IEEE 802.15.3a Wireless Personal Area Networks – The MBOA Approach

Guido R. Hiertz, Yunpeng Zang, Jörg Habetha and Hamza Sirin

***Abstract*—A new generation of *Wireless Personal Area Networks (WPANs)* aims at high data rates of several hundred Mb/s. Based on *Ultrawideband (UWB)* technology theses WPANs make use of a decision of the *Federal Communications Commission (FCC)* which decided to allow low power emissions in the spectrum from 3 to 10GHz. Among direct sequence spread spectrum proposals the IEEE 802.15.3a *Task Group (TG)* received an OFDM based proposal from the *Multi Band OFDM Alliance (MBOA)*. Unlike competing technologies, the MBOA approach provides both, a new Physical Layer (PHY) proposal and a new, decentralized Medium Access Control (MAC) protocol, which differs from the legacy IEEE 802.15.3 MAC. In this paper we give technical description of the new MBOA MAC and PHY layer and provide insight to their performance by means of simulation.**

***Index Terms*—Multi Band OFDM Alliance (MBOA), Wireless Personal Area Networks (WPAN), Medium Access Control (MAC), Distributed Reservation Protocol (DRP), Quality of Service (QoS), Ultrawideband (UWB)**

I. Introduction

WIRELESS *Personal Area Networks (WPANs)* have become a ubiquitous technology. Bluetooth, as standardized by the IEEE WPAN *Working Group (WG)* 802.15 in 1999 [20], combines low cost and ease of use to a new class of wireless applications. Similar to Bluetooth in terms of cost, availability and customer satisfaction, the *Universal Serial Bus (USB)* became the dominating standard for short-range wired connections. With the introduction of version 2.0 of USB [21] the maximum throughput is increased from 12Mb/s to 480Mb/s. To combine the high data throughput of USB 2.0, its cheap deployment and availability in nearly every device of today's markets for Consumer Electronics (CE), multi-media systems and PC peripherals, with the wireless convenience and simple set-up features of Bluetooth, the *Multi Band OFDM Alliance (MBOA)* [1] proposes a new kind of WPAN, which fits the needs of a mass market. For a seamless integration of a wide variety of devices, the MBOA *Medium Access Control (MAC)* supports *Quality of Service (QoS)* by means of isochronous, as they are needed for support of wireless IEEE 1394 (Firewire, [17]) for example, and asynchronous data streams.

The IEEE 802.15.3 MAC [4] is based on central coordination. In a highly dynamic environment, which is typical for mobile applications of WPANs, frequent topology changes may happen, when devices switch on and off, move in and out of coverage. To overcome these drawbacks in terms of set-up and clustering overhead, the MBOA MAC works without any central coordination. Besides major industrial companies the MBOA receives support by the WiMedia Alliance [23], too.

In 2002 the *Federal Communications Commission (FCC)* opened the spectrum from 3 to 10GHz for a new class of PHY technology, called *Ultrawideband (UWB)* [24]. To support data rates of several hundred Mb/s, two competing consortia propose different *Physical Layer (PHY)* technologies to meet the requirements [18], [19] of the IEEE high rate WPAN *Task Group (TG)* 802.15.3a. On the one hand, the UWB Forum favors a *Direct Sequence (DS)* UWB approach. On the other hand, the MBOA favors the UWB OFDM approach. The latter one is based on well-known *Orthogonal Frequency Division Multiplexing (OFDM)* technology, which has proven its reliability in many applications and devices. Since silicon design manufacturers are familiar with OFDM, first products are likely to be shipped in 2005. Thus, and because of its huge market support, it can be expected that MBOA will set the de facto standard for the next generation of WPAN.

The authors have contributed key features to the MBOA MAC specification, which will be presented in this paper. The paper is organized as follows. In the following section (II.A) we will give an overview of the MBOA PHY technology. Then we will present the new MBOA MAC [5] in more detail in section III.A. Chapter IV contains simulation results for the MBOA MAC, and some conclusions are drawn in section V. Throughout this paper all units and abbreviations are defined according to [7].

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II. High Speed WPAN PHY

In this section we introduce the MBOA *Physical Layer (PHY)*, which uses the well known Orthogonal Frequency Division Multiplexing (OFDM) technology. The combination of band hopping, 528MHz wide frequency bands and OFDM technology forms a powerful basis for next generation high speed WPANs.

A. Multiband OFDM

To support a wireless version of USB 2.0 [22] the MBOA PHY is designed to achieve data rates of up to 480Mb/s. In between 3168MHz and 10560MHz five band groups are defined. Support of band group 1 is mandatory. Support for all others is optional. Besides the highest band group, all groups consist of three frequency bands. One frequency band in MBOA is 528MHz wide and is divided into 128 OFDM subcarriers. 122 out of them are used for data and pilot subcarriers, see Table 1.

TABLE 1
MODULATION, CODING & DATA RATES

Data Rate (Mb/s)	Modulation	Coding rate (R)	Coded bits per OFDM symbol (NCBPS)
53.3	QPSK	1/3	100
80	QPSK	½	100
106.7	QPSK	1/3	200
160	QPSK	½	200
200	QPSK	5/8	200
320	DCM	½	200
400	DCM	5/8	200
480	DCM	¾	200

Up to seven *Time Frequency Codes (TFC)* in conjunction with different preamble patterns and cover sequences support an efficient spatial reuse of every band group. Each TFC provides a hopping sequence. According to the TFC pattern, devices hop through the frequency bands in their band group. Hopping is done per OFDM symbol. Each symbol lasts 312.5ns. Time spreading is not applied for *Dual-Carrier Modulation (DCM)* with data rates in excess of 320Mb/s.

TABLE 2
PHY PARAMETERS

Parameter	Value
Number of data subcarriers	100
Number of pilot carriers	12
Number of guard carriers	10
Number of total subcarriers	122
Subcarrier frequency spacing	4.125MHz
Symbol interval (TSYM)	312.5ns

Robustness is increased due to bit interleaving. The symbol interleaver permutes the bits into blocks of six OFDM symbols. Thus a PHY PDU consists of a minimum of six OFDM symbols plus Preamble and PLCP header.

TABLE 3
INTERFRAME SPACES DEFINDED FOR MBOA

PHY Parameter	Value
pMIFSTime	6 * TSYM = 1.875µs
pSIFSTime	32 * TSYM = 10µs
pCCADetectTime	15 * TSYM = 4.6875µs
pBandSwitchTime	9.47ns

III. NEXT GENERATION WPAN MAC

In this section, we describe version 0.72 of the new MBOA MAC layer. It is designed for high-speed, short-range communication infrastructure-less networks.

A. MBOA

Support for QoS is a crucial feature for WPANs. Thus, eight traffic classes enable prioritization. These traffic classes are mapped to four *Access Categories (ACs)*. Furthermore, MBOA supports asynchronous and isochronous traffic based on packets of arbitrary length of up to 4095B.

1) Medium Access

To combine the efficiency of TDMA based systems with packet based technology MBOA introduces the Prioritized Channel Access (PCA) and the Distributed Reservation Protocol (DRP) [2], [3]. While the first one is well known from the Enhanced Distributed Channel Access (EDCA) defined in [8], the latter one is based on an advanced reservation scheme providing collision free access to the channel.

a) Prioritized Channel Access

The PCA is very similar to the *Enhanced Distributed Channel Access (EDCA)* [8] as surveyed by the authors in [9], [10], [11], [12]. It is a contention-based *Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)* scheme relying on a prioritized backoff procedure.

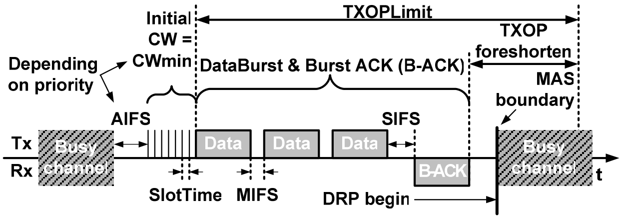

Fig. 1. The PCA is based on CSMA/CA. Devices start transmitting after a random period.

Virtual devices of different priority inside every physical device compete for the channel access. Prior to every transmission attempt a device has to sense the channel as idle for a static period called *Arbitration Interframe Space (AIFS)*. Afterwards, it has to keep on sensing the channel for multiples of a SlotTime. For the current MBOA PHY [6] a SlotTime is equal to "pSIFSTime + pCCADetectTime". The amount of SlotTimes is a random number drawn from a uniformly distributed interval of (0, CW). The initial value of CW is CWmin. The duration of AIFS and CWmin depend on the priority of the backoff. Whenever the device senses the channel as idle it decreases its slot counter by one. If the slot counter reaches zero the device may transmit a data packet. If the device senses the channel as busy, it freezes its slot counter. After the channel is sensed as idle for an AIFS period again, the backoff procedure starts counting down the remaining slots. With every failed transmission a device doubles its CW to reduce the probability of a collision with other devices.

b) Distributed Reservation Protocol

The *Distributed Reservation Protocol (DRP)* provides a collision free channel access. It announces future transmissions and thus allows devices to coordinate their channel access, see [2], [3]. Time is divided into superframes, which are comprising 256 *Medium Access Slots (MASs)* of length 256µs each. At the beginning of a superframe a *Beacon Period (BP)* consisting of n MAS, with 1≤n≤ mMaxBPLength, allows for the transmission of n*3 beacons. Each device must send a single beacon per BP. At the end of the BP the *Data Transfer Period (DTP)* starts, which lasts (256-n)*MASs.

Beacons enable device discovery, sleep-mode operation and other functions. Furthermore, beacons are used to announce reservations. All active devices listen to all beacons in the BP. Therefore, they learn from their neighbors about blocked MASs, since a reserving device provides information about the starting MASs and the number of MASs to be reserved. The MBOA MAC supports hard or soft reservations. A hard reservation enables the device owning the slot to start its transmission immediately at the beginning of the reserved MASs, since all other devices must complete their transmissions a SIFS plus a guard interval before the reserved MAS. The reserved MAS itself may be used solely by the reserving device and its communication partners. No other transmission is permitted during that period. The *Unused DRP Announcement (UDA)*, *Unused DRP Response (UDR)* frame exchange provides unused duration of a hard reservation to other devices. In summary, via DRP [2], [3] the MBOA MAC is able to support isochronous *real-time (rt)* traffic.

With soft reservations DRP supports more flexible QoS demands. In the very first MAS of a soft reservation, the reservation owner accesses the medium according to the PCA mechanism, however its contention window is set to zero. All other devices have to use standard PCA for channel access. The purpose of soft DRP is that, if the owner of the reservation does not fully use the reserved MASs, other devices can still use the unused MASs in PCA mode.

A reservation can be negotiated explicitly or implicitly between sender and receiver(s) of a data stream. The sender initiates an explicit DRP negotiation with a DRP Request frame that it sends to the intended receivers of the data. Immediately the receiver acknowledges the unicast DRP Request. A multicast frame is not acknowledged. Afterwards, the intended receivers respond with a DRP Response frame, which establishes the reservation. An implicit DRP negotiation is performed using the beacon frame. The device, which starts a DRP reservation, includes a so-called *DRP Information Element (DRPIE)* in its beacon frame. The intended receiver responds in its next own beacon with a corresponding Information Element.

In both cases of implicit or explicit DRP negotiation the receiver indicates to the sender whether the reservation must be shifted, is acceptable or not. Once a DRP session has been established both the sender and the receiver inform their neighbors about the reservation by including the reservation in a DRPIE in their own beacon frames.

c) Device ID

To reduce the overhead, the MBOA MAC transforms the well known 802 MAC addresses of 6B length to shorter *Device IDs (DEVIDs)* of 2B length.

"Assigned DEVIDs" are used by devices with limited computing power. Until a different device has assigned a unique address to those, the self assigned address is used to achieve the stage of an "Assigned DEVID" device. A "Generated DEVID" is a randomly chosen address, see Table 4. However, a device may not use a DEVID, which is already in use. Any device that detects a DEVID conflict announces the conflict in its beacon to allow fast and reliable detection. Devices involved in the conflict regenerate their DEVID.

TABLE 4
DEVIDS USED BY MBOA

DEVID Type	Begin	End
Assigned	0x0000	0x00FE
Self assigned	0x00FF	0x00FF
Multicast	0x0100	0x01FE
Broadcast	0x01FF	0x01FF
Generated	0x0200	0xFFFF

d) Transmission Opportunities

Regardless if a device accesses the channel via PCA or DRP, the duration of every frame exchange is bounded by the TXOPLimit. For *Transmission Opportunities (TXOPs)* gained via DRP the TXOPLimit equals the duration of the reserved MASs. For PCA channel access the MBOA standard defines the TXOPLimit per priority. However, the duration of a TXOP gained under PCA is further restricted by the closest DRP reservation, since no PCA transmission may delay or foreshorten any DRP reservation. When accessing the medium with PCA or making a new DRP reservation, a device has to respect all existing reservations. Besides these limitations, all decisions regarding the data exchange are solely up to the transmitting device.

e) Acknowledgment policies

MBOA defines three *Acknowledgment (ACK)* policies:

- No-ACK
- Immediate ACK
- Burst ACK.

Each directed frame carries an "ACK policy" field in the frame control field inside the MAC header, to allow the receiver to use the desired one. With No-ACK policy no ACKs are generated at all. With *Immediate ACK (Imm-ACK)* policy each successfully received *Mac Protocol Data Unit (MPDU)* is acknowledged after a *Short Interframe Space (SIFS)* period by the receiver. The SIFS period is needed for *transceiver (TRX)* turnaround and frame checking. It is used in between every frame exchange. Burst ACK policy increases the efficiency, since a group of MPDUs is acknowledged with a single frame by the receiver [16].

f) Minimum interframe space & frame aggregation

With Burst ACK policy, the transmitter may further enhance the efficiency by using the *Minimum Interframe Space (MIFS)* in between every consecutive frame, since MIFS is shorter than a SIFS interval. Alternatively, every device may benefit from frame aggregation. Frame aggregation concatenates subsequent frames into a single data stream. However, the aggregated stream is subject to the same maximum size as any data frame payload.

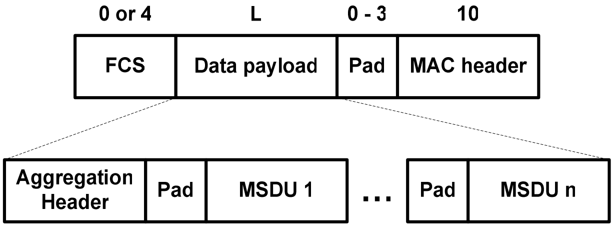

Fig. 2. An aggregated frame consists of multiple independent PDUs. The aggregation header indicates the length of each MSDU.

g) Fragmentation & RTS/CTS handshake

To reduce the *Packet Error Ratio (PER)* under bad channel conditions a device may choose to split any MSDU into a maximum of eight fragments.

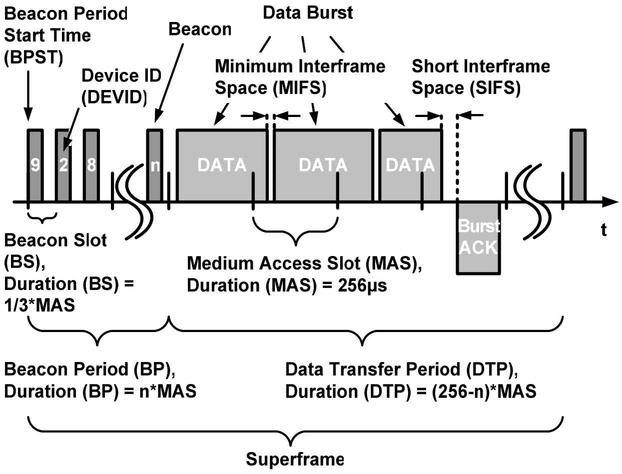

Fig. 3. Each Superframe consists of 256 MASs. n MASs are used for the BP. The rest is used for the DTP.

To cope with the hidden device problem inherent in every wireless network, the *Request To Send (RTS)/Clear To Send (CTS)* handshake known from 802.11 may be used. However, the overhead of an RTS/CTS handshake is needless when DRP is used.

Beacon period & Beacon frames

Each superframe starts with a *Beacon Period (BP)*. The maximum length of the BP is defined as mMaxBPLength which is a multiple of MASs. Each MAS in the BP consists of three Beacon slots. During the BP devices sequentially broadcast Beacons at the base rate (currently 55Mb/s). Each Beacon shall not exceed a length of mMaxBeaconLength which is equal to mBeaconSlotLength - SIFS - mBeaconGuardTime. mBeaconSlotLength is one third of a MAS. The mBeaconGuardTime is 4µs. Hence, a Beacon lasts 71µs.

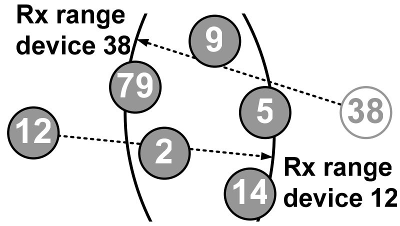

Fig. 5. Device 38 enters an existing WPAN. However, device 12 and 38 are mutually out of reception range. Hence, device 38 cannot receive beacon information from 12.

With every received beacon a device learns about its direct neighborhood. In a beacon a device broadcasts which beacon slots are occupied by which DEVID. Thus, each device learns about its neighbor's neighborhood, too, see Fig. 5. Therefore, if during the last three superframes a device did not receive a Beacon in a Beacon slot and it does not learn via neighbor beacons that the slot is occupied it regards the slot as empty. Once a device is powered up it scans for an empty beacon slot during "mScanBeacons" superframes. Then it announces its presence in one randomly chosen Signal Beacon Slot, see Fig. 4. The beacon is sent a second time in a randomly chosen Beacon slot in between the highest-numbered Beacon slot and the end of the BP. If all Beacon slots are occupied, a device proceeds to send during the Signal Beacon Period and prolongs the BP by adding its Beacon to the succeeding MAS of the BP of the next superframe.

Every n-th superframe a device does not transmit a beacon to be able to detect beacon collisions. The value of n depends on the implementation. Additionally, a

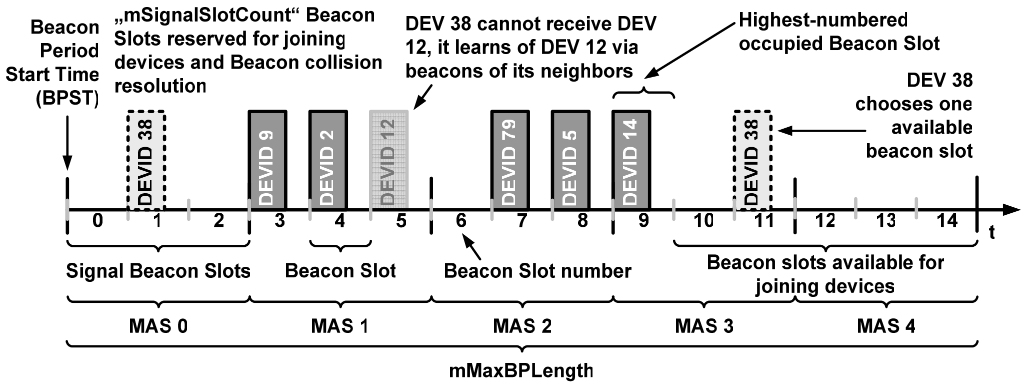

Fig. 4. Having sensed the channel and waited for a least a full superframe, device 38 learned about its neighborhood and its neighbors' neighborhood. Hence, it is aware of all occupied beacon slots and is able to join the WPAN.

device may detect a beacon collision if neighboring devices report an empty Beacon Slot or a different DEVID than its own in the corresponding Beacon Slot.

Establishing a single, joint BP with overlapping WPANs is important for energy conservation, since the BP is the only period a device must stay awake and be able to receive. Thus, battery powered devices may stay in sleep mode mainly and need to power up during the BP and DRP periods they are involved in only.

A BP may be contracted to reduce the BP length. Therefore, the highest-numbered device which does not experience any collisions shifts its beacon slot to the earliest empty beacon slot in the next superframe.

In a situation of overlapping networks a coordination procedure is needed, since both WPANs are very likely to have different BPs. Hence, devices which detect alien BPs have to refrain from interference to alien BPs and DRP reservations. However, an additional BP provokes extra overhead and reduces energy conservation for sleeping devices. Therefore, MBOA defines a procedure to merge coexisting BPs. After announcing a protection DRP period for the alien WPAN, devices start shifting their beacons, thereby merging the BPs into a single BP.

IV. Simulative Analysis

We use event-driven stochastic simulations to analyze the efficiency of the MBOA MAC layer. Simulation campaigns have been performed based on the MBOA *Orthogonal Frequency Division Multiplexing (OFDM) Physical Layer (PHY)*. For delay results, we give the empirical *Complementary Cumulative Distribution Function (CDF)* of the resulting stochastic data, using the discrete *Limited Relative Error (LRE)* algorithm that also measures the local correlations of the stochastic data [13]. By measuring local correlations, the accuracy of empirical simulation results can be estimated. All results presented in this paper are within a maximum limited relative error of 5%.

The simulations were performed using the *Wireless Access Radio Protocol 2 (WARP2)* simulation environment developed at the Chair of Communication Networks, RWTH Aachen University [14]. It is programmed in the *Specification and Description Language (SDL)* using Telelogic's TAU SDL Suite (previously named *SDL Design Tool (SDT)*). The error model used in WARP2 to accurately simulate the Wireless Medium (WM) is presented in [15]. To evaluate the efficiency of the MBOA MAC layer, all simulations presented here use a fixed *Packet Error Ratio (PER)* of zero.

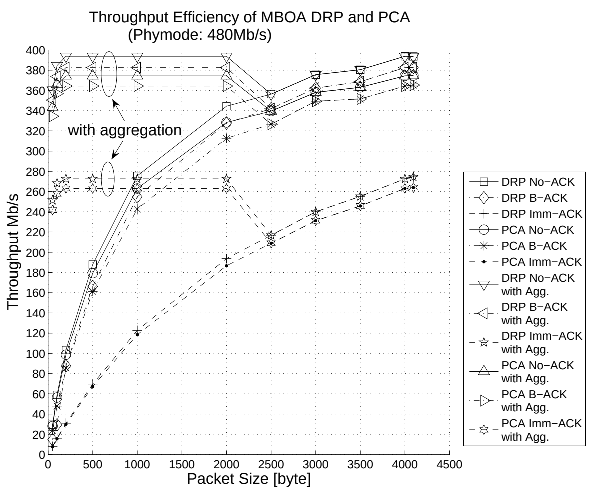

Fig. 6. Scenario 1: the efficiency of MBOA MAC with access methods of DRP and PCA combined with three ACK policies and frame aggregation as a function of packet size.

In the following all devices are within reception range of each other. Thus no hidden devices appear in our simulations. In scenario 1 we survey the maximum achievable throughput of MBOA. Using a simple scenario of one transmitting and one receiving device we provide simulation results on the upper boundary of the throughput. In this simulation both DRP and PCA with a user priority of 7 are evaluated with the three kinds of acknowledgement policies and frame aggregation. The simulated superframe consists of a BP lasting 8 MASs and a data period of 248 MASs, which is used as the TxOP length in DRP mode. The TxOP length of PCA mode is 1024µs and the QoS parameter set of UP7 used in this simulation can be found in Table 5. All results with ACK policy set to Burst-ACK are derived with a burst buffer size of 16 frames. The aggregation function is evaluated with a timeout value of 100µs. The MIFS and Stream Mode preamble are used in the stream mode transmission.

TABLE 5
PCA QoS Settings Used in The Simulation

Priority	AC	CWmin	CWmax	AIFSN
1	AC_BK	63	1023	7
2	AC_BK	63	1023	7
0	AC_BE	63	1023	3
3	AC_BE	63	1023	2
4	AC_VI	31	1023	2
5	AC_VI	15	31	1
6	AC_VO	7	15	1
7	AC_VO	3	7	1

It can be seen in Fig. 6 that the throughput of DRP always outperforms the one of PCA with the same ACK policy by several Mb/s. That is because in the PCA mode even with the highest UP, the sender has to wait for an AIFS duration and perform a backoff before transmitting, which decreases the throughput. As expected, in both DRP and PCA modes the No-ACK policy achieves the highest throughput, followed by the Burst-ACK which reaches a slightly lower throughput than No-ACK due to the overhead of transmitting acknowledgement frames. As illustrated here, frame aggregation is very important for an efficient packet oriented MAC. The throughput that is achieved with frame aggregation is comparable to the throughput of long packets.

In scenario 2 we examine a duplex route connection. Two devices share the channel capacity. The throughput and delay of the duplex route are evaluated in three cases. In the first case, the DRP mode is used for both devices while the PCA with UP7 and UP0 are used in

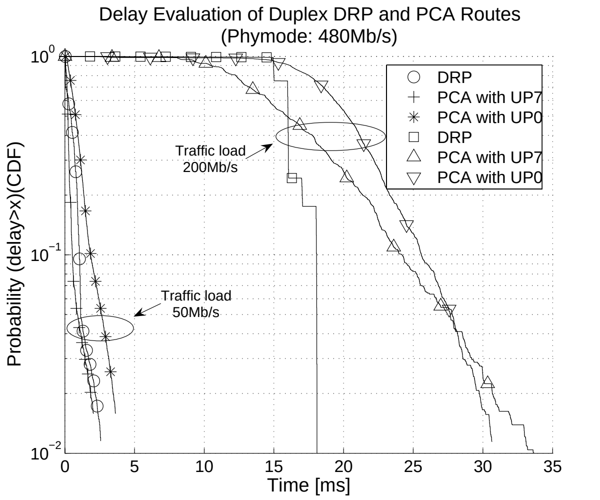

Fig. 7. Scenario 2: Delay evaluation under light traffic load (50Mb/s) and heavy traffic load (200Mb/s) of the duplex route between two devices when DRP, PCA with UP7 and PCA withUP0 are used as the channel access methods.

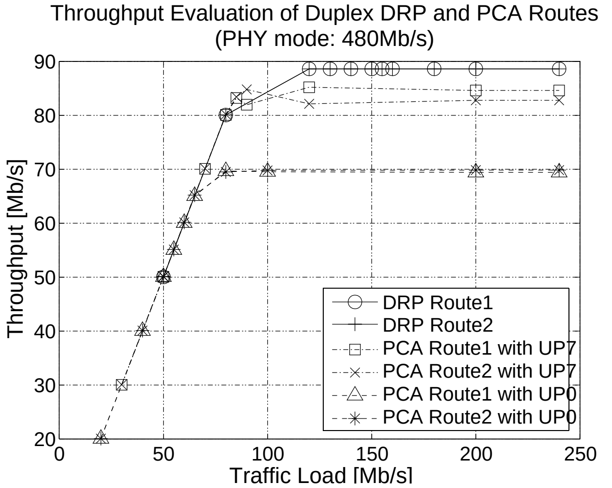

Fig. 8. Scenario 2: Throughput evaluation of the duplex route between two devices, when DRP, PCA with UP7 and PCA with UP0 are used as the channel access methods. ACK policy: Imm-ACK. Packet length=1800B.

the other two cases respectively. In all three cases, the packet length is fixed to 1800B, the ACK policy is set to Imm-ACK and no aggregation is performed.

In Fig. 8 the throughput results are presented as a function of the traffic load offered by the upper layer. Since the two unidirectional routes of the duplex connection have their own reservation in the first case, the same throughput can be achieved by each route without suffering from the contention. However, in the two PCA cases, the two unidirectional routes have to content with each other for the channel resources. Therefore a throughput difference of these two routes can be observed, even if all the settings are the same. PCA routes with UP7 can offer higher throughput than those with UP0 due to the shorter AIFS time and smaller backoff window size.

Delay evaluation results in Fig. 7 indicate that the PCA routes experience a good delay performance for light traffic load, but suffer from quite high delays in a heavily loaded situation. However, the DRP routes can provide a bounded maximal delay even with heavy load.

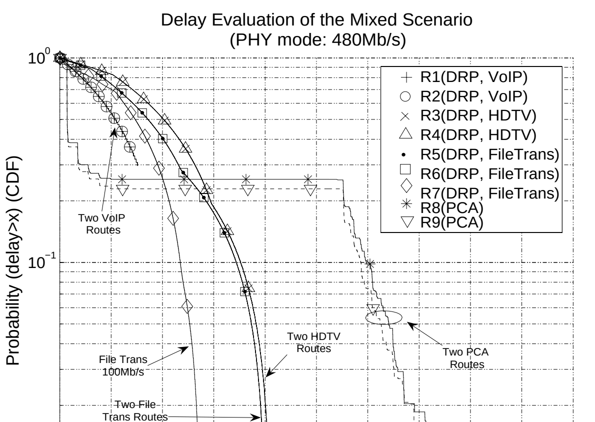

Fig. 9. Scenario 3: Delay evaluation of the mixed scenario with 7 DRP routes and 2 PCA routes sharing a single 480Mb/s channel.

Scenario 3 describes a mixed scenario. One pair of devices communicates via *Voice over IP (VoIP)* (150kb/s each direction, 120B packets, R1-2). A wireless streaming server provides HDTV to two different clients (24Mb/s each, 1500B packets, R3-4). Two devices handle file transfers at 30Mb/s (R5-6) and one device handles a file transfer a 100Mb/s (R7), each using 1500B packets. The above mentioned streams all use DRP. However, two additional PCA connections complete our scenario (best effort, 1500B, R8-9). As Table 6 presents, DRP enables constant support for QoS to the high priority transmissions, while PCA access fits the needs of low priority background services. As depicted in Fig. 9 DRP gives well bounded delays. However, for traffic carried by PCA large delays can occur for some packets, even though other packets also experience a lower delay than DRP packets. The reason for the shape of the PCA delay distribution is the slot reservation scheme. Sometimes packets immediately access the channel via PCA when a MAS is not reserved. Thus the delay is small. However, reserved MASs can lead to large delays for PCA of more than 60ms.

TABLE 6
THROUGHPUT RESULTS FOR SCENARIO 3

Route	Traffic Load (Mb/s)	Frame Size (B)	Access Method	ACK Policy	Throughput (Mb/s)
R1	0.15	120	DRP	No	0.15
R2	0.15	120	DRP	No	0.15
R3	24	1500	DRP	No	23.98
R4	24	1500	DRP	No	23.98
R5	30	1500	DRP	Burst	30.00
R6	30	1500	DRP	Burst	30.02
R7	100	1500	DRP	Burst	99.89
R8	200	1500	PCA	Imm.	13.86
R9	200	1500	PCA	Imm.	15.04

V. CONCLUSIONS

In this paper we have presented the new MBOA

MAC protocol, in the development of which we have been heavily involved. We have implemented the MAC protocol in an event driven simulator and provide a performance evaluation of both the DRP and the PCA access methods. Simulation results indicate that the protocol is very efficient and that real-time services can be supported very well with DRP. PCA should only be used for all non-delay critical types of access, because larger delays can be expected.

Based on the complete PHY and MAC specifications of MBOA a very powerful WPAN with data rates of several hundred Mb/s can be set up and several companies have announced chipsets for the year 2005. In conclusion, MBOA seems to be well positioned for the race of the competing WPAN standards.

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