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The paper at hand is the correct and final version. By mistake, a preliminary version has been submitted and uploaded to IEEEXplore.

Document DOI:10.1109/MOBHOC.2007.4428715 is inaccurate and shall not be considered.

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IEEE 802.11s MAC Fundamentals

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***Abstract*—The tremendous success of the Institute of Electrical and Electronics Engineers (IEEE) 802.11 Wireless Local Area Network (WLAN) standard led to severe competition. Due to Wi-Fi Alliance (WFA)'s marketing, 802.11 became a universal solution for wireless connectivity. However, still a WLAN depends on wired infrastructure that interconnects the central Access Points (APs). To become independent of backbone networks leading to cheap deployments, the traditional single-hop approach needs to be replaced by Wireless Mesh Networks (WMNs). Since several years, the research community develops routing protocols designed for wireless multi-hop networks. With 802.11s an integrated WMN approach is under development that adds the necessary functionality for interworking, security and routing. As its Medium Access Control (MAC), 802.11s relies on the existing schemes. However, the current 802.11 MAC has been designed for wireless single-hop networks. Its application to WMNs leads to low performance. The capacity of the wireless medium can hardly be exploited. Thus, 802.11s provides an optional MAC that has been specifically designed for WMN.**

In this paper we explain the fundamental operation of the 802.11s MAC, explain its extensions and provide detailed simulation results on their performance.

***Index Terms*—IEEE 802.11s, WLAN, Wireless Mesh Network, Mesh Deterministic Access (MDA)**

I. Introduction

802.11 is the most successful Wireless Local Area Network (WLAN) standard in the market. Until 2008, analysts expect one billion 802.11 chipsets to be shipped. Several amendments enable new markets for 802.11 based products. However, still 802.11 relies on a wired infrastructure. At present, 802.11 networks mostly operate in the infrastructure mode. A central device, called Access Point (AP) manages the WLAN and operates as a portal (gateway) to non-802.11 networks. Stations that associate with the AP rely on it for Internet connectivity. However with increasing demands for high speed, range becomes a limiting factor. APs need to be densely deployed to enable sufficient coverage. Therefore, demands for cheap, infrastructure-less deployments increase. Wireless Mesh Networks (WMNs) provide the solution [1], [2].

With 802.11s an extension for Mesh networking is under development. In its current form [3], 802.11s adds the necessary functions for path selection, frame forwarding over multiple wireless hops, a decentralized security framework and power saving concepts. Although the 802.11 Medium Access Control (MAC) has not been designed for wireless multi-hop network, 802.11s relies on it. Therefore, many products and proposal circumvent the MAC inherent performance issues with multiple transceivers. Each of them operates in a different frequency channel, thus providing separated wireless links to neighboring devices. However, the application of multiple transceiver technology is limited due to adjacent channel interference. When transmitting, today's radios emit energy also in the side bands of the channels they are tuned to. Thus, collocated radios in the same cabinet are interfered. Due to the increasing amount of users and devices, other technologies entering the unlicensed spectrum that 802.11 operates in, and for pure cost reasons in price sensitive markets such as for Consumer Electronic (CE), a focus on multiple radio solutions is undesirable. With its optional MAC scheme, 802.11s improves the performance when limited resources are available. Thus, in this paper we study the 802.11s single channel/single radio WMN.

A. Outline

This paper bases on [3] and [4]. The latter is the 2007 revision of 802.11 that incorporates all previously approved amendments. In Section II we briefly introduce the 802.11 and 802.11s architecture. Section III introduces the design principles of the 802.11 MAC. A short overview to the basics of wireless communication in Section IV helps to illustrate the fundamental problems of the current 802.11 MAC in VII. In Section VIII, we explain the engineering goals of the optional 802.11s MAC scheme and explain why it fits much better to the harsh radio environments of WMNs. We analyze the new MAC by simulative means in Section IX. Section X concludes our paper and Section XI provides an outlook to future evolution of WMNs.

II. 802.11 & 802.11s Architecture

In 1980, IEEE project 802 started. Today, 802 provides a family of standards for different applications. The basic documents are 802 (overall concept) 802.1 (bridging) and 802.2 (logical link control). 802.11 describes one set of Medium Access Control (MAC) and Physical Layer (PHY) that work below 802.1 and 802.2. At present, most 802.11 Wireless Local Area Networks (WLANs) operate in the infrastructure Basic Service Set (BSS) mode. In it, all stations communicate via single wireless hops with a central entity denoted as Access Point (AP). An AP collocated with a portal bridges the 802.11 with a non-802.11 network, see Fig. 1. Without 802.11s, APs solely connect through non-802.11 networks (802.3 e.g.).

802.11s introduces the Mesh Point (MP). MPs form the Mesh BSS. Unlike the traditional 802.11 BSS, the Mesh BSS provides connectivity over multiple wireless hops. Path selection and forwarding operate transparently within the MAC. Thus, an 802.11s Mesh integrates with any other 802 network.

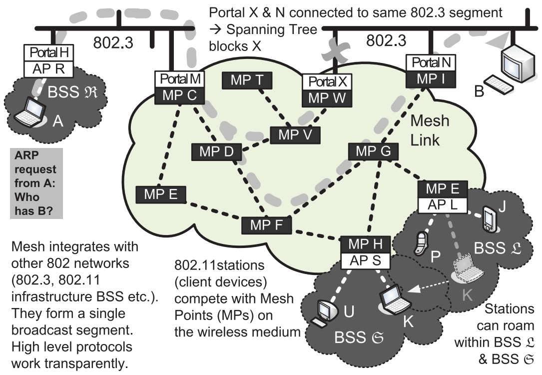

Figure 1. An 802.11s Mesh can transparently integrate with other 802 networks. Here, it interconnects two Ethernet (802.3) segments and the infrastructure BSSs $\mathfrak{L}$, $\mathfrak{R}$ and $\mathfrak{S}$. Stations J, P and K , U associate with AP L resp. S. In a wireless single frequency channel network, they equally compete on the wireless medium with any other 802.11 device.

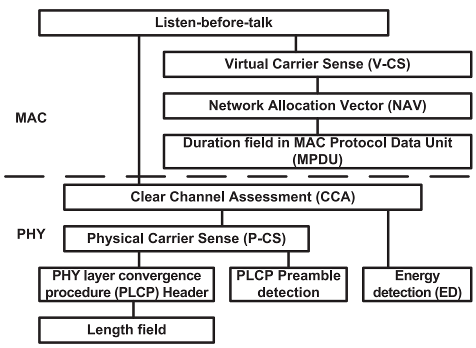

Figure 2. Medium access control in 802.11 implements Listen-before-Talk. As long as the CCA or V-CS indicates a busy wireless medium, an 802.11 device shall not transmit. While V-CS resides in the MAC, CCA is implemented in the PHY.

Furthermore, the 802.11s Mesh may be used to interconnect other 802 Local Area Network (LAN) segments. A detailed overview can be found in [5].

III. Basic Medium Access Control in 802.11s

Before 802.11 stations initiate a frame transmission, they sense the wireless medium. This is known as Listen Before Talk (LBT). 802.11 supports Physical Carrier Sense (P-CS) and Virtual Carrier Sense (V-CS). P-CS is part of the Physical Layer (PHY)'s Clear Channel Assessment (CCA), while V-CS is a Medium Access Control (MAC) layer function. Fig. 2 provides an overview. If either of the mechanisms indicates busy medium conditions, the station shall not attempt to transmit. Once the wireless medium is idle, a station may send a frame. To avoid multiple frames being transmitted at the same time, 802.11 implements the Collision Avoidance (CA) scheme. Accordingly, stations need to wait for a random duration before accessing the wireless medium. In the following, we explain CCA, Energy Detection (ED), P-CS, V-CS and CA. Without loss of generality, in this paper we assume the 802.11 Orthogonal Frequency Division Multiplexing (OFDM) PHY for the unlicensed 5 GHz band (aka 802.11a).

A. Clear Channel Assessment

Clause 9.2.1 of [4] states that P-CS shall be performed by the PHY. More precisely, P-CS is one means of the CCA. While P-CS detects transmissions of similar systems, the additional ED provides information about medium usage by dissimilar PHY technologies or pure interference.

1) Energy Detection: ED indicates medium usage independent of a signal's modulation, shape or other characteristics. With 802.11a, ED shall indicate a busy wireless medium if the receive power level exceeds -62 dBm. Therefore, a station continuously collects the energy received at the antenna in periods of less than 4 µs.

2) Physical Carrier Sensing: If a station detects a valid OFDM transmission at a minimum level of -82 dBm it shall indicate a busy wireless medium within 4 µs with a probability exceeding 90%. The threshold equals the minimal required receiver sensitivity for a frame that uses the Binary Phase Shift Keying (BPSK)$\frac{1}{2}$ (6 Mb/s payload data rate) Modulation and Coding Scheme (MCS). For any valid Physical Layer Convergence Protocol (PLCP) header received, P-CS will indicate a busy wireless medium for the duration of the frame.

B. Virtual Carrier Sensing

V-CS informs stations about ongoing or planned transmission. All stations that are not in power-save mode, constantly monitor the Wireless Medium (WM). Stations retrieve reservation information from any frame they could decode. 802.11 frames provide the reservation information in the MAC header. If the duration field is present, stations set their Network Allocation Vector (NAV) to the according value. The NAV works as a count-down timer. As long as the timer has a value different than zero, V-CS indicates a busy WM. The value of the NAV may be updated at any time. Thus, NAV duration may be prolonged or foreshortened.

C. Collision Avoidance

With the basic 802.3 (Ethernet), stations constantly monitor the medium. If a station detects the medium as idle, it may transmit a frame. Multiple, concurrent transmissions lead to a collision on the shared medium. As in wired communication the energy emitted by the transmitter propagates with low attenuation to the receiver side, local echo cancellation enables Collision Detection (CD). In contrast, in wireless communication the received strength is several degrees smaller than the emitted. Thus, stations cannot transmit and receive concurrently. As 802.11 cannot enable CD, it relies on CA. With CA, stations wait for a random period before transmitting. 802.11 defines two basic durations.

- Between consecutive frames, the Short Interframe Space (SIFS) provides sufficient time for transceiver turnaround. The receiver of a frame switches to transmit mode and the the transmitter turns to receive mode.
- slot defines the time needed to perform ED and to indicate the result to the MAC layer.

Their durations depend on the PHY layer technology. At earliest, a station can access the wireless medium if the wireless medium remains idle for at least a duration of $SIFS + 1 * aSlot$. This duration is known as Point (Coordination Function) Interframe Space (PIFS). To provide a central coordination entity (Point Coordinator (PC) or Hybrid Coordinator (HC)) with highest priority, other stations wait longer. They access the wireless medium at earliest after $SIFS + 2 * aSlot$, called Distributed Coordination Function Interframe Space (DIFS). To diminish the possibility of multiple stations transmitting at the same time, following DIFS stations need to wait for a random amount of aSlot – the so called Backoff Time. The amount of slots is determined by a random number drawn from the interval $(0, CW)$. For every aSlot duration the wireless medium remains additionally idle after a period of DIFS, a station decreases its backoff counter by one. It the counter reaches zero, the station transmits. As soon as the station senses the wireless medium to be busy, it halts the backoff. Once the wireless medium becomes idle again, the station counts down for the remaining backoff slots.

D. Medium Access Coordination in 802.11s

The Distributed Coordination Function (DCF) is the basic 802.11 Coordination Function (CF). It implements Carrier Sense Multiple Access (CSMA) and CA. For every frame transmission that fails, DCF doubles the Contention Window (CW) size and draws a random number from $(0, CW)$. Following the station may try to send the frame again. To detect transmission failures, the receiver acknowledges every successfully received frame. The absence of an Acknowledgment (ACK) frame indicates a failure. DCF provides equal end-to-end throughput among all competing stations. With a low MCS scheme, the transmission duration increases and vice versa. However, regardless of a frame's MCS a station may send one frame per contention.

For the support of Quality of Service (QoS), 802.11 introduces a new CF called Enhanced Distributed Channel Access (EDCA). In contrast to DCF, EDCA supports eight different Traffic Categories [6]. They are mapped to the four Access Categorys (ACs) Best effort, Background, Video and Voice.

Each AC has its own frame queue and parameter set for medium access. With EDCA, Arbitration Interframe Space (AIFS) replaces DIFS. The duration of AIFS is calculated as $AIFS = SIFS + AIFSN * aSlot$. Arbitration IFS Number (AIFSN), CWmin and CWmax depend on the AC.

Furthermore, EDCA changes the fairness principle. When stations perform EDCA, they contend for Transmission Opportunitys (TXOPs). The duration of a TXOP depends on the AC. As long as station does not exceed the TXOPlimit, it may send frames. Hence, EDCA provides equal transmission duration to all stations. However with EDCA, the end-to-end throughput a station achieves depends on the MCS it uses for its frame exchange. In conjunction with Block ACK [7], EDCA operates more efficiently than DCF.

IV. Wireless Basics

In wireless communication, the Signal to Interference plus Noise Ratio (SINR) is the important value to consider for frame reception. (1) provides the SINR that station s_n experiences when it receives a signal from s_m at a distance $d_{n,m}$ transmitted at power $P(m)$ while devices s_k, $k \notin (n, m)$ concurrently emit other unwanted power $P(k)$ at a distance $d_{n,k}$. f denotes the frequency and c the velocity of propagation.

Table I
SNR subject to a device's noise figure N_f and receiver sensitivity

N_f	0 dB (ideal)	5 dB (low)	10 dB (high)
$P_{\text{Noise}_{\text{thermal}}}$	-100 dBm	-95 dBm	-90 dBm
BPSK½ sensitivity (6 Mb/s PHY data rate)	Minimum SNR for frame reception		
-82 dBm (802.11 requirement [4])	18 dB	13 dB	8 dB
-91 dBm (example product [14])	9 dB	4 dB	-1 dB
64QAM¾ sensitivity (54 Mb/s PHY data rate)	Minimum SNR for frame reception		
-65 dBm (802.11 requirement [4])	35 dB	30 dB	25 dB
-73 dBm (example product [14])	27 dB	22 dB	17 dB

$$\text{SINR}_n(m) = \frac{\frac{P(m)}{d_{n,m}^{\gamma}} * (\frac{c}{4\pi f})^2}{P_{n,\text{Noise}_{\text{thermal}}} + \sum_{k=1}^{N} \frac{P(k)}{d_{n,k}^{\gamma}} * (\frac{c}{4\pi f})^2}, k \notin (n, m) \quad (1)$$

The path loss exponent γ depends on the environment [2...6]. Noise is of thermal nature. With Boltzmann's constant k_B, the receiver temperature T and the signal bandwidth Δf it is calculated as (2).

$$P_{\text{Noise}_{\text{thermal}}} = k_B * T * \Delta f + N_f \quad (2)$$

The receiver sensitivity defines the minimum level of power a device needs to receive a frame of 1000 B length with less than 10% Packet Error Rate (PER). It is measured under ideal conditions in a closed cabinet. Therefore, we can calculate the minimum Signal to Noise Ratio (SNR) needed:

$$\text{SNR}_n(m) = \frac{P(m) * (\frac{c}{4\pi f d_{n,m}})^2}{P_{n,\text{Noise}_{\text{thermal}}}} \quad (3)$$

Depending on the noise figure N_f and receiver sensitivity at a temperature of 300 K, today's Wi-Fi products require SNR values presented in Table I for the MCSs BPSK½ resp. 64 Quadrature Amplitude Modulation (QAM)¾. Our findings for the low N_f (~5 dB) comply with recent publications [8]–[13].

V. Problems

In 802.11, Listen Before Talk (LBT) is fundamental. The network performance severely depends on the specific interaction of Medium Access Control (MAC) and Physical Layer (PHY) layer based Carrier Sense (CS).

A. The hidden station problem

In wireless communication, interference occurs at the receiver side but Physical Carrier Sense (P-CS) solely detects the transmitter side. Thus, depending on the network topology devices may become mutually hidden. Consider station C being in reception range of station B but outside P-CS range of station A. The latter may transmit a frame to B. However, C cannot detect A's transmission. Thus, it may initiate a frame transmission. Depending on the distance to B, C's transmission may significantly reduce the Signal to Interference plus Noise Ratio (SINR) of A's transmission to B. This effect is known as hidden station problem.

To avoid the hidden station problem, 802.11 introduces a handshake mechanism. Based on a manually set threshold and depending on the actual frame size, A would send a Request To Send (RTS) frame. Its duration field sets the Network Allocation Vector (NAV) in stations surrounding A to the the duration of the intended frame exchange sequence. If B receives the frame, it replies by a Clear To Send (CTS) frame. The latter sets the NAV of stations in the surroundings of B. Thus, any station that received the RTS and/or CTS refrains from medium access.

B. The exposed station problem

The exposed station problem is the counterpart to the hidden station problem. A station that is in range of the transmitter but far from the receiver of a frame exchange, senses the wireless medium as idle or might have its NAV being set. As the station is far from the receiver, it cannot interfere with its frame reception. However, due to a busy wireless medium the exposed station can not reuse the channel for a concurrent transmission. Thus, the capacity of the wireless medium cannot be exploited.

802.11 does not provide a solution to tackle the exposed station problem. Due to its sensitive medium sensing thresholds, the exposed station problem occurs often. Furthermore, an 802.11 relies on frame acknowledgment. As the 802.11 frames have arbitrary length, the Acknowledgment (ACK) may follow any time. Both entities of an 802.11 frame exchange constantly change roles of transmitter and receiver. Furthermore, the amendments of 802.11n introduce data transmission reversal. The owner of a Transmission Opportunity (TXOP) may provide remaining duration to the receiver. Thus, data frames may be send in both directions.

VI. Absence of RTS/CTS in real 802.11 deployments

With -62 dBm sensitivity for Energy Detection (ED) and -82 dBm for Virtual Carrier Sense (V-CS), the latter seems to be the dominating mechanism. However, V-CS is only helpful when the Request To Send/Clear To Send (RTS/CTS) frames can be decoded. As today's Wireless Fidelity (Wi-Fi) products provide sensitive receivers, the ED threshold decreases too. Thus, ongoing transmissions over large distances can be detected. ED sufficiently blocks devices from colliding with ongoing transmissions [15]. The hidden station problem never occurs. Therefore, V-CS only adds to the overhead and remains unused. Accordingly, our measurements during Institute of Electrical and Electronics Engineers (IEEE) 802 standardization meetings (January and March 2007) indicated not a single RTS/CTS handshake in the 5 GHz. Furthermore to the best knowledge of the authors, no product in the market supports adaptive RTS/CTS usage. Unlike the early 802.11 Direct Sequence Spread Spectrum (DSSS) (1 Mb/s, 2 Mb/s) and High Rate Direct Sequence Spread Spectrum (HR/DSSS) (1 Mb/s - 11 Mb/s) products, the vast majority of today's devices (802.11a/g) do not provide any user interface to manually set the RTS/CTS threshold. Thus, RTS/CTS is never used. Furthermore, [16]–[18] show that RTS/CTS has a negative effect on the performance in Wireless Mesh Networks (WMNs).

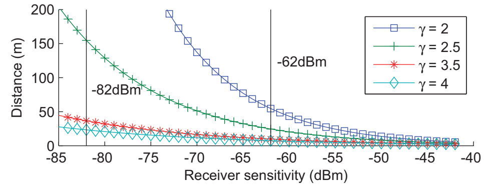

Figure 3. Depending on the path loss γ and the ED threshold, a device transmitting at 100 mW (20 dBm) may block other devices over large distances.

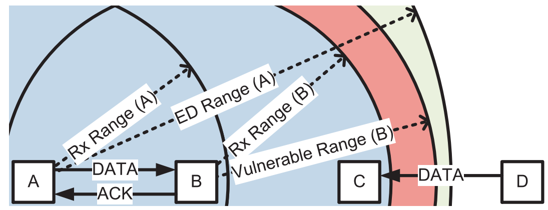

Figure 4. A sends a data frame to B. With current ED threshold settings, A's transmission can be sensed over large distances. Thus, even without usage of the RTS/CTS handshake, the hidden station problem does not occur.

VII. Problems with EDCA in Wireless Mesh Networks

Enhanced Distributed Channel Access (EDCA) [19] is the mandatory Coordination Function (CF) in 802.11s. EDCA has been designed for wireless single-hop networks. Energy Detection (ED) implements a primitive coexistence support as neighboring stations can be detected. However, a Wireless Mesh Network (WMN) is more than the sum of overlapping Wireless Local Area Networks (WLANs). Its to a station's own interest to support its neighbors in frame forwarding. A pure "transmit and forget" strategy disregards the fact that the wireless medium needs to be shared.

A. Inefficient medium usage

Due to its conservative ED and Physical Carrier Sense (P-CS) threshold settings, the hidden station problem never occurs in 802.11. Thus, devices with a large area and therefore a large amount Mesh Points (MPs) within a Mesh around the transmitter of a frame exchange refrain from medium access. Fig. 3 presents an example overview. Therefore, the capacity of the wireless medium cannot be exploited. Especially in Mesh networks, MPs must be in mutual reception range to relay frame wirelessly over multiple hops. Thus, MPs are densely deployed and each frame transmission leads to a large amount of exposed devices.

Furthermore, MPs transmit frames of arbitrary length. Neighboring MPs cannot predict a frame exchange's duration. The transmitter may request an Acknowledgment (ACK)

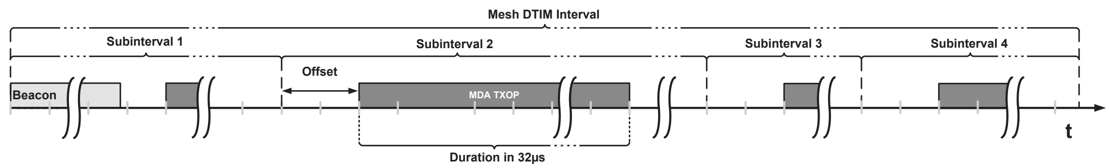

Figure 5. An MDAOP Setup may initiate several, periodic MDAOPs. The subinterval and Offset uniquely identify each MDAOP in multiples of 32 µs.

frame at any time by the receiver. As the absence of an ACK frame indicates a transmission failure, 802.11 blocks devices around the transmitter and receiver of a frame exchange. Even with perfect knowledge on the mutual interference levels, a neighboring MP could not transmit concurrently to an ongoing frame transmission, as the physical information flow may reverse arbitrarily.

B. The unaware station problem

Fig. 4 depicts a major source for low EDCA performance. Stations detect A's transmission within "ED Range (A)". Due to 802.11's conservative settings, this range exceeds B's "Vulnerable Range" by far [20]. We denote the latter as the area within any other transmission at the same power level as A provokes a failure of A's transmission to B. Within WMNs, the problem occurs at D. D can neither interfere with B nor sense A's transmission. As it detects the channel idle, D may initiate a frame transmission to C. As long as A's transmission prevent C from decoding D's transmission, C cannot reply to D. D's transmission fails. With EDCA's default values for a video Transmission Opportunity (TXOP) duration, A's transmission to B may take up to 3 ms. During that time, D can start several retransmissions until it finally discards the frame.

C. Conclusions for Wireless Mesh Networks

In a WMN, devices need to cooperate. MPs must be in mutual reception range to be able to forward frames. Therefore, the Medium Access Control (MAC) needs to consider more than their local frame transmissions to neighbor MPs. Devices multiple hops away become performance limiting as they cannot detect the status of their neighbors. The unaware station problem leads to unnecessary retransmissions. Furthermore, each retransmission itself blocks the wireless medium for other frame exchanges. Thus, performance sharply degrades.

The current 802.11 MAC has been designed for wireless single-hop networks. EDCA considers the local Basic Service Set (BSS) only. Its opportunistic approach leads to selfish behavior. Thus, MPs do not consider cooperative frame forwarding. MPs handle relayed frames similar to locally generated frames. When receiving a frame that needs to be forwarded, the MP stores it in its local queue and handles it as any other frame. Thus, the Mesh network does not treat frames fairly that traversed several hops already.

Furthermore, MPs have no means to prioritize over (legacy) stations. In many scenarios, an MP may be collocated with an Access Point (AP). The AP provides access to the wireless network for stations. The MP allows for cheap and easy deployment. With a single radio, the Mesh and the local BSS need to compete on the wireless medium. However, stations cannot be throttled. According to EDCA, they access the wireless medium whenever it is idle. Thus, MPs may not achieve the desired throughput and higher layer protocols need to reduce the transmission rate. But even with separate radios, the Mesh network needs to carry the aggregated traffic of the stations it serves. Thus, the local single hop link from a station to its AP can easily congest the Mesh network where the achievable throughput with multiple hops to the final destination is low.

VIII. 802.11s – Mesh Deterministic Access

The basic idea of Mesh Deterministic Access (MDA) is the separation of contention for the medium from medium access. MDA is a CF specifically designed for WMNs. It roots in the 802.11s proposal of the industry forum Wi-Mesh Alliance (WiMA). WiMA and the competing industry group SEE-Mesh merged their proposals in February 2006. The merged document became the baseline document of 802.11s that forms the current draft [3].

With MDA, the Mesh wide Delivery Traffic Indication Message (DTIM) interval is slotted. The DTIM interval is the time between two Mesh DTIM beacons. MPs periodically send beacon frames to propagate path selection, association, broadcast announcements and other Mesh wide information. Furthermore, MPs use beacon frames to detect each other, to maintain connectivity and to synchronize their local clocks.

Each MDA slot has 32 µs duration. Multiple slots are grouped to an MDA Opportunity (MDAOP). A single MDAOP Setup handshake may be used to initiate multiple, periodic MDAOPs. Therefore, the message contains information on the subinterval, relative offset with in the subinterval and the MDAOP duration, see Fig. 5.

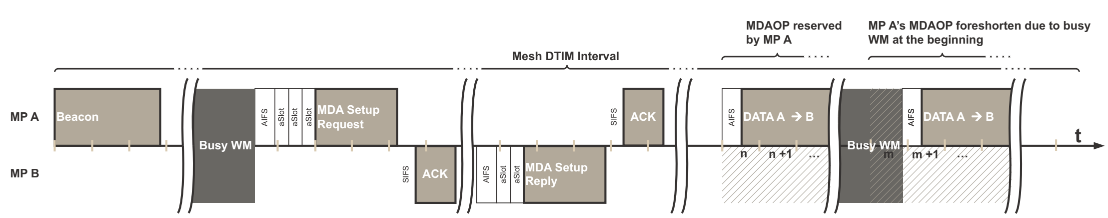

Figure 6. MP A negotiates on an MDA set-up with MP B. After establishing, MP A uses periodic MDAOPs to send data to B. MP A does need to undergo the backoff procedure to access the wireless medium during its MDAOP. If the wireless medium is busy at the beginning of an MDAOP, it is foreshorten.

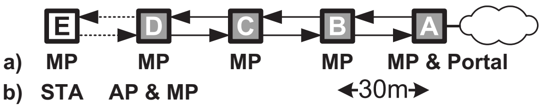

Figure 7. MP A provides Internet connection through its collocated portal. MPs B to D forward any traffic that A & E exchange. In (a), all devices are MPs. In (b), E is a legacy that associates with the AP collocated at MP D.

MPs negotiate on the usage of the wireless medium via management (action) frames, see Fig. 6. Once an MDAOP is set-up, the MP broadcasts an TX-RX times report. Each MP keeps a record of MDAOP it learned about. Additionally, MPs indicate the duration and slot time of MDAOP of neighboring MPs too. The MDAOP of neighbors' neighbors are indicated in the interfering times report. Together with the TX-RX times report, the times are broadcasted in the beacon frames. Thus, MPs become aware of the medium usage in their neighborhood. With MDA, MPs can avoid the unaware station problem.

An MP accepts or declines a setup request with an MDA reply message. If an MP declines, it may propose other MDA parameters. Thus, the MP initiator may choose different interval and offset values. The TX-RX and the interfering times reports help MPs in the set-up, decline and alternate suggestions of MDAOP. Instead of blindly accessing the wireless medium, MDA capable MPs are able to schedule their medium access. Furthermore, MDA transmission attempts are more likely to succeed. Surrounding MPs have learned about the planned transmission and thus refrain from medium access.

At the beginning of the MDAOP, the MDAOP owner access the wireless medium with special settings for Arbitration IFS Number (AIFSN) and CWmin. The settings provide it with highest priority for medium access, see Fig. 6. During the MDAOP, MPs follow the same transmission rules as applied for the EDCA TXOP. Regardless if the beginning of an MDAOP has been delayed or not, MPs do not exceed the announced MDAOP duration. Thus, their transmission become predictable. Furthermore, within the MDAOP MPs may use any kind of frame exchange sequence defined by 802.11. Thus, Block Acknowledgment (BA) and frame aggregation can be efficiently used.

IX. Simulation results

We use event-driven stochastic simulations based on the Wireless Access Radio Protocol 2 (WARP2) simulation environment that has been developed at ComNets [21]. It is programmed in Specification and Description Language (SDL) using Telelogics TAU SDL Suite. To avoid false conclusions as criticized in [22], the channel model of WARP2 accurately simulates erroneous radio propagation on the Wireless Medium (WM), see [23]. In accordance with Institute of Electrical and Electronics Engineers (IEEE) recommendations, throughout this paper all mathematical notations and units are given according to [24]. In the following, we set the attenuation factor $\gamma = 3.5$. All transmissions use Quarternary Phase Shift Keying (QPSK) modulation with coding rate $1/2$. Thus, the maximum Physical Layer (PHY) speed is $12\,\mathrm{Mb/s}$. All devices transmit at $20\,\mathrm{dBm}$ output power.

The initial scenario is depicted in Fig. 7 (a). Mesh Point (MP) A is collocated with a portal. It serves the Mesh with Internet connectivity. MP E receives and sends data of $80\,\mathrm{B}$ size. The intermediate MPs operate a relays that forward any traffic. Fig. 8 presents the total system throughput (up- and down-link). Depending on the MDA Access Fraction (MAF), MPs use Mesh Deterministic Access (MDA) for the indicated percentage of the Mesh Delivery Traffic Indication Message (DTIM) interval. Only with a large MAF the throughput stabilizes. A low MAF enforces MPs to Enhanced Distributed Channel Access (EDCA) for forwarding. However, with EDCA the network easily congests and its non-cooperative design leads to severe performance reduction. When the amount of traffic offered to MP A resp. MP E is high, they access the wireless medium more frequently. However, their increased medium usage leaves no capacity for the intermediate MPs that forward the traffic. Thus, the achievable throughput severely drops.

Fig. 7 (b) presents the second scenario. The topology remains the same as in the previous scenario. However, MP E becomes a simple station that relies on Access Point (AP) for connectivity. Thus, E's neighbor MP D is collocated with an AP. As stations do not implement MDA, station E solely applies EDCA for medium access. The remaining MPs use MDA for medium access. The traffic flow and payload size remains the same as in the previous simulation. Fig. 9 presents the simulation results. With a single MDA unaware station using the same frequency channel, MDA has difficulties to achieve better performance than a pure MDA network. Owing to EDCA's uncooperative design, the MP/AP needs to cooperate with station E on medium access. Assuming unacknowledged User Datagram Protocol (UDP) traffic on a higher layer, a single station can easily congest the wireless medium therefore. Station E has no knowledge about the neighboring MPs that provide the forwarding service to it. As the basic 802.11 does provide neither a flow control nor means for APs to moderate their associated stations' medium access, the Mesh network suffers from station E's opportunistic medium access.

X. Conclusions

With Enhanced Distributed Channel Access (EDCA), 802.11s operates very inefficient. The low performance relates to its EDCA's Medium Access Control (MAC) design. A Wireless Mesh Networks (WMNs) is not a simple extension from single to multiple hops. In a WMN, devices need to cooperate and to become radio neighborhood aware. While in a traditional 802.11 Basic Service Set (BSS) stations solely care about connectivity to the Access Point (AP), in a WMN that is not sufficient. In a WMN, WMNs need to consider their neighbors when forwarding frames. The opportunistic, non-cooperative behavior of EDCA relies on higher layers to detect issues with the wireless link. But within a WMN, problems may occur outside a device's radio horizon. However, discarding frame locally is costly as frames may traversed

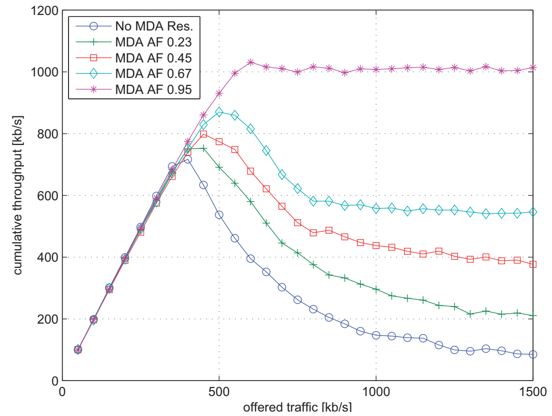

Figure 8. With EDCA (no MDA Res.), MPs are not aware of their neighbors' neighbors. Thus, it suffers from frequent medium accesses at the frame generating MPs A and E. They congest the network. Thus, less frames can be forwarded. With MDA, MPs become aware of the medium usage. Even under high load, the network does not congest.

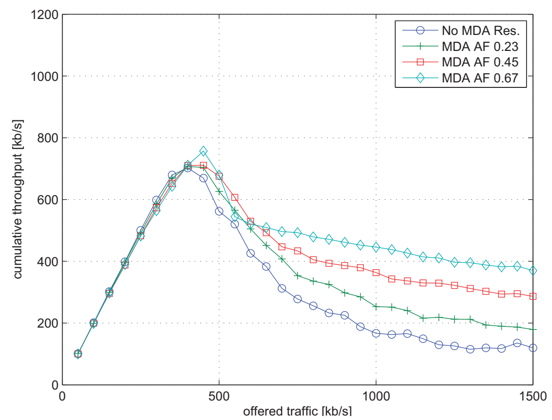

Figure 9. With a single MDA unaware device (station E that is associated with the AP/MP D) in the network, a performance increase becomes difficult. Due to its current design, MDA capable MPs have to accept interference from non-MDA capable devices.

several hops already. Thus, with WMN the MAC needs to evolve.

In the past, a related evolution occurred to 802.11's wired relative – 802.3. In the basic Ethernet, all stations share a single cable for communication. Every additional station taps the cable to become part of the network. However, often the taps are source of failures that bring the network down. Thus, with the introduction of layer-1 relays (Ethernet hub, Physical Layer (PHY) repeater) the physical topology changes from bus to star. Therefore, a failure of a single device or on the wiring to the hub does not impact the rest of the network. However, the logical structure remains the same. The Ethernet hub remains a shared medium for all stations. Thus, at any time a single device can transmit only. With increasing size of the network, the shared medium concept does not scale. The performance drops sharply. Products that offered connectivity for several hundreds of Ethernet ports had low performance.

The introduction of layer-2 bridging (Ethernet switch, MAC bridge) was a significant change for 802.3. In a switched Ethernet, every station can concurrently transmit and receive. While an Ethernet hub floods an incoming frame to all its ports, an Ethernet switch forwards the frame only to the port where the intended receiver is attached. Hence, a switched Ethernet segment enables point-to-point connections. The switched structure allows high throughput over several hops (interconnected Ethernet switches). Furthermore, new logical concepts such as Virtual Local Area Networks (VLANs) are enabled. For the wireless 802.11, a similar evolution is needed.

XI. Outlook

Due to Moore's unbeaten law for the silicon industry, tremendous speed-up in wireless technology becomes possible:

- Ultrawideband (UWB) communication provides up to 480 Mb/s at low power within 512 MHz frequency channels.
- 802.11n uses Multiple Input/Multiple Output (MIMO) technology to achieve up to 600 Mb/s within a 40 MHz frequency channel.

The wireless industry depends on the increase of computing power, decrease of power consumption and increasing miniaturization. However, the computing industry did not only shrink its designs. Furthermore, constant enhancements of CPU designs, logical structure and internal behavior are necessary to achieve highest performance. Today's processors apply pipelined and superscalar designs, speculative execution, branch prediction, memory prefetch, out-of-order execution and many more. All this methods shall utilize the shared resources to their full capacity – Arithmetic Logic Unit (ALU), Floating Point Unit (FPU), instruction fetch and decode, memory and register access etc. Notably performance increase becomes possible due to the high degree of parallelism at instruction, thread and data level. The shared execution units can be used concurrently. A similar evolution is needed in wireless communication.

In WMNs, the wireless medium forms the shared resource for all participating devices. Today, most high performances approaches benefit from the fact that the unlicensed band provides large capacity for free. No expensive license fee needs to be paid and multiple radios separate different links and areas. However, with increasing amount of wireless devices and WMN deployments relying on cheap spectrum does not carry forward. Furthermore, price sensitive markets cannot accepts the introduction of additional radios that need to be costly separated due to adjacent channel interference. Thus, a solution for single frequency channel WMNs is needed. Devices need to be mutually aware of the medium usage. Furthermore, predictable channel access enables concurrent medium usage that solves the exposed station problem. At present, 802.11 combines different functional elements:

- spectrum management via contention for medium access (idle periods),
- data transmission, and
- failure indication (data acknowledgment).

Thus, large areas around the receiver and the transmitter of a frame exchange are blocked. Even a single frame exchange involves the reversal of the information flow: Data flows from in one direction and the Acknowledgment (ACK) in the reverse. Thus, both devices are active on the wireless medium. The arbitrary frame length leads to unpredictable traffic flows. At any time, the data frame exchange initiator may request an ACK. All these characteristics of the basic 802.11 MAC prevent efficient exploitation of the wireless medium. With 802.11s, Mesh Deterministic Access (MDA) is a first step towards a Mesh aware MAC. It allows for planned and reliable medium usage. Furthermore, interference free periods can be guaranteed.

With the decision of 802.11 to establish a new Study Group (SG) that works on a standard for 1 Gb/s Wireless Local Area Networks (WLANs), new ideas will evolve the 802.11 MAC and PHY. Spatial frequency reuse and MIMO diversity lay the foundation. Adaptive carrier sensing, energy detection and the separation of data and ACK transmission form the supplements in the MAC. Then, a switched architecture known from 802.3 can be applied in 802.11 too. This paradigm shift will become necessary as increasing PHY speeds cannot solely satisfy the challenges.

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