Adaptive Hybrid Contention and Reservation for UWB Mesh Networks

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***Abstract*—With license-exempt usage, huge bandwidth and very low power consumption Ultra Wideband (UWB) technology is an attractive candidate for high-rate Wireless Personal Area Networks (WPANs). However, restricted power emission limits the maximal coverage range to a few meters. Especially for dense indoor UWB systems, wireless multi-hop communication extends the transmission range easily and cost-effectively. WiMedia, world's first commercial UWB standard, is adapted to indoor environments, where collisions are expected often due to hidden devices. This paper evaluates WiMedia for wireless mesh networks by simulation and proposes a combination of the two channel access protocols, on the one hand to limit frame delay and on the other hand to gain system capacity.**

***Index Terms*—wimedia, uwb, wireless mesh networks, medium access, PCA, DRP, HCaR**

I. INTRODUCTION

Wireless systems for WPANs meeting users demands on very high data rate for high definition video and voice communication are still missing. IEEE 802.15 Task Group 3a was founded in 2004 in order to develop a high-rate physical layer using UWB. Two different technologies proposed by industry led consortia competed to get the majority vote required for standardisation. However, the process was blocked, leading to withdrawal two years later. One of the competing consortia was the WiMedia Alliance originally founded as Multiband OFDM Alliance (MBOA). The MBOA derives its name from the proposed physical layer using Orthogonal Frequency Division Multiplex (OFDM). Corresponding to the Federal Communications Commission (FCC) enactments on UWB systems, the signal occupies 528 MHz.

Recently WiMedia has published version 1.5 of its high-rate UWB standard [5]. This amendment offers data rates up to 1 Gb/s. Since 2009 the most important markets around the world for UWB systems are regulated and frequency spectrum between 3.1 GHz and 10.6 GHz has been opened for license-exempt UWB communication. As this process took a long time, it led to delayed international products shipping.

In contrast to IEEE 802.15.1, also known as Bluetooth, WiMedia does not define any device acting as a central controller. The medium access is organised in a fully distributed manner. This makes WiMedia well suited for wireless short range communication. The system targets typical WPAN services like wireless HDTV, video, voice or Internet. Multimedia traffic calls for isochronous and reliable channel access, whilst bursty Internet traffic has less strict demands on frame delay or throughput. Accordingly, WiMedia offers two different channel access protocols, Prioritized Contention Access (PCA) and Distributed Reservation Protocol (DRP). The latter one utilises channel time in a Time Division Multiple Access (TDMA) fashion. Resource allocation for DRP channel access poses a major challenge in WiMedia networks. An inappropriate allocation either degrades system capacity by wasting channel time or degrades devices' throughput. Combining PCA and DRP into a common protocol appears promising to use channel time more efficiently, especially in typical indoor environments. This paper proposes the Hybrid Contention and Reservation Protocol (HCaR) (see Section IV-C) in order to combine both PCA flexibility and DRP reliability for multi-hop WiMedia mesh networks. The channel access protocols are compared by simulations of an typical office, where several devices are involved in multi-hop communications. In the following first the related work is shown in Section II, Section III gives an introduction to the WiMedia standard, afterwards the adaptive distributed scheduling is introduced in Section IV, Section V describes the scenario and finally simulation results are presented in Section VI.

II. RELATED WORK

An overview on wireless mesh networks is given in [8], addressing applications, current research state and challenges for future developments. For an efficient support of bursty video traffic, [1] presents a hybrid Medium Access Control (MAC) protocol for UWB networks. It is shown that DRP protects large frames from collisions. Large frames are more important than short frames for video quality. Simulation results point out that channel resources are used efficiently, if the DRP resource reservation is calculated taking into account the bursty nature of video traffic. In [9] a Distributed Relay MAC protocol is introduced to enhance WiMedia channel access. It is based on a new Information Element (IE) for relay detection, aiming to find an optimal route to the destination. [2] evaluates the upper bound capacity of UWB mesh networks. An omniscient and omnipotent MAC is assumed to schedule data transmission optimally by means of concurrent transmissions. The benefit of introducing mesh points is shown in comparison to pure ad-hoc communication. Mesh points enable system capacity to be independent of the scenario size. The scenario investigated in this paper is the one introduced in [2], but channel impairments and a non-omniscient MAC scheduler is assumed. In comparison to [1] and [9] the WiMedia protocol is evaluated in a mesh topology, compliant to the standard. However, for a more

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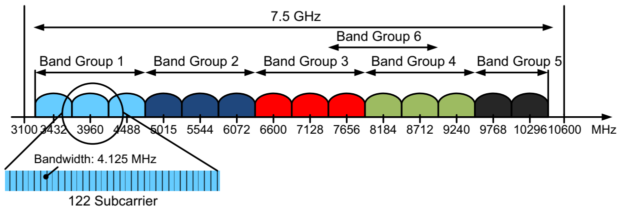


Fig. 1. The WiMedia frequency bands.

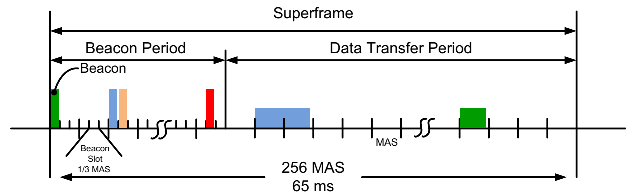


Fig. 2. Superframe structure.

realistic scenario, we consider channel access in presence of hidden devices, which is a major challenge in mesh topologies.

III. The WiMedia Standard

The WiMedia standard was published by the European Association for Standardizing Information and Communication Systems (ECMA) as ECMA-368 [4] and has been approved as ISO/IEC 26907. WiMedia shares frequency bands with other systems being a UWB overlay secondary system. Due to its low transmission power, namely -41.3 dBm/MHz restricted by FCC Part 15, interference is not harmful to comparatively narrow band systems.

A. Physical Layer

The frequency range of 7.5 GHz is divided into 14 frequency bands with 528 MHz bandwidth each, as depicted in Figure 1. Consecutive frequency bands are further grouped. Band Group 1 to 4 consists of 3 frequency bands and Band Group 5 consists of 2 bands. Band Group 6 is specified, targeting different national frequency regulations, to be worldwide available. Each 528 MHz wide frequency band is subdivided into 128 subcarriers. Data is modulated using 100 subcarriers, exploiting Quadrature Phase Shift Keying (QPSK) or Dual Carrier Modulation (DCM). WiMedia offers data rates from 53.3 Mb/s to 480 Mb/s using different Modulation and Coding Schemes (MCSs).

B. Medium Access Control Layer

To support low cost ad-hoc communication and few efforts on installation and maintenance, the MAC is fully distributed. Time is structured into superframes. Each superframe lasts for 65 ms and is divided into 256 Medium Access Slots (MASs), as shown in Figure 2. The whole superframe is composed of a Beacon Period (BP) and a Data Transfer Period (DTP). It is mandatory for each device to send management information at the beginning of each superframe during the BP. A beacon lasts 85 μs, containing different IEs for network topology discovery, reservation announcements, broadcast of a device's capability etc. The device's individual neighbourhood is called Beacon Group. The union of all Beacon Groups is referred to as extended Beacon Group. The BP and DTP lengths are variable and depend on the number of active devices. In order to cope with different traffic characteristics and Quality of Service (QoS) requirements, WiMedia offers two different channel access protocols. Prioritized Contention Access (PCA) is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with priorities, derived from IEEE 802.11e. It allows for a flexible but unreliable channel access. In contrast, DRP, originally introduced in [10] as Distributed Reservation Request Protocol (DRRP), allows for collision free channel access with reserved channel time, measured in MASs per link.

1) PCA: PCA provides a CSMA/CA channel access with 4 Access Categories (ACs) for prioritising a device's traffic. After sensing the channel as idle for a Distributed Interframe Space (DIFS), a randomly chosen backoff counter is decremented as long as the channel remains idle. If the channel is sensed as occupied, the backoff counter freezes until the channel becomes idle again. If the backoff counter reaches zero, the device is allowed to send its data. Data transmission must be completed before the next BP starts or before start of a MAS reserved by DRP from a neighbour device.

2) DRP: In contrast, DRP allows contention-free channel access, achieved by assigning several MASs to a certain device for exclusive use. Before accessing the channel both communicating partners have to negotiate the required resources. During negotiation the source device, called reservation owner, informs the reservation target device about the desired connection. The owner sends a Distributed Reservation Protocol Information Element (DRPIE) in its beacon and suggests certain MASs for reservation. If the proposed MASs are not occupied in the view of the target, the target device accepts the reservation and includes a DRPIE in its next beacon. This two-way handshake inhibits transmissions confirming the reservation of hidden devices but delays connection establishment by a superframe duration. The reserved MASs are fixed for the time of reservation. The reservation owner may renegotiate the number of MASs for an existing connection. Both, reservation owner and target broadcast a DRPIE in their beacons to notify other devices about the MASs claimed to be reserved. Neighbour devices will defer from channel access to these MASs; hence, collision free use of MASs for user data transmission is guaranteed. Usually, a reservation comprises a multiple of MAS. Finding a suitable MAS pattern for a new connection is out of scope of WiMedia and depends on manufacturers' implemented reservation algorithm.

IV. Distributed Scheduling for WiMedia Mesh Networks

The estimation of required resources is crucial for DRP, in particular for multi-hop communication: Due to the fully

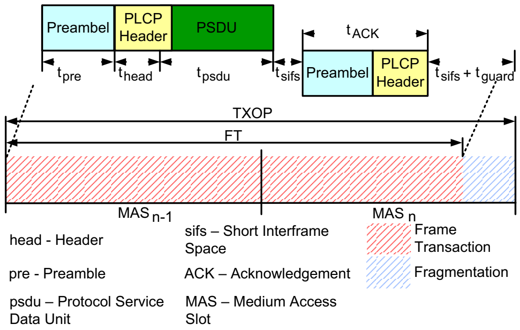


Fig. 3. Frame Transaction.

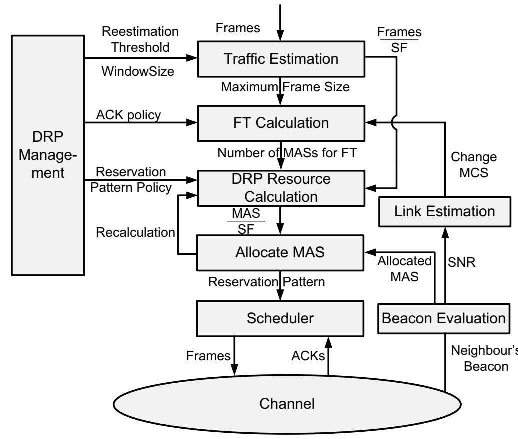


Fig. 4. Resource Allocation and Maintenance Process.

distributed MAC, each device involved in multi-hop communication has to make an estimate on channel resources correctly, as the weakest link on a route defines the whole performance. Setup delay increases with number of hops a connection spans, as each pair of devices per hop has to negotiate on reservation. In the following a combination of PCA and DRP, referred to as Hybrid Contention and Reservation (HCaR) protocol is introduced. HCaR combines scalable and flexible PCA contention based access, with DRP controlled reservation based channel access. There, PCA is used during time of DRP negotiation to lower the frame queuing delay. And, PCA is used by devices operating a DRP connection to serve unexpected demand immediately.

A. Frame Transaction

A Frame Transaction (FT), depicted in Figure 3, is composed of frame transmission and reception of the expected acknowledgment. The duration depends on the MCS chosen, whereas acknowledgment duration is fixed according to the robust MCS specified for control messages in the standard. Further, FT comprises receiver turnaround time and guard time. A frame can only be transmitted, if FT fits into the reserved MASs of the devices involved.

B. Adaptive DRP Reservation Pattern

MAS reservation offers channel time, periodically repeated in each superframe. Usually more than one MAS is needed to carry the traffic between devices connected to each other. It is the reservation owner's decision which MASs are chosen for DRP reservation. Reservation of consecutive MASs, in the following called a reservation block, offers continuous channel time. Reserved channel time is referred to as Transmission Opportunity (TXOP). As guard time appears only once in each TXOP, a reservation block is more efficient than a reservation of multiple, non consecutive MASs. The minimal size of a reservation block depends on the FT. The position of reserved MASs in the superframe has a direct impact on the frame delay, especially for multi-hop communication, where the reservation target is the reservation owner of the next mesh link in a multi-hop connection. It is unfavourable to schedule outgoing data before the incoming, since delay caused by the multi-hop transmission is increased then. MASs for outgoing traffic of a connection therefore should follow the MASs reserved for the incoming connection. In Figure 4 the MAS allocation process for DRP connection establishment and maintenance is shown. At first the traffic is estimated to calculate the channel resources. The minimal reservation block duration is determined by the FT duration, which depends on the chosen MCS and the frame size. The DRP resource calculation is done taking the reservation pattern policy, the reservation block size and the number of frames which should be transmitted per superframe into account. If the reservation policy cannot be fulfilled due to neighbours' MASs allocation, a resource recalculation is necessary. After DRP channel establishment, the reservation information is given to the scheduler. A link estimation is done by calculating the beacon signal strength. The BP is assumed to be interference free, as WiMedia's beacon protocol effectively prevents from collisions. The Signal-to-Noise Ratio (SNR) of the beacon frame is used to estimate an initial MCS for user data transmission. The resource calculation targets to transmit the estimated traffic in reserved MASs. If the buffer size exceeds a given threshold, a reestimation is done, following a reevaluation of the reserved MASs. Overestimating the MASs for DRP reservation intentionally is an option to lower queuing delays and to compensate delays in consequence of DRP channel establishment duration. A disadvantage of this option is the DTP fragmentation, if these additional MASs are released. Using the HCaR protocol, described in the following, is another option.

C. Hybrid Contention and Reservation Protocol

HCaR combines both channel access protocols, PCA and DRP, as depicted in Figure 5. In contrast to DRP, transmitting data in the DTP based on PCA is permitted all times. DRP based channels are available after connection establishment has been finished. If a device gains channel access according to PCA the frame at the head of the queue is sent. If a reservation owner has more than one reservation target, PCA is done in a round robin order. A frame will again become head of the

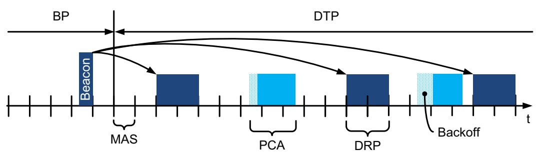


Fig. 5. Hybrid Contention and Reservation Protocol.

queue, if it is not delivered successfully. Retransmission is done by using either DRP or PCA. Concerning the channel access, the HCaR protocol is comprised of a DRP- and PCA part. The MAS reservation according the DRP part of the HCaR protocol is done as mentioned before and depicted in Figure 4. The decision of the MCS for HCaR depends also on the beacon SNR estimation as mentioned before.

D. Scheduling Algorithm for DRP and HCaR Channel Access

The distributed DRP and HCaR scheduling algorithm used for evaluation of WiMedia in multi-hop communication is summarised in the following:

- Condition of equilibrium: frame arrival rate equals frame departure rate. The devices reserve MASs to carry the estimated traffic. For the HCaR protocol it means, that MASs are reserved to carry the traffic without gaining PCA channel access.
- No unused MASs: Devices reserve only as much MASs as needed, hence no intentional overestimation of MASs is done.
- Efficient use of channel resources: Reserve directly adjacent MASs to lower the number of reservation blocks. If renegotiation is necessary, try to enlarge the existing reservation block.
- Minimise the frame delay in multi-hop communication: Reserve the MASs for outgoing connection after the MASs of the incoming connection, referred to as adaptive MAS reservation.

Algorithm 1 AllocateMASs

```
FTCalculation(FrameSize, MCS, AckPolicy)
MASTXOPCalculation(FTduration, MASReservationPolicy, FrameArrivalRate)
while NeededResources do
    FindIncomingMAS()
    SearchForFreeMASinDTP(ReservationBlock)
    if NoFreeMASforReservationBlock then
        SplitReservationBlock()
        ResourceRecalculation(ReservationBlock)
    else
        ReserveMAS(MASinReservationBlock)
    end if
end while
```

A pseudo code for MAS allocation is shown in Algorithm 1. The number of reservation blocks to be reserved is predetermined and is based on the reservation owner's requirement. Here, this number is fixed for each device. The MASs reservation is done as described in following: First, for adaptive alignment, MASs of the incoming traffic is found. The reservation owner tries to allocate directly adjacent MASs after the allocation belonging to the incoming connection. A possible reservation pattern is depicted in Figure 6. The reservation block is split into several smaller ones, if there are no unoccupied MASs left for a MAS reservation according to the reservation policy.

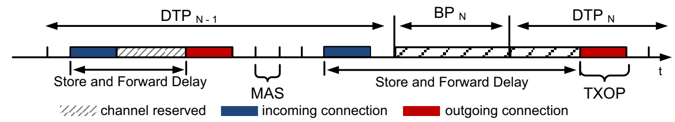


Fig. 6. Adaptive DRP reservation pattern.

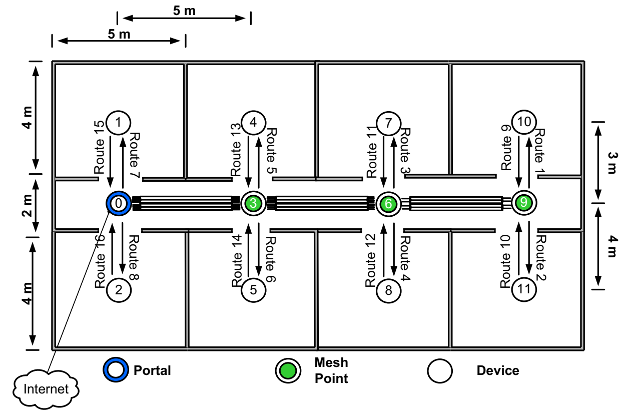


Fig. 7. Office scenario.

V. Scenario

The scenario is depicted in Figure 7, it is taken from [2]. It consists of eight offices. A device is located in each office. Four devices are positioned on the floor. Three of it, the green ones, are neither source nor destination, they are mesh points. The most left device is a portal, which is connected to a wired backbone. The portal is the source for the downlink traffic to the devices located in the offices and the sink of the uplink traffic. Each device uses PCA, DRP or HCaR for channel access. Due to network topology, the number of hops varies from one to four according to different multi-hop connections. For simulation the open Wireless Network Simulator (openWNS) [7] is used. In Table I the parameters are given.

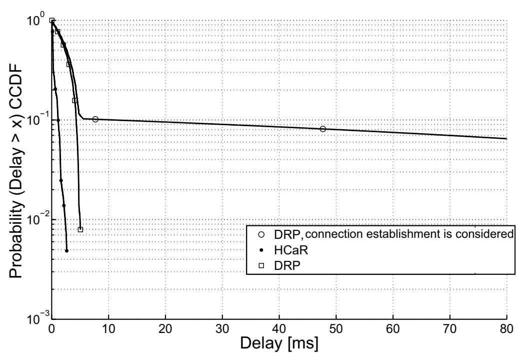
VI. Results

First, traffic is only offered for the uplink of device 1 and device 2 (route 7, route 8) to depict the consequence of the described algorithm in Section IV-D. Figure 8 shows the frame delay and the system throughput comparing DRP and HCaR. In Figure 8(a) the Complementary Cumulative Distribution Function (CCDF) of the frame delay is given. The diagram

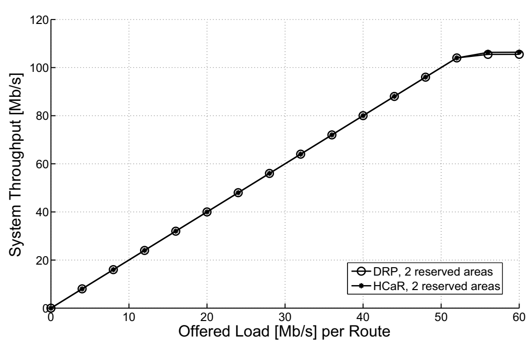
TABLE I
SCENARIO PARAMETERS

Parameter	Value
Frequency	3.8 GHz
TXOP for PCA	1024 μs
Path loss exponent	2.9
Channel Model (CM)	2 [6]
Wall loss	10 dB
Traffic characteristic	Constant Bit Rate
Frame size	1500 B
Acknowledgement (ACK)	Immediate-Ack
Window size for traffic estimation	3 Superframes
Reestimation threshold	5%

depicts two results for DRP, one considers the DRP connection establishment. The simulation time is 500 s. If the DRP connection establishment is considered, it can be seen that 10% of frames have a delay greater than 10 ms, whilst HCaR performs much better. The strong delay is a consequence of the second requirement of the distributed scheduling algorithm, described in IV-D. Using the HCaR protocol devices gain PCA channel access during DRP connection establishment.



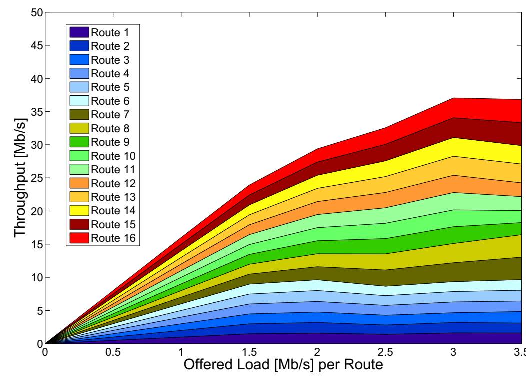
(a) Frame delay, route 7 and route 8, offered load 20 Mb/s.



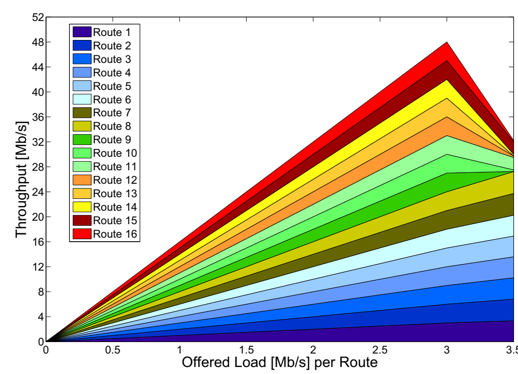
(b) System throughput route 7 and route 8.

Fig. 8. Delay and system throughput for DRP in comparison to HCaR.

Figure 8(b) shows the system throughput versus the offered load per route. There is no difference between HCaR and DRP. With an increasing offered load the impact of PCA decreases as more MASs are reserved for the DRP based channel access of HCaR. Hence, the saturation point of the HCaR protocol is the same as of DRP for the proposed resource allocation algorithm. In the following, to compare PCA, DRP and HCaR in multi-hop UWB mesh networks, frame delay is shown without taking connection establishment duration into account. The load is offered in down- and uplink directions. Figure 9 depicts the cumulative throughput of PCA, Figure 9(a) and DRP, Figure 9(b). The MAS reservation pattern is composed of two reservation blocks, as described in Section IV-B.



(a) PCA.



(b) DRP, two reservation blocks.

Fig. 9. Cumulative throughput DRP in comparison to PCA, the same load is offered in both directions.

The system saturation point for PCA is at about an offered load of 1.5 Mb/s per route. For DRP this value is doubled to 3 Mb/s. The collision probability of the uplink from devices located in the offices to the mesh points positioned on the floor is higher than in downlink direction. Comparing Figure 7 for example, device 7 is not able to detect transmissions from device 9, as the signal power is attenuated by concrete wall and path loss.

For the same offered load in both directions of 1 Mb/s, Figure 10 shows the CCDF of the delay for one of the four hop routes.

The frame delay for DRP with and without adaptive MASs alignment is depicted. If the MASs for the outgoing transmission do not follow the reserved MASs for the incoming transmission, 100% of the frames have a delay greater than 35 ms. A comparison of both channel access protocols DRP and HCaR is shown in Figure 11. Both routes are the four hop routes in this scenario. The same load is offered in both directions with 2 Mb/s, which is below system saturation. In Figure 11(a) it can be seen, that there is no difference between DRP and HCaR for the delay in downlink direction. 90% of

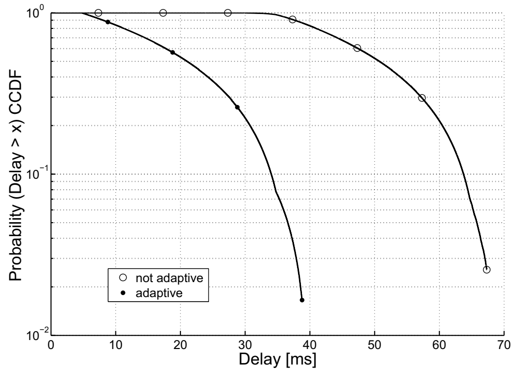
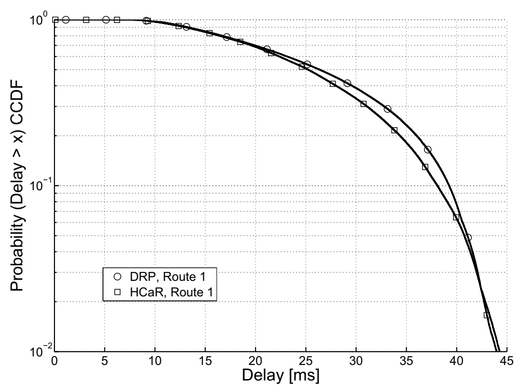
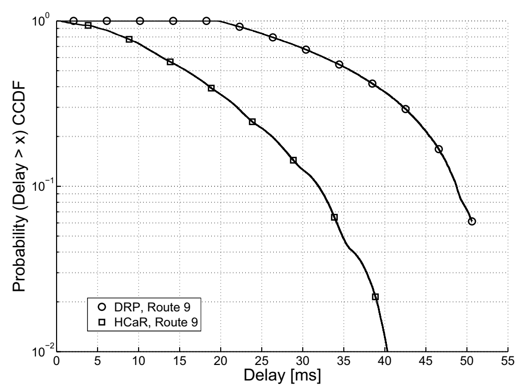


Fig. 10. Frame delay, comparison of DRP adaptive and not adaptive, route 1, offered load 1 Mb/s.

the frames are delivered with a frame delay lower than 38 ms.



(a) Downlink, route 1.



(b) Uplink, route 9.

Fig. 11. Frame delay, comparing HCaR and DRP, same offered load of 2 Mb/s in both directions.

In the uplink, depicted in Figure 11(b), the frame delay for DRP and HCaR differ. In the simulation the traffic in downlink direction is offered first, before the devices start their MASs reservation for uplink transmission. This means, that each device is able to align the MASs for outgoing transmission according to Section IV-B. Afterwards the uplink connections are established. It is impossible for the reservation owner to align the MASs according to the MASs for the incoming transmission, as some parts of the DTP are already allocated for downlink transmission. In consequence for the uplink transmission the devices take advantage of the random access of the HCaR protocol.

VII. Conclusion

DRP offers a predictable medium access in a TDMA fashion to overcome collisions due to hidden devices, as one can see in Figure 9. Hidden devices are still a problem in dense wireless mesh topologies. The collision free access comes at a price. DRP is inflexible and negotiation for MASs reservation takes time, especially in indoor environments, where lots of devices are member of an extended beacon group. For wireless mesh networks, DRP channel establishment is a time consuming process, as each device involved in multi-hop communication has to negotiate MAS reservation. HCaR lowers the impact on frame delay, depicted in Figure 8. Further, showing in Figure 11, combining DRP and PCA into the HCaR protocol takes advantages of both protocols: flexibility and reliability. To keep the frame delay within a limit, especially when reusing MASs, devices benefit from adaptive MASs alignment, as it is depicted in Figure 10. The HCaR offers a powerful medium access for WiMedia based mesh networks.

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References

[1] R. Zhang, R. Ruby, J. Pan, L. Cai and X. Shen. A Hybrid Reservation/Contention-Based MAC for Video Streaming over Wirless Networks. *IEEE Journal on Selected Areas in Communications*, pp. 389-398, 2010.

[2] S. Max, E. Weiss, G. R. Hiertz. Analysis of WiMedia-based UWB Mesh Networks. *IEEE Conference on Local Computer Networks*, pp. 919-926, 2007.

[3] H Zha. QoS Support over UWB Mesh Networks. *IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 2283-2288, 2008

[4] Standard ECMA-368: High Rate Ultra Wideband PHY and MAC Standard, December 2008.

[5] Distributed Medium Access Control (MAC) for Wireless Networks, Release 1.5. *http://www.wimedia.com*, December 2009

[6] S. Max, Y. Zang. OFDM-UWB Physical Layer Emulation for Event-Based MAC Simulation. *In Proceedings on Personal, Indoor and Mobile Radio Communications* pp. 1-5, Finnland, 2006.

[7] D. Bueltmann, M. Muehleisen, K. Klagges and M. Schinnenburg. openWNS - open Wireless Network Simulator. *In Electronic Proceedings European Wireless Conference* pp. 205-210, Denmark, 2009.

[8] I. F. Akyildiz, X. Wang and W. Wang. Wireless mesh networks: a survey. *Computer Networks Journal* Vol. 47, pp. 445-487, 2005.

[9] H. Shin, Y. Kim and C. Kang. A Distributed Relay MAC Protocol in WiMedia Wireless Personal Area Networks. *IEEE International Symposium on Parallel and Distributed Processing with Applications*, pp. 784-789 , 2008 .

[10] Hiertz, J. Habetha, P. May, E. Weiss, R. Bagul, S. Mangold. A Decentralized Reservation Scheme for IEEE 802.11 Ad Hoc Networks. *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Beijing, China, September 2003.