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Comparison of IEEE 802.11e and IEEE 802.15.3 MAC

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Abstract— **IEEE 802.11 and IEEE 802.15.3 target at designing PHY and MAC specifications for wireless local area network (WLAN) and wireless personal area network (WPAN), respectively. They adopt different philosophies for MAC design, namely CSMA/CA in 802.11 and TDMA in 802.15.3. An interesting problem is the performance of each MAC working on the same physical layer, e.g., ultra wideband (UWB). This problem has gained much attention in industry standard meetings recently. In this paper, we compare the performance of two access methods defined in IEEE 802.11e (hybrid coordination function (HCF)) and IEEE 802.15.3 (TDMA) under the same UWB physical layer in terms of the throughput and power management. The results show that the newly added mechanisms of 802.11e, such as transmission opportunity (TXOP) and Block Ack, improve its throughput greatly, making it comparable to that of 802.15.3. In addition, 802.15.3 MAC has easier power management by utilizing its TDMA access method.**

Keywords— **Media access control (MAC), 802.11, 802.15.3, Ultra Wide Bind (UWB), WLAN, WPAN.**

I. INTRODUCTION

IEEE 802.11 [6] and IEEE 802.15.3 [7] are two of the most popular wireless systems currently. IEEE 802.11e, also known as MAC level QoS enhancement of 802.11 [6], introduces the key concept, HCF, which combines and enhances the access capabilities of DCF and PCF. IEEE 802.15.3, unlike 802.11e which is based on CSMA/CA, adopts a TDMA MAC scheme. Now, a natural question is what their performance will be under the high speed PHY, e.g., UWB, in terms of throughput, power management, etc. This has actually gained much attention in industry and IEEE standard meetings. Although there has been some research in the field of 802.11e, there is seldom work reported in 802.15.3 MAC, let alone the comparison between them. In this paper, we will give a detailed comparison between IEEE 802.11e MAC and IEEE 802.15.3 MAC based on the same UWB PHY, e.g., proposed by Intel [12]. Note that the basic 802.11 a/b MAC can be regarded as a special case of 802.11e. Based on the comparison, we can gain some basic insight regarding the performance of the two MAC schemes.

In [1-3], Xiao and Rosdahl pointed out that the throughput limit for current 802.11 DCF is 75Mbps, which is unacceptable for high data rate applications. They also showed that a new acknowledge scheme (burst transmission, now called Block Ack) can greatly increase the throughput limit, but no more details. XtremeSpectrum® gave a brief comparison between IEEE 802.11e MAC and IEEE 802.15.3 MAC [4]. Based on [4], IEEE 802.11e is good for dynamic traffic but with the cost of complexity. On the other hand, 802.15.3 MAC requires a request-response scheme to adapt to network changes. In [5], Magis Networks® analyzed the throughput of 802.11a/e systems and showed that a lot of overhead or waste are from headers, inter frame spaces and channel errors. In [9], Grilo and Nunes presented the results of comparison between 802.11e and legacy MAC (802.11 DCF and PCF), and showed that 802.11e can improve performance considerably. In [10], Mangold et al. discussed the performance of HCF in various conditions, including TXOP size impact, overlapping QoS BSSs. In [11], Choi et al. evaluated the contention based channel access method (used called EDCF, now called EDCA) with the TXOP feature enabled. However, the previous studies did not consider some latest key features, such as Block Ack. More important, there is no work to address the question: the performance comparison between 802.11e MAC and 802.15.3 in the upcoming high speed PHY. This is what we will discuss in this paper.

In the following sections, we first give an overview of the 802.11e MAC and 802.15.3 MAC. Then we compare the two access methods in terms of: 1) throughput, 2) power management in Section III and IV, respectively. We draw the conclusion in Section V.

II. OVERVIEW of 802.11e and 802.15.3 MAC

2.1 IEEE 802.11e HCF

The HCF uses both enhanced distributed channel access (EDCA) mechanism for contention based transfer and a hybrid controlled channel access (HCCA) mechanism for contention free transfer. The former one is for Prioritized QoS services while the latter one is for Parameterized QoS services. Under HCF, the basic unit of channel allocation is the transmission opportunity (TXOP). Each TXOP is defined by a starting time and a defined maximum length. The TXOP obtained by EDCA contention is called EDCA TXOP and the TXOP obtained by receiving a CF-Poll during contention period or contention free period is called HCCA TXOP or polled TXOP.

2.1.1 EDCA

The EDCA mechanism provides differentiated, distributed access to the wireless medium for 8 user priorities (UPs) for QoS stations (QSTAs). EDCA mechanism defines access categories (ACs) that provide support for the delivery of traf-

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fic with UPs at the QSTAs. EDCA is similar to the usual legacy DCF access schemes, but differs in the following aspects. First, EDCA is defined for each AC, instead of each STA. Second, EDCA contends for TXOP which may allow multiple frame transmissions instead of one frame transmission. Third, EDCA uses a set of EDCA parameters from the EDCA Parameter Set element for TXOPs contention, which are different from the constant values used in DCF. Some of these parameters are:

- The arbitration inter frame spacing (AIFS), is different for each AC.
- The contention window sizes CW_{min} and CW_{max} are different for each AC.

2.1.2 HCCA

The HCCA manages access to the wireless medium using a hybrid coordinator that has higher medium access priority than non-AP STAs. This allows it to transfer traffic from itself and to allocate TXOPs to non-AP QSTAs. In HCCA scheme, the QSTAs win TXOPs by receiving CF-Poll from HC. The HC is a type of centralized coordinator (point coordinator), but has fundamental differences from the PC used in PCF. The most important one is that HCF frame exchange sequences may be used during both CP (contention period) and CFP (contention free period). Another difference is that the HC grants a non-AP QSTA a polled TXOP with duration specified in a QoS (+) CF-Poll frame which enables multiple frame exchange sequences instead of only one frame transmission of PCF scheme. In addition, 802.11e also introduces the Block Acknowledgement (Block Ack) mechanism which allows a block of MPDUs (MAC Protocol Data Units) to be transmitted before an ACK frame is issued by the recipient, each separated by a SIFS period. This improves channel efficiency by aggregating several acknowledgements into one frame. Another new mechanism is the direct link protocol (DLP) which allows direct frames transmissions between QSTAs. However, the set up of DLP requires QoS AP's (QAP) involvement.

2.2 IEEE 802.15.3 TDMA

In 802.15.3, the basic component is piconet and devices (DEV) among a piconet can communicate with each other. One of the DEVs is assumed the role of piconet coordinator (PNC) which can provides the basic timing via beacons as well as QoS, power management and etc.

In 802.15.3, the channel time is divided into superframes, with each superframe beginning with a beacon. Each superframe is composed of three major components: the beacon, the optional contention access period (CAP) and the channel time allocation period (CTAP). The CAP uses CSMA/CA for medium access. The CTAP, on the other hand, uses TDMA protocol where the DEVs are assigned specified time slots for medium access. The time slots of DEVs are called Channel Time Allocations (CTAs) which is allocated by the PNC. Each CTA is defined by a start time and a duration value so that each DEV knows when and how long it can transmit. In CTAP of 802.15.3, the guard times are used to keep transmissions in adjacent CTAs from colliding. In addition, a SIFS time is required to ensure sufficient turnaround time between transmissions.

In IEEE 802.15.3 system, three ACK policies are defined, namely, Imm-ACK, No-ACK, and Dly-ACK. For Imm-ACK, the receiver issues an ACK frame to the transmitter on every received MPDU. No-ACK means no ACK frame is issued; while Dly-ACK is the tradeoff between above two. The receiver issues an ACK frame for multiple received MPDUs.

III. THROUGHPUT COMPARISON

The throughput comparison is based on MAC level payload data and protocol overheads without considering the retransmissions. In each scheme, we derive the throughput based on normal Ack (Immediate Ack), Block Ack or Dly-Ack respectively. For 802.11e HCF, we consider EDCA and HCCA. For 802.15.3, we only consider the mandatory access scheme based on TDMA.

Currently, WLAN and WPAN both support multiple PHY rates. However, higher rates are more prone to errors. So base rate set or basic rate set is defined to ensure the robustness of some key control frame or key part of frame, such as MAC header. In 802.11, some control frames, such as Ack, can only be transmitted at basic rates. In 802.15.3, MAC headers are transmitted at base rates. When the base/basic rate is low, a large portion of channel time may be occupied by control frame or MAC header transmissions.

The overheads of data transmission in an 802.11e and 802.15.3 are composed of the following items:

- PHY preambles and MAC headers. MAC header is transmitted at base rate for 802.15.3.
- Control frames and other non-Data frames (e.g., CF-Poll in 802.11e).
- Inter-frame spaces (AIFS, SIFS and PIFS in 802.11e, Guard time, SIFS and MIFS in 802.15.3).
- Backoff time for 802.11e EDCA and 802.11 DCF scheme.

3.1 IEEE 802.11e MAC Throughput

For each frame transmitted in 802.11, the total transmission time is composed of the following durations: PHY preamble length, PHY header, MAC header, frame body (if any) and frame check sequence (FCS). The transmission time of a data or management frame is shown in Fig 1 and is given by

$$T_{mpdu} = T_{Preamble} + T_{PHY_HDR} + T_{MAC_HDR} + T_{MSDU} + T_{FCS}. \quad (1)$$

The time for control frame transmission is shown in Fig 2.We should point out that control frames (head and body if any) should be transmitted at basic rates (except for Block-

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AckReq and BlockAck). The transmission time is given by

$$T_{ctrl} = T_{Preamble} + T_{PHY_HDR} + T_{MAC_HDR} + T_{ctrl_body} + T_{FCS} \quad (2)$$

Fig.1. Data or Management frame overheads

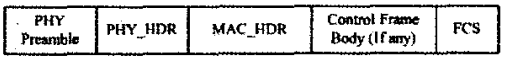

Fig.2. Control frame overheads

3.1.1 EDCA Scheme

a) Normal Ack

The normal Ack (Imm-ACK) is shown in Fig. 3. If an AC is allocated a TXOP with T_{TXOP}, and the MPDU is with size L Bytes, then the number of MPDU that can be fit in this TXOP is given by

$$N = \left\lfloor \frac{T_{TXOP}}{T_{MPDU} + SIFS \times 2 + T_{ACK}} \right\rfloor. \quad (3)$$

where [x] denotes the largest number no greater than x. Now, assume CW is the mean of the contention window, the throughput with normal Ack is given by

$$Th_{ACK} = \frac{L \times N \times 8}{AIFS + CW \times aSlotTime + T_{TXOP})}. \quad (4)$$

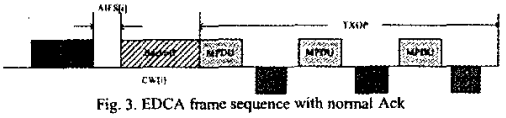

Fig. 3. EDCA frame sequence with normal Ack

b) Block Ack

If using Block Ack, the receiver can send a Block Ack frame to acknowledge multiple frames. We assume that the BlockAckReq (BAR) frame and Block Ack (BA) frame are completed in the same TXOP. The frame exchange sequences are shown in Fig 4. Given the TXOP as T_{TXOP}, the number of MPDUs in the TXOP is given by

$$N = \left\lfloor \frac{T_{TXOP} - T_{BAR} - SIFS \times 2 - T_{BA}}{T_{MPDU} + SIFS} \right\rfloor. \quad (5)$$

The throughput of Block Ack is given by

$$Th_{BA} = \frac{L \times N \times 8}{AIFS + CW \times aSlotTime + T_{TXOP}}, \quad (6)$$

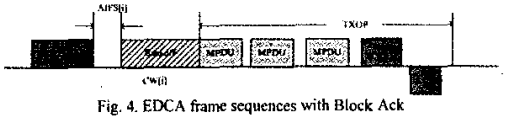

Fig. 4. EDCA frame sequences with Block Ack

3.1.2 HCCA Scheme

a) Normal Ack

The frame exchange sequences are shown in Fig. 5. The number of frames transmitted in a given TXOP can be obtained similarly as (1). So, the throughput of normal Ack in HCCA is given by

$$Th_{ACK} = \frac{L \times N \times 8}{T_{CF-Poll} + SIFS + T_{TXOP}} \quad (7)$$

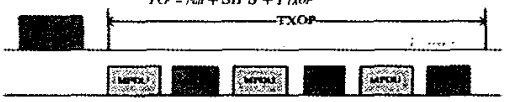

Fig. 5. HCCA frame sequences with normal Ack

b) Block Ack

Similarly, the HCCA Block Ack throughput is given by

$$Th_{BA} = \frac{L \times N \times 8}{T_{CF-Poll} + SIFS + T_{TXOP}}. \quad (8)$$

3.2 IEEE 802.15.3 MAC Throughput

As mentioned before, we do not consider the optional CAP part of 802.15.3 MAC. For the TDMA method, the main overheads are the IFS and guard times, as well as the control frame and low rate of MAC headers. From Fig. 6, we can see that the time used to transmission a frame is given by

$$T_{MPDU} = T_{Preamble} + T_{PHY_HDR} + T_{MAC_HDR} + T_{MSDU} + T_{FCS} \quad (9)$$

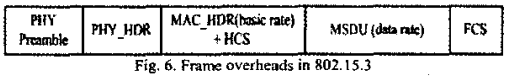

Fig. 6. Frame overheads in 802.15.3

3.2.1 Imm-Ack

The Imm-Ack is shown in Fig 7. Given the CTA time as T_{CTA}, and MPDU as L bytes, the frame number that can be transmitted in a CTA is given by

$$N = \left\lfloor \frac{T_{CTA} - T_{guard}}{T_{MPDU} + SIFS \times 2 + T_{ACK}} \right\rfloor. \quad (10)$$

The throughput of Imm-ACK in 802.15.3 is given by

$$Th_{Imm-ACK} = \frac{L \times 8 \times N}{T_{CTA}}. \quad (11)$$

Fig. 7. Imm-Ack frame exchange sequences

3.2.2 Dly-Ack

The Dly-Ack is depicted in Fig. 8.

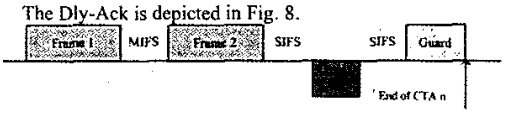

Fig. 8. Dly-Ack frame exchange sequences

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The number of data frames is given by

$$N = \frac{T_{CTA} - T_{Dly-ACK} - T_{guard} - SIFS \times 2 + MIFS}{T_{MPDU} + MIFS}, \quad (12)$$

The throughput of Dly-ACK is given by

$$Th_{Dly-ACK} = \frac{L \times 8 \times N}{T_{CTA}}. \quad (13)$$

3.3 Numerical Results

We assume there are always data in buffer for transmission. Some of the PHY parameters are from the Intel's proposal [12]. Other parameters are listed as below:

- Basic rate= 54 Mbps, PHY rate for data = 200 Mbps.
- PHY preamble and header = 9.4μs.
- MIFS = 5μs, SIFS = 8μs, Slot time = 6μs.
- MPDU size = 1000 bytes, TXOP or CTA = 3 ms.
- CW_{min} = 15 for 802.11e EDCA and CW_{min} = 31 for 802.11 DCF.

The TXOP and CW_{min} values are similar to those specified for the video class in 802.11e.

Case 1: Throughput vs. PHY rate

Fig. 9 shows that the throughputs for 802.11e (EDCA and HCCA) are very close. The throughputs of 802.15.3 MAC are greater than those of 802.11e in all the cases. However, the differences are not significant (16.6% for normal Ack and below 10% for Block Ack or Dly-ACK). In addition, we can see for both 802.11 and 802.15.3, the improvement of block acknowledgement is significant (from 50% to 100%). Finally, we can also see that DCF can only achieve around 50 Mbps throughput even when the PHY rate is 600 Mbps. This is due to the large part of overheads in DCF, such as the CW, the inter-frame space and control frames.

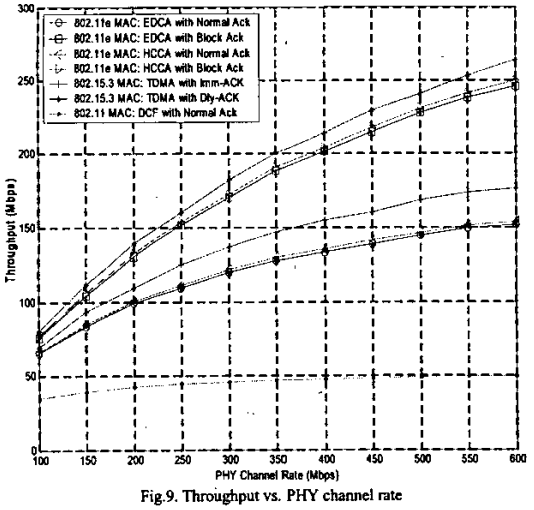

Fig.9. Throughput vs. PHY channel rate

Case 2: Throughput vs. TXOP/CTA length

The results in Fig 10 show that when TXOP or CTA length is less than 0.5 ms, the throughput may fluctuate. This is due to the waste of some TXOP/CTA time when another MDPU cannot be fit into this TXOP/CTA. When the TXOP/CTA is greater than 1ms, the throughput grows steadily. When the TXOP/CTA is around 0.2 ~ 0.5 ms, the throughput of HCCA is better than that of EDCA, while TDMA is a little better than that of HCCA.

From above figures, we can see that: 1) Block Ack can significantly improve the channel efficiency, 2) the TXOP/CTA length is an important mechanism to improve throughput, 3) the EDCA/HCCA/TDMA can get comparable throughput if TXOP/CTA length is with reasonable value, and 4) DCF is not suitable for high rate PHY.

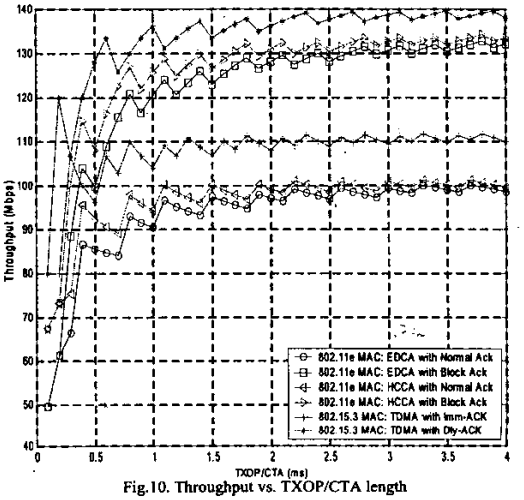

Fig.10. Throughput vs. TXOP/CTA length

IV. POWER MANAGEMENT

Power management is pretty easy in 802.15.3. This is because the DEV can know exactly his CTA location in the superframe from the beacon broadcasting. It can sleep in the CTA which does not belong to its flows and wake up only in its own CTA. 802.15.3 defines three modes to enable DEVs to turn off for one or more superframes: device synchronized power save (DSPS) mode, piconet-synchronized power save (PSPS) mode and asynchronous power save (APS) mode. The goal of those modes is to enable synchronized wakeups and sleeps for those communicating DEVs.

In 802.11, the power management is complicated since STA cannot know in advance its granted channel time. The STA in 802.11 should wake up to track information from the beacons to know if it has buffered data at AP. If so, it should try to send PS-Poll frame to AP to ask for the data. Before it has successfully received the data, it should be active. This may be quite a long time if the traffic load is heavy in the

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network. To illustrate this, we calculate the waiting time of a STA from the point it tries to send PS-Poll to the point that it receives the data from AP.

Suppose there are two ACs, namely AC_BE and AC_VI, in the WLAN. The PS-Poll is sent with AC_BE parameters to reduce collision probabilities after beacon, as specified by IEEE 802.11e [6]. We use the p-persistent model to calculate the waiting time of receiving a frame from AP using PS-Poll [8]. Suppose the CW_{min} of AC_VI and AC_BE are CW_1 and CW_2, respectively. The flow number of AC_VI and AC_BE are N_1 and N_2. The transmission probabilities τ_1 and τ_2 are given by [8],

$$\begin{cases} \tau_i = \dfrac{2}{1+CW_i+P_{busy,i}\times CW_i\times\sum_{j=0}^{m-1}(2P_{busy,i})^j} \\ P_{busy,i} = 1-(1-\tau_i)^{Ni-1}\times\prod_{j\neq i}(1-\tau_j)^{Nj} \end{cases} \quad (14)$$

where m is the Backoff stage and $P_{busy,i}$ is the conditional busy probability of a station belonging to class i.

The transmission probability of the power saving STA, the probability that the channel is idle and the probability that other stations (except the power saving station) transmit are given respectively by

$$\begin{cases} P_{ps} = \tau_2\times(1-\tau_1)^{N1}\times(1-\tau_2)^{N2-1} \\ Pidle = (1-\tau_1)^{N1}\times(1-\tau_2)^{N2} \\ P_{other} = 1-P_{ps}-P_{idle} \end{cases} \quad (15)$$

The waiting time is given by

$$Twait = (P_{idle}\times aSlotTime + P_{other}\times T_{data})/P_{ps} \quad (16)$$

where T_{data} denotes the time for data frame transmission, including payload data transmission, SIFS and ACK frame. The total time for receiving the frame from buffer is given by

$$T_{total_wait} = T_{wait} + T_{ps-poll} + SIFS + T_{data} \quad (17)$$

For evaluation, we assume N_2 is 1 and the average data frame is 1000 bytes. In Fig. 11, the Y-axis is the ratio between the total time (waiting time+ actual data transmission time) and the actual data transmission time for AC_BE. From Fig. 11, we can see that when the station number with video like traffic (AC_VI) increases, the waiting time increases considerably. The higher the contention probability, the longer the STA will wait. For CW_1=7, CW_2=15 and CW_1=15, CW_2=31, AC_BE has similar priority, however, STA waits longer for [7, 15] due to more contentions. We can see that the pure CSMA/CA based scheme is very inefficient in power saving due to uncertain waiting time and potential collisions.

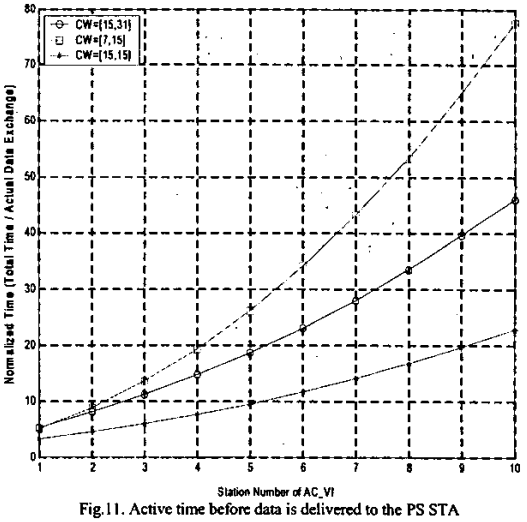

Fig.11. Active time before data is delivered to the PS STA

In 802.11e, a new mechanism, called APSD is introduced to enable power management efficiency. The key point is that the station only wakes up in pre-scheduled time, which is supported by QAP with HCF. This is very similar to the TDMA mechanism used in 802.15.3. This mechanism may improve the power save performance of 802.11e but increase complexity.

V. CONCLUSION

In this paper, we compared the 802.11e HCF MAC and 802.15.3 TDMA MAC mainly in terms of throughput and power management. The throughput difference between them is quite small. On the other hand, the power management of 802.15.3 is easier than that of 802.11e. However, this paper is not to draw any conclusion regarding which one is superior since there are many other issues such as complexity, QoS, etc need to be considered. These will be done in our future work.

REFERENCES

[1] Yang Xiao and Jon Rosdahl, "Throughput Analysis for IEEE 802.11a Higher Data Rates," IEEE 802.11 Plenary Meeting, March 2002. doc.: IEEE 802.11-02/138r0.

[2] Yang Xiao and Jon Rosdahl, "Throughput Limit for IEEE 802.11," IEEE 802.11 Interim Meeting, May 2002. doc.: IEEE 802.11-02-291r0.

[3] Yang Xiao and Jon Rosdahl, "Burst Transmission and Acknowledgement for Higher Data Rates over 100 Mbps," IEEE 802.11 WG. doc.: IEEE 802.11-02/309r0.

[4] XtremeSpectrum, "Trade-Off Analysis (802.11e versus 802.15.3 QoS Mechanism) White Paper", July 2002.

[5] Magis Networks, "IEEE 802.11e/a Throughput Analysis", 2003.

[6] IEEE 802.11e, MAC Enhancement for QoS, IEEE Std. 802.11e/D5.0, July 2003.

[7] IEEE 802.15.3, Wireless MAC and PHY Specifications for High Rate WPAN, IEEE 802.15.3™2003.

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INTEL-1029
U.S. Patent 8,219,129

[8] Jun Zhao, Qian Zhang, Zihua Guo and Wenwu Zhu, "Throughput and QoS Optimization in IEEE 802.11 WLAN," in *Proc. 3Gwireless'2002*, May 2002.

[9] Antonio Grilo and Mario Nunes, "Performance Evaluation of IEEE 802.11e," in *Proc. PIMRC*, September 2002.

[10] Stefan Mangold, Sunghyun Choi, Peter May, Ole Klein, Guido Hiertz and Lothar Stibor, "IEEE 802.11e Wireless LAN for Quality of Service," In *Proceedings of the European Wireless*, Vol. 1, pp. 32-39, Florence, Italy, February 2002.

[11] Sunghyun Choi, Javier del Prado, Sai Shankar N and Stefan Mangold, "IEEE 802.11e Contenion-Based Channel Access (EDCF) Performance Evaluation," in *Proc. IEEE ICC 2003*, May 2003.

[12] Jeff Foerster, V. Somayazulu, S. Roy, E. Green, K. Tinsley, C. Brabenac, D. Leeper and M. Ho (Intel Corporation), "Intel's Multi-band UWB PHY Proposal for IEEE 802.15.3a", IEEE 802.15.3 TG, doc.: 802.15-03/109r1, March 2003.

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