structures.

B. Basic Algorithm

Here we present the simplest coordination algorithm, which is referred to as the *Basic* in what follows. This algorithm operates under both shared and separate antennas technical limitations (see Table 1) and its main idea is to allow 802.11 transmission only in gaps between 802.16 activity (see Fig. 4). The Basic algorithm utilizes static *atomic operation*, which may be reasonably set to the maximum TXOP duration. Therefore, as actual TXOP duration is always less than its maximum, some operation time gets wasted. This necessarily leads to the less effective performance.

The implementation of the above algorithm is straightforward and involves an additional function call to the MC. 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 atomic operation from the MC. Analyzing the 802.16 schedule, the MC 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.

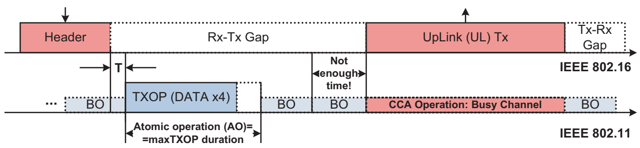

Figure 4: Basic algorithm operation.

Summarizing, we may list the following properties of the Basic algorithm:
+ Easy implementation.
+ Suitable for both shared and separate antennas.
− Static atomic operation, resources waste.
− Uses only activity gaps, low performance.

C. Enhanced Algorithm

In order to upgrade the performance of the Basic algorithm, an *Enhanced* algorithm may be introduced. Its idea is similar with the coexistence-aware TXOP adaptation approach from [1]. It also operates under both types of antenna limitations (see Table 1) and utilizes only gaps between 802.16 activity. However, the Enhanced algorithm varies the atomic operation to adjust tighter to the available operation time (see Fig. 5).

Firstly, the 802.11 MAC calculates the exact time, necessary for performing the atomic operation to avoid its waste. Importantly, that the Enhanced algorithm calculates the actual TXOP duration to avoid operation time waste. This value is obtained by fitting the maximum of buffered data packets into a TXOP. Secondly, a blank request is issued to the MC. The MC analyzes the 802.16 schedule and returns the time remaining before the forthcoming 802.16 activity. 802.11 MAC then decides, whether this time is sufficient to transmit the pending TXOP. In case it not, 802.11 MAC tries to fit less data packets into the TXOP unless the transmission is possible within the time available or TXOP is empty.

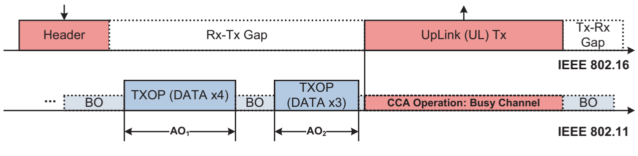

Figure 5: Enhanced algorithm operation.

The summary of the Enhanced algorithm is as follows:
+ Dynamic atomic operation, upgraded performance.
+ Suitable for both shared and separate antennas.
− High computational intensity, more difficult implementation.
− Uses only activity gaps, not-maximum performance.

D. *Suppressing Enhanced Algorithm*

We emphasize, that the previous two algorithms utilize only the gaps between 802.16 activity. By relaxing this restriction, the higher performance could be achieved. However, enabling simultaneous Tx-Tx and Rx-Rx operation is only possible in the framework of the separate antennas technical limitations (see Table 1). We refer to this algorithm as the *Suppressing* enhanced algorithm in the rest of the paper.

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

The Suppressing algorithm may be regarded as the extension of the Enhanced algorithm for separate antennas (see Fig. 6). The operation during 802.16 activity gaps is thus remains unchanged. In order to enable simultaneous operation, the transmission of a TXOP 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). The typical TXOP transmits RTS, DATA and, optionally, CFE frames, while receives CTS and BA frames (see Fig. 1). To simplify Tx/Rx TXOP separation we introduce a modified TXOP, which consists of CTS to itself and DATA frames in the Tx part and BA frame in the Rx part (see Fig. 6). Summarizing, the algorithm's features are:
+ Use of 802.16 UL activity, additional Tx time.
+ Dynamic atomic operation, upgraded performance.
− Suitable only for separate antennas.
− Need of CCA suppression, more difficult implementation.

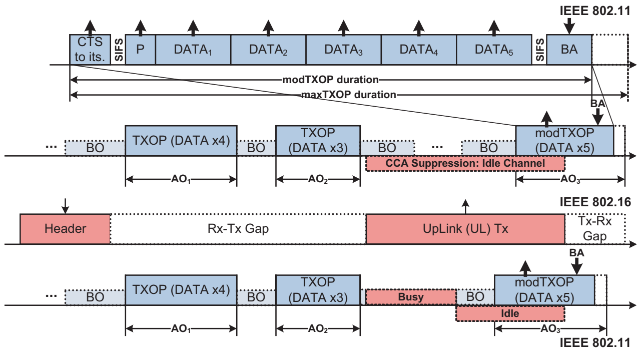

Figure 6: Fully-suppressing (above) and Partially-suppressing (below) enhanced algorithms operation.

The *Fully-suppressing* implementation of the Suppressing algorithm jams the CCA signal during the whole UL activity of 802.16. Following the Enhanced algorithm rules, the 802.11 backoffs until the transmission of the modified TXOP is possible and its Rx part avoids coincidence with 802.16 UL subframe. The *Partially-suppressing* implementation of the Suppressing algorithm starts to jam the CCA signal after the predefined time, necessary to avoid the coincidence of the Rx part of the modified TXOP with the UL sub-frame of 802.16.

IV. Performance Analysis

A. *System Model*

Remember, that during the MC operation the schedule of 802.16 remains unchanged. We, therefore, define the MAC *goodput* of the MR station as the portion of 802.11 PHY layer data rate available for the data transmission at the MAC layer. Below the system is observed under the set of restrictions. We firstly assume that there is only one user station in the system, which is a MR station. It transmits useful data in both 802.11 and 802.16 networks and receives service information.

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. 802.11 part of the MR station transmits constant-size data packets and is observed under *saturation conditions*, that is it always has a packet ready for transmission. The communications channel is noiseless and since no other 802.11 station is present in the system, the MR station always initiates backoff with the minimum contention window size of CW_{min}. Clearly, thus defined goodput value is the achievable maximum for the practical system operation.

B. *Single TXOP per Frame*

Consider the behavior of the Basic coordination algorithm. Practically, the number of TXOP transmissions per frame is not constant and varies due to the random backoff time. However, the difference between the maximum number of TXOPs per frame and the respective minimum number is always 1. Here we concentrate on the case, when either 0 or 1 TXOP transmission is possible per 802.16 Rx-Tx gap and the corresponding goodput value (G_1^B).

In Fig. 4 we observe that the MC 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 ($T_{maxTXOP}$). However, of the tagged backoff only the remainder should be accounted for, that does not coincide with the header of 802.16 (denoted by T in Fig. 4).

Generally, the backoff time (T_{BO}) is a concatenation of a deterministic AIFS interval and a random number of slots, that is, $T_{BO} = T_{AIFS} + WT_{slot}$, where $W \in \{0, 1, ..., CW_{min}\}$. We firstly compute the probability that the number of slots in the tagged backoff (W') equals to the exact value of y ($Pr\{W' = y\}$). Accounting for the fact that the number of consecutive backoffs before the tagged one is sufficiently large and applying the renewal theory [11] we obtain the following expression for the sought probability:

$$Pr\{W' = y\} = \frac{T_{AIFS} + yT_{slot}}{\sum\limits_{i=0}^{CW_{min}} T_{AIFS} + iT_{slot}}. \quad (1)$$

From the above arguments it follows that the interval T is distributed uniformly over the duration of the tagged backoff, which implies:

$$Pr\{T = x|W' = y\} = \begin{cases} \frac{1}{T_{AIFS}+yT_{slot}}, 1<x<T_{AIFS}+yT_{slot} \\ 0, otherwise. \end{cases} \quad (2)$$

By averaging over the possible values of y we get the respective unconditional probability as:

$$Pr\{T = x\} = \sum_{y=0}^{CW_{min}} Pr\{T = x|W' = y\}Pr\{W' = y\}. \quad (3)$$

Let X present the threshold value of the backoff part T that still results in one TXOP transmission per frame. This value is given by:

$$X = T_{RxTx} - T_{maxTXOP}, \quad (4)$$

where T_{RxTx} is the duration of the 802.16 Rx-Tx gap. The probability that T does not exceed X is readily obtained as:

$$Pr\{T \le X\} = \sum_{x=1}^{X} Pr\{T = x\}. \quad (5)$$

The final goodput value for the considered case may be calculated using the above probability:

$$G_1^B = \frac{8LQ \cdot Pr\{T \le X\}}{T_{frame}}, \quad (6)$$

where L is the packet length in bytes, Q is the maximum number of packets that fit into one TXOP and T_{frame} is the duration of 802.16 frame.

C. *Multiple TXOPs per Frame*

Here we concentrate on the case, when the minimum number of the TXOPs per frame is q and the maximum number is $q+1$. Due to the space limitations we consider only the value of $q = 1$ below. The calculations for any natural $q > 1$ are made similarly. As before, we derive the threshold value for the random backoff (X) that now results in two TXOP transmissions per frame. However, this time the random backoff comprises two parts: the remainder T and the full backoff time T_{BO} between two consecutive TXOPs. The indicated threshold is thus equal to:

$$X = T_{RxTx} - T_{TXOP} - T_{maxTXOP}, \quad (7)$$

where T_{TXOP} is the actual duration of the (first) TXOP with the maximum of packets. Further, we calculate the probability, that T_{BO} is equal to the exact value of x:

$$Pr\{T_{BO} = z\} = \begin{cases} \frac{1}{CW_{min}+1}, z=T_{AIFS}+iT_{slot} \\ 0, otherwise, \end{cases} \quad (8)$$

for all $i \in \{0, 1, ..., CW_{min}\}$. The probability that the sum of T and T_{BO} is equal to some exact value of y may now be computed as the convolution of the distributions (3) and (8):

$$Pr\{T + T_{BO} = y\} = \sum_{x=1}^{y} Pr\{T = x\}Pr\{T_{BO} = y - x\}. \quad (9)$$

The value of $Pr\{T+T_{BO} \le X\}$ is obtained similarly to (5) and may be substituted into the final expression:

$$G_2^B = \frac{8LQ \cdot (1 + Pr\{T + T_{BO} \le X\})}{T_{frame}}. \quad (10)$$

D. *Enhanced Algorithm*

The goodput estimation of the Enhanced algorithm is obtained as the generalization of the above approach. We notice, that under the saturation conditions only the last TXOP of those transmitted per frame may vary, subject to the remaining time in the Rx-Tx gap. Again, a general problem may be solved for q and $q + 1$ TXOPs, which we do below for $q = 1$. We firstly compute a set of thresholds $X(i)$ that result in the transmission of the second TXOP, containing exactly i data packets:

$$X(i) = T_{RxTx} - T_{TXOP} - T_{TXOP}(i), \quad (11)$$

where $T_{TXOP}(i)$ is the actual duration of the TXOP, containing exactly i packets. Once the thresholds are computed, we consider the event E_i that the TXOP with i packets is transmitted, conditioning on the fact that TXOP with $i+1$ packets is not transmitted. Further, we establish the probabilities $Pr\{E_i\}$ using (9), (5) and the respective thresholds $X(i)$. Denote the random number of packets in the last TXOP by Q_{last}. The average of Q_{last} is thus given by:

$$E[Q_{last}] = \sum_{i=1}^{Q} iPr\{E_i\}. \quad (12)$$

The resulting goodput value is thus:

$$G_2^E = \frac{8L \cdot (Q + E[Q_{last}])}{T_{frame}}. \quad (13)$$

E. Suppressing Enhanced Algorithm

To derive the MAC goodput of the Suppressing algorithm, we should add to the Enhanced algorithm goodput the term of one modified TXOP per frame (see Fig. 6). As the system operates in the saturation conditions, the modified TXOP contains the maximum number of packets (Q_{mod}), which immediately yields the following:

$$G_3^S = G_2^E + \frac{8LQ'}{T_{frame}} = \frac{8L \cdot (Q + E[Q_{last}] + Q_{mod})}{T_{frame}}. \quad (14)$$

V. Numerical Results

A. Simulation Scenario Summary

In order to verify the above analytical results, a simplified event-driven simulation program was developed, that accounts for the necessary details of the considered system model. In particular, to saturate the UL transmission, the constant DVD flow of 9.8 Mbps is transmitted in the UL sub-frame of IEEE 802.16e standard. IEEE 802.11n+e part of the MR station also transmits data packets and is put into saturation conditions. Each simulation run lasts 10 s, the other common simulation scenario parameters are summarized in Table 2.

Table 2: Common 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_{RxTx})	2.5 ms

IEEE 802.11 parameter	Value
Maximum TXOP duration ($T_{maxTXOP}$)	1.3 ms
Contention windows: CW_{min}/CW_{max}	7/15
AIFS interval duration (T_{AIFS})	43 μs
Slot time (T_{slot})	9 μs
Packet length (L)	1500 bytes

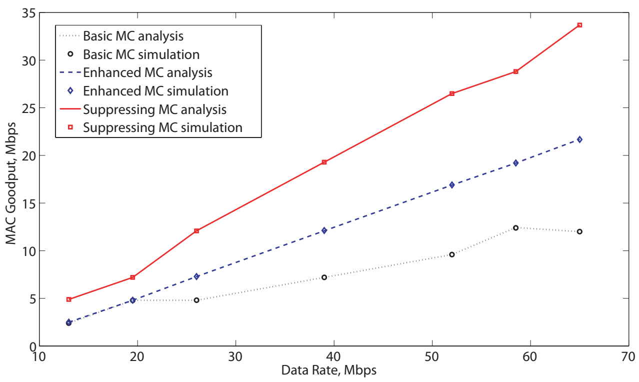

Figure 7: Coordination algorithms performance comparison.

B. Comparative Analysis

We plot both analytical and simulation MAC goodputs for the available set of PHY data rates in Fig. 7. Firstly, we observe that the introduced theoretical approach shows very good accordance with the simulation. Notice also, that the goodput of the Basic coordination algorithm is the lowest of the considered set, mainly due to it simplicity. The dependence for the Enhanced algorithm is almost linear, which is clear as the dynamic TXOP size makes it independent of the variable system parameters. Finally, the Suppressing algorithm outperforms its counterparts for the cost of a more difficult implementation. Additionally, we see that its effectiveness grows with the increasing data rate, as more data packets fit the additional TXOP per frame.

VI. Conclusion and Future Work

We demonstrated an approach to enable the simultaneous operation of IEEE 802.11 and IEEE 802.16 communication standards within a single multi-radio station. Three various algorithms were discussed that present the performance-complexity trade-off. The limitations of their implementation were also addressed. The performance of the considered algorithms was estimated in the framework of the simplified system model, which could be extended for the addition of the other stations into the network, as well as for the noisy channel conditions. It may be shown, that in the noisy channel the appropriate rate adaptation strategy may sufficiently improve the network performance. The development of the rate adaptation algorithms is thus the most likely direction of the future work.

References

[1] J. Zhu, A. Waltho, X. Yang, and X. Guo. Multi-radio coexistence: Challenges and opportunities. *Proceedings of 16th International Conference on Computer Communications and Networks*, 13-16:358–364, 2007.

[2] A. Kamerman. Coexistence between bluetooth and ieee 802.11 cck solutions to avoid mutual interference. Technical report, Lucent Technologies Bell Laboratories, also available as IEEE 802.11-00/162, 1999/2000.

[3] F. Wang, A. Nallanathan, and H. K. Garg. Introducing packet segmentation for the ieee 802.11b throughput enhancement in the presence of bluetooth. *2004 IEEE 59th Vehicular Technology Conference*, 4 (17-19):2252–2256, 2004.

[4] *IEEE Std 802.11e-2005, San Francisco, CA, USA, July, 2005.*

[5] *IEEE Std 802.16e-2005, Piscataway, NJ, USA, December 2005.*

[6] P. Djukic and S. Valaee. 802.16 mcf for 802.11a based mesh networks: A case for standards re-use. *23rd Biennial Symposium on Communications*, 1:186–189, 2006.

[7] S. Mangold. *Analysis of IEEE 802.11e and Application of Game Models for Support of Quality-of-Service in Coexisting Wireless Networks*. PhD thesis, RWTH Aachen University, 2003.

[8] L. Berlemann, C. Hoymann, G. R. Hiertz, and S. Mangold. Coexistence and interworking of ieee 802.16 and ieee 802.11(e). *IEEE 63rd Vehicular Technology Conference*, 1:27–31, 2006.

[9] K. Kahn. Directions in wireless research. In presentation, 2006. $http://www.soi.wide.ad.jp/class/20060000/materials\_for\_student/03/20060609-utokyo-kevin.pdf$.

[10] C. Zhang, S. Yang, H. K. Pan, A. E. Fathy, S. El-Ghazaly, and V. Nair. Reconfigurable antenna for simultaneous multi-service wireless applications. *IEEE Radio and Wireless Symposium*, 9-11:543–546, 2007.

[11] L. Kleinrock. *Queueing Systems Volume I: Theory*. New York, 1975.