IEEE 802.11s: WLAN Mesh Standardization and High Performance Extensions

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Abstract

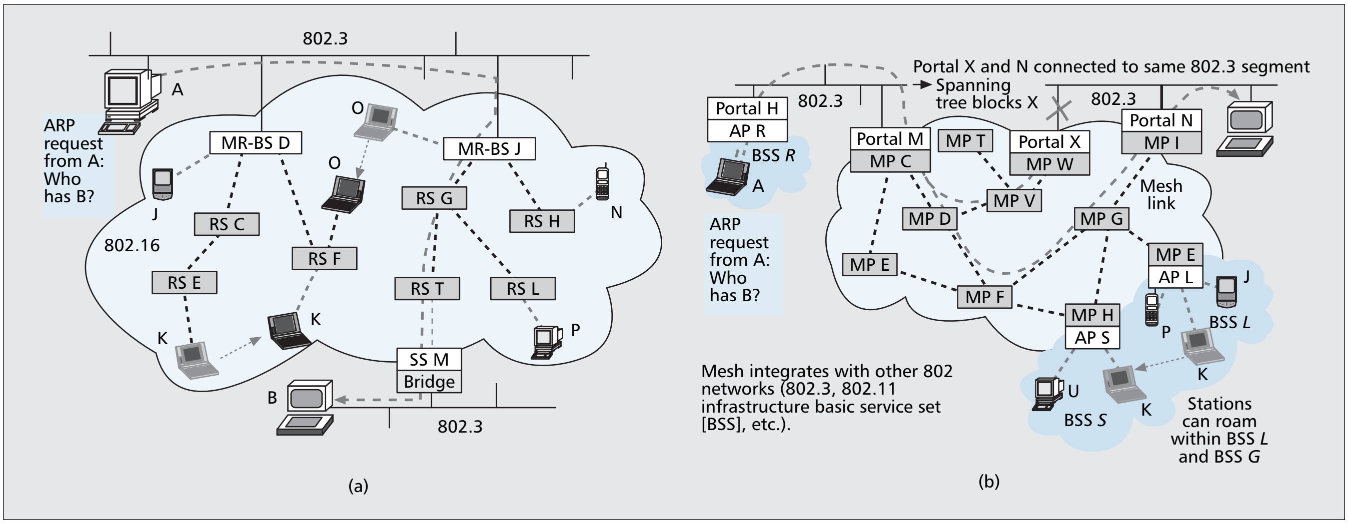
In recent years, remarkable market competition and economy of scale has resulted in the price erosion of wireless devices for consumer electronics. Especially for wireless data networks, IEEE project 802 provides the standards for mass markets. With ever-growing usage, the demand for ubiquitous wireless networks increases. However, the achievable data rates decrease with the increasing distance of client devices from the infrastructure, and a sufficiently dense deployment of infrastructure devices is required to fulfill the customers' demand for broadband access. Today, these infrastructure devices rely on a wired backbone for background services; however, to reduce their costly deployment, they should interconnect wirelessly. In this case, devices mutually serve as wireless relays that forward and route packets over multiple wireless hops, and wireless mesh networks come into existence. In this article we provide an overview of wireless mesh networking and provide insights into the related standardization efforts in IEEE 802. For a more in-depth analysis, we focus on the draft WLAN mesh standard IEEE 802.11s and identify challenges for medium access control in multihop communication. Derived from our proposal to 802.11s, the current draft incorporates an optional medium access scheme that circumvents a performance gap. By means of simulations, we compare the performance of both solutions and provide an outlook for future 802 wireless systems that will be more reliable.

Wireless communication devices improve at a tremendous rate. Presumably, the most eye-catching enhancement consists of the increase in data rates enabled by today's advanced modulation and coding schemes (MCSs). However, this increase in speed comes at a price. With increasing data rates, the required signal to interference plus noise ratio (SINR) at the intended receiver — required for reliable frame reception — also increases. Even for distances of a few meters, the signal strength drops sharply. As the transmit power is limited by regulation and device constraints (battery lifetime, size, etc.), the SINR limits the maximum communication distance. Additional environmental shadowing further attenuates the signal. Therefore, the infrastructure network must be sufficiently close to the client devices to provide ubiquitous high-speed connectivity. As a result, dense deployment of the infrastructure is required because today, the wireless link provides only the initial (uplink) or final (downlink) hop of a data packet.

However, the infrastructure itself relies on a wired backbone and is costly to install. This limits the deployment of the wireless infrastructure and its coverage. To remedy the situation, wireless mesh networks (WMNs) are desirable. With WMNs, a data packet traverses over multiple wireless hops. In a WMN, the wireless link becomes a part of the infrastructure over which packets are forwarded, relayed, and routed. Due to their independence of wired backbones, WMNs can be deployed rapidly at a low cost. Only with WMN technology can the benefits of increased data rates be fully exploited.

WMNs conquered several markets. For consumer electronics, WMN technology provides the means for range extension to achieve full coverage of the home environment. Office and enterprise networks benefit from the flexibility that a ubiquitous wireless network provides. Municipal networks have established a totally new market segment that would not exist without WMN technology. For safety, emergency, and military applications, WMNs provide ad hoc connectivity even in disaster areas and on the battle field. Although their operation provides manifold advantages, the seamless integration of a WMN into existing networks is challenging.

In this article, we first provide an overview of WMN concepts and the related work in IEEE project 802. The rest of the article focuses on its most mature draft mesh standard — IEEE 802.11s and in particular, on the medium access. Following a brief description of the envisioned architecture, we identify the performance limitations of the current 802.11 [1]



■ Figure 1. *a) In a wireless relay network, the multihop base station and its relay stations form a tree topology; b) in a wireless mesh network, mesh devices may set up connections to all of their neighbors.*

medium access scheme in WMNs. Then, we introduce the Mesh Networks Alliance (MNA) medium access proposal to 802.11s. Inspired by MNA, 802.11s integrates an optional medium access control (MAC) called mesh deterministic access (MDA), which we review later in the article. We explain its similar concept and conclude our work with performance simulations. Then, we end with a summary and conclusions.

Wireless Mesh Networks in IEEE 802

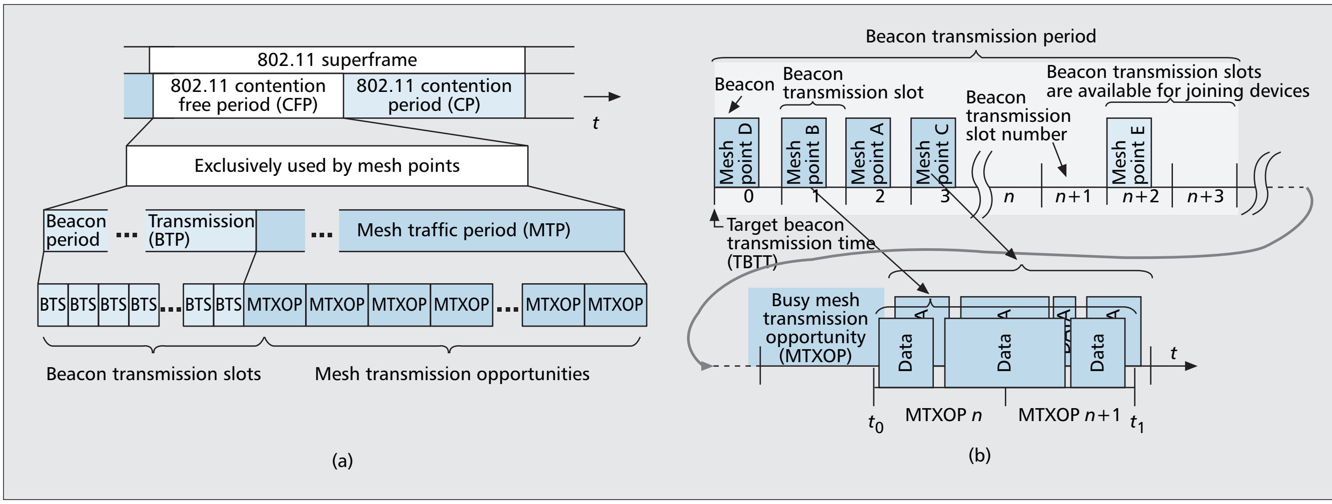
Currently, there are a number of mesh products on the market. These products act as wireless IP routers. Like an overlay, the WMN operates on top of the wireless links. This architecture has a number of disadvantages. To transport protocols other than IP through the mesh, they must be encapsulated. Therefore, handling of broad and multicast traffic is complicated. As radio conditions constantly change, wireless links are unstable. Hence, well-known routing protocols for wired networks cannot be applied. To achieve reasonable forwarding decisions, the mobile ad hoc networks (MANET) group of the Internet Engineering Task Force (IETF) defines special ad hoc routing protocols. Because the IP layer cannot perceive the radio environment (neighboring devices, MCS applicable to a link, etc.), they constantly broadcast routing messages to acquire reasonable metrics. These metrics include additional characteristics that reflect the differences from wired links. In addition to routing and security, medium access mechanism concepts also must be adapted for WMNs. As the wireless medium access determines the overall network performance, in this article we focus on the radio channel and its efficient sharing by multiple direct and indirect neighbors. Details on issues regarding the security and routing can be found in [2].

To counter the drawbacks of current mesh products, a number of new standards are under development in IEEE 802. These standards foresee the integration of routing and frame forwarding into the MAC layer, so that they operate transparently from the perspective of higher layers [3]. To differentiate layer 3 (IP) from layer 2 (MAC)-based wireless routing, the latter one is denoted as path selection. Therefore, an IEEE 802 WMN appears as a single logical broadcast domain, and Address Resolution Protocol (ARP), Dynamic Host Configuration Protocol (DHCP), Spanning Tree, and any other layer 3 protocol can be supported. Furthermore, the MAC layer has the required information on the wireless medium. Thus, seamless WMN solutions have the ability to operate more efficiently than IP-based WMNs. Currently, 802.15.5 [4] and 802.11s [5] develop WMN solutions for wireless personal area networks (WPANs) and wireless local area networks (WLAN), respectively.

The wireless metropolitan area network (WMAN) standard 802.16 [6] already specifies a mesh mode. Due to the 802.16 scheduled medium access, devices propagate their access plans into two sets: the neighborhood and the extended neighborhood. The neighborhood contains all devices that are in communication range, and the extended neighborhood consists of all the neighbors of the neighbors. A device transmission may interfere with receiving devices in both sets. Therefore, each device takes into account the medium access schedules of its neighbors. Unfortunately, the mesh mode is poorly specified. With 802.16j, a replacement is under development. This amendment describes wireless relay networks (WRNs) [7] that fit much better with the extensively used 802.16 point-to-point and point-to-multipoint configuration. In WRNs, a central device coordinates the operation of the attached relay stations (RSs). The WRN operates in a master-slave mode; see Fig. 1a. The central multihop relay BS (MR-BS) has full control over the wireless medium and associated devices. Under the guidance of the MR-BS, RSs provide other subscriber stations with broadband wireless access services. Because the MR-BS schedules up and downlink traffic, the RSs do not operate on their own. Depending on the deployment, the fixed, nomadic or mobile RSs increase the SINR in the cell to enable the use of advanced MCSs or to enlarge the coverage area of the central BS [8].

The 802.15 family provides standards for high (WPAN) and low (sensor networks) rate applications. Due to the broad scope of 802.15, 802.15.5 aims at a recommended practice instead of a standard. Whereas 802.16j defines a strictly centralized concept, 802.15.5 specifies an intermediate solution. In 802.15.5, full-function devices form a WMN and serve reduced-function devices with connectivity. Nor do the latter forward frames or participate in the formation of the WMN. In contrast to 802.16j, the WPAN mesh medium access relies on decentralized scheduling. Full-function devices negotiate on access to the wireless medium and thus continuously exchange their access plans. In January 2008, the second letter ballot on the 802.15.5 draft was completed.

The WLAN Mesh amendment 802.11s maintains the decentralized operation of its base standard 802.11; see Fig. 1b. The basic mesh device is referred to as a mesh point (MP). Due to



■ Figure 2. *a) With MNA, the mesh operates during the contention-free period; b) beacon frames coordinate the medium access during the mesh traffic period.*

their forwarding capability, MPs can form a WLAN mesh. Depending on collocated functionality, an MP may integrate the access point (AP), portal, or other services. The competition-based access scheme coordinates the medium access of single and multihop devices. Thus, an 802.11s WMN has a flat topology. In response to its first letter ballot, 802.11s received more than 5700 comments that address every detail of the draft. This tremendous interest, the already existing, manifold IP-based WMN products that rely on 802.11, and its remarkable market perspectives make 802.11s the most promising WMN solution. Consequently, we focus on 802.11s. In the following, we explain its basic concept, identify performance bottlenecks, and provide a solution to circumvent them.

IEEE 802.11s — Draft Standard for WLAN Mesh

802.11s provides an extensible framework for 802.11 WMNs [9]. For medium access, MPs use the enhanced distributed channel access (EDCA) [10] that is defined in the base standard. The contention-based medium access mechanism relies on carrier sense (CS) that does not require synchronization among MPs. Before an 802.11 device transmits, it uses the clear channel assessment (CCA) to ensure that the wireless medium is idle. The CCA indicates an idle wireless medium to the MAC layer if neither physical nor virtual CS indicates the busy state.

Physical CS indicates busy medium conditions if the energy received exceeds a certain level or if the preamble part of a frame can be decoded. Therefore, physical CS detects transmissions in the vicinity of a device. In contrast, virtual CS may detect hidden transmissions. A device is referred to as hidden if it is far from the transmitter but close to the receiver of a frame exchange. Thus, physical CS would indicate an idle wireless medium.

Virtual CS tries to resolve the hidden device problem. It relies on the exchange of control frames prior to the data frame. Through a request-to-send (RTS) frame, the transmitter indicates to its communication partner the intended duration of the upcoming data frame. This is referred to as (immediate) medium reservation. The intended receiving device repeats the reservation information in a response frame (clear-to-send [CTS]). Any device that overhears the information in at least one of the control frames sets its network allocation vector (NAV) to the desired duration and refrains from channel access during this time. Hence, devices in the reception range of the receiver or the transmitter will not interfere with their frame exchange if the RTS/CTS handshake is performed successfully.

If CCA indicates that the wireless medium is idle, an 802.11 device performs a backoff procedure. The back off requires each device to wait for a random duration before initiating a transmission. If CCA indicates a busy medium during that time, the back off is postponed and resumes as soon as CCA indicates idle medium conditions again. Thus, the backoff mechanism reduces the probability of multiple simultaneous transmission attempts of different devices, which would result in collisions. In WMNs such waiting periods delay frame forwarding on every hop.

Performance Limitations

EDCA has been designed with a single-hop topology in mind. However, its application in WMNs presents performance drawbacks. In a single-hop wireless network, all devices are either in mutual reception range or have at least one common neighbor device. In a WMN, the topology is different: it can be treated as a sum of continuously overlapping neighboring networks. Therefore, devices are mutually unaware of each other. The virtual CS cannot be easily applied because it relies on hidden devices being able to receive the reservation information. In WMNs, virtual CS only adds to the overhead [11]. Because physical CS cannot detect which neighboring devices have their NAV being set, devices outside the detection range may attempt to transmit to devices inside the range. Either the successful reception leads to an acknowledgment that causes interference to the frame exchange in progress, or it cannot be decoded, and the outside device initiates a costly retransmission.

Additionally, CCA introduces the exposed node problem. Devices that are far from the receiver (due to distance or shadowing), cannot interfere a transmission. However, because of CCA indicating busy medium conditions, the devices around the transmitter are blocked from medium access. Although possibly they could reuse the wireless medium for their own transmissions to other devices without introducing interference to concurrent frame exchanges, CCA operates too carefully, thus wasting an opportunity for spatial frequency reuse.

In many scenarios, the WLAN mesh replaces a wired backbone. It interconnects and serves the APs. Thus, the mesh carries the aggregated traffic of all devices. As proposed in 802.11s, devices share equally the wireless medium, and MPs and APs have no priority over non-mesh devices (stations). To prioritize an AP, 802.11 provides the hybrid coordination function (HCF) controlled channel access (HCCA). As a hybrid coordinator (HC), the AP accesses the wireless medium without back off and need not contend for the medium. However, this scheme relies on exclusive access and does not provide a mechanism to share the wireless medium with other HCs in the surroundings. In a WLAN mesh, where the transmission ranges of many neighboring devices overlap, mutual negotiation and coordination is required, and HCCA cannot be applied.

As a result, mesh networks often rely on separate radios for the MP and the AP to allow them to operate in different frequency bands (e.g., at 2.4 GHz and at 5 GHz). There are many scenarios where this solution is less desirable, mainly for cost reasons. In the next section, we outline an alternative protocol to improve the medium access that does not require multiple radios.

The Mesh Networks Alliance Proposal for 802.11s

In accordance with the 802.11s call for proposals (CFP), the MNA submitted a system concept [12]. Unlike all other concepts received by 802.11s, MNA proposes a scalable design that efficiently handles access and backhaul (mesh) traffic over a single wireless channel. Therefore, the MNA proposal fulfills the requirements of consumer electronic products that cannot be equipped with multiple radios.

To segregate access from backhaul traffic, MNA uses the 802.11 contention free period (CFP); see Fig. 2a. The CFP immediately follows the periodic broadcast message of the AP called beacon frame. Stations use the beacon frame to detect the presence of WLAN and to learn from the AP about required settings in the network. Furthermore, the beacon may announce the beginning and the duration of a future CFP. Stations that have learned about a CFP with prior beacons preset their NAV. During the CFP, stations remain silent and do not compete for the wireless medium even if no beacon could be received. The point coordinator (PC), usually collocated with the AP, is the only device to initiate a frame exchange sequence. As wireless networks may overlap, stations preset their NAV for any CFP they learn of, regardless whether their local AP or neighboring APs demand contention free access.

Beacon Transmission Period

As MPs are safe from interference of 802.11 stations throughout the CFP, they can apply an enhanced protocol for frame exchange. In the MNA proposal, the CFP begins with a beacon transmission period (BTP), divided into beacon transmission slots (BTS). Each MP exclusively owns a BTS. The MNA proposal provides a coordinated, sequential transmission of beacon frames to enable neighboring mesh devices to broadcast without collisions. To achieve a mesh-wide synchronized CFP, every MP announces the same beginning of the next CFP regardless of whether it sends the first beacon or not. Hence, all surrounding stations preset their NAV to the same start time. MPs mutually inform each other about the beacon slot occupancy by the inclusion of a beacon period occupancy map into the beacon. Given the local point of view of the MP, this bitmap denotes a beacon slot as

- Occupied by itself
- Occupied to receive a beacon of a neighboring MP
- Occupied, but the MP cannot decode the beacon transmitted here (thus the slot is interfered)
- Unoccupied

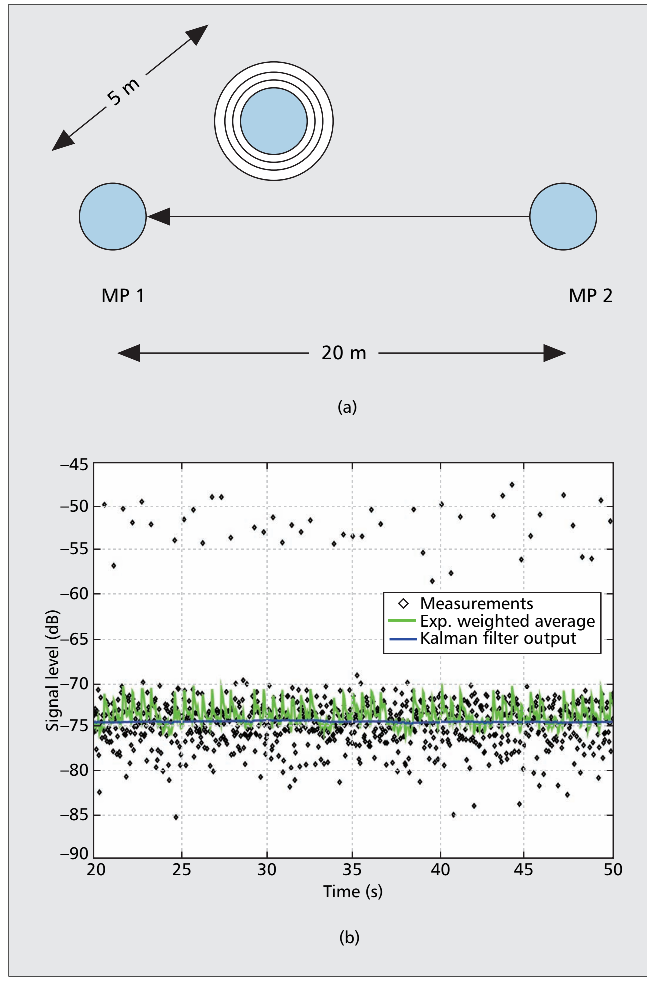
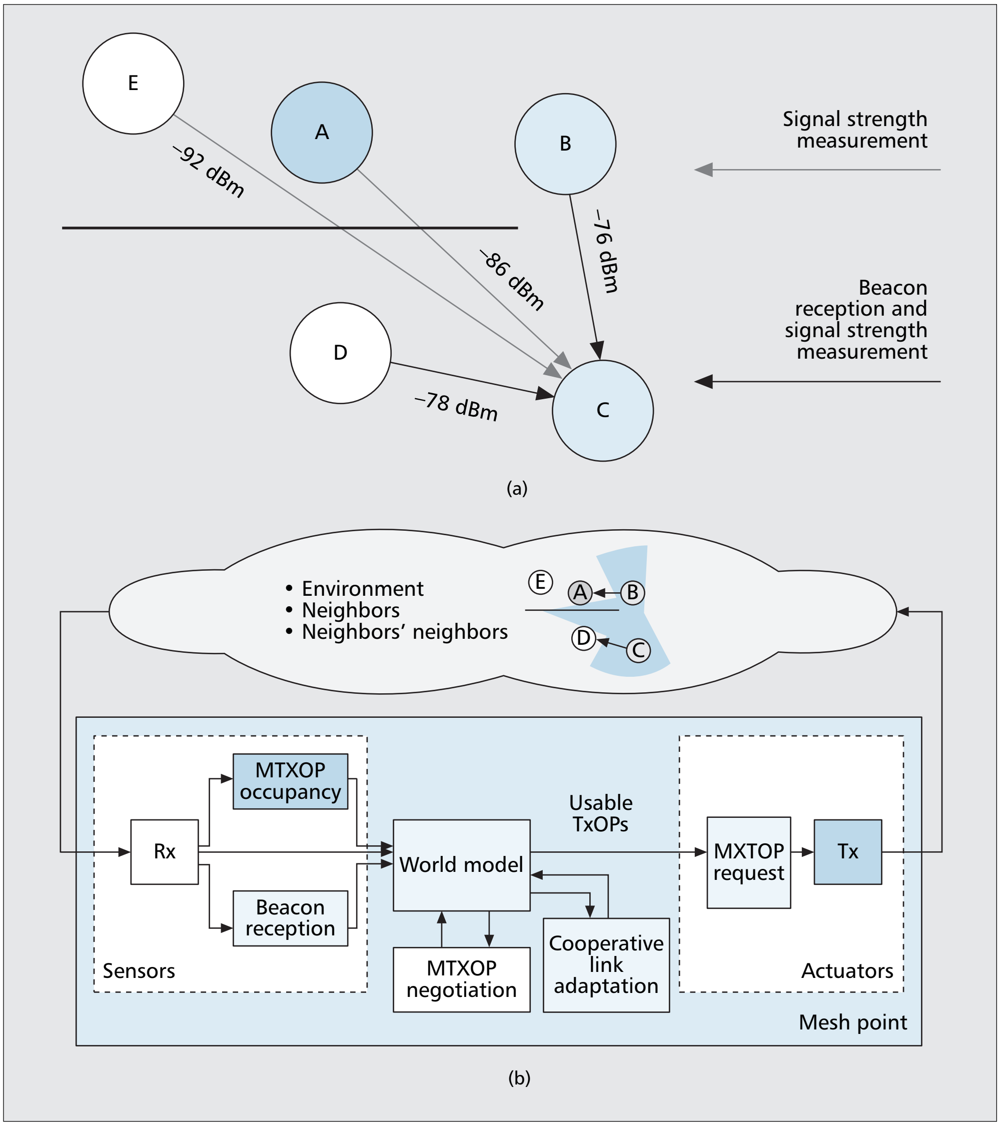


Figure 3. *a) MP2 sends beacon frames that are received by MP 1. An interferer sends bursts of 366 µs duration at an interval of 21 ms; b) the Kalman filter stabilizes the signal strength measurement.*

In the second case, an MP also provides the address of the beacon owner. Thus, MPs learn about their local and extended neighborhood. In its neighborhood and extended neighborhood, the MP is the only device that uses its beacon slot, because all devices that belong to one of the sets have learned about the beacon slot owner, either by direct beacon reception or via the announcements by one of its neighbors. Thus, they know the address of the beacon slot owner.

To provide for the third case, an MP listens and measures the signal strength of the ongoing transmission during a beacon slot that it does not use. Even if it cannot decode the beacon due to the noisy environment, the application of a Kalman filter [13] enables the accurate estimating of a stable value of the received signal strength; see Fig. 3. The beacon signal strength measurement at MP 1 fluctuates according to a Ricean fading model. Although both the interferer and MP 2 transmit at 20 dBm output power, a Kalman filter provides a reliable received signal strength estimation. Consequently, each MP can set up a local view of its radio environment, a so-called signal-strength graph. With the help of these measurements, an MP may predict the local signal strength that can be expected when one of the devices in its extended neighborhood transmits; see Fig. 4a.

Devices that join the WLAN mesh must scan the wireless medium for at least a full BTP. Thus, they learn about their neighborhood and extended neighborhood. For joining purposes, empty beacon slots at the end of every beacon period



■ Figure 4. *a) Entities A–E share a single frequency channel; b) the world model in each MP helps to identify possibilities for spatial frequency reuse.*

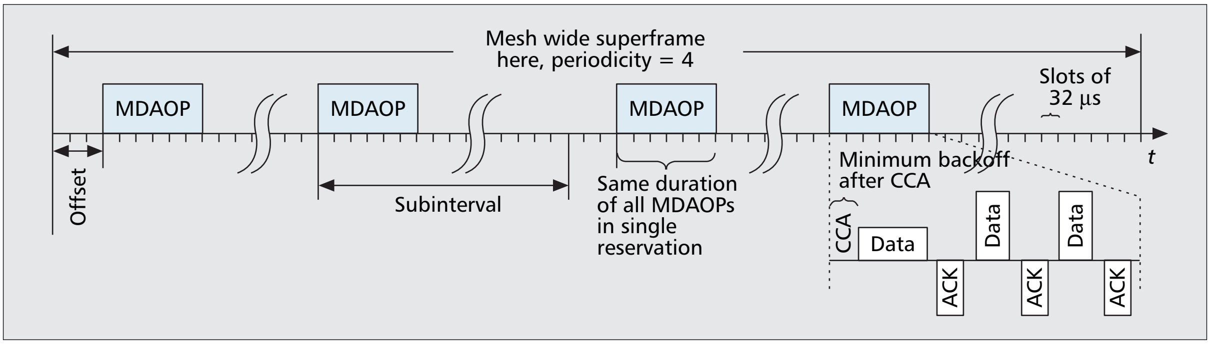
are reserved. To become part of the WLAN mesh, new devices randomly pick one of those. As soon as a joining device receives beacon period occupancy maps from its neighbors containing its address, it knows that its beacon frames have been received without collision and it has successfully joined the network. Additional mechanisms avoid fragmentation of the beacon period. Devices arrange their transmissions to avoid idle beacon slots outside the joining slots.

Mesh Traffic Period

The mesh traffic period (MTP) follows the BTP. During the MTP, MPs exchange frames. To allow for efficient use of the scarce capacity of the wireless medium, MPs follow the Distributed Reservation Protocol (DRP) [14]. The MTP is divided into equal mesh transmission opportunities (MTXOPs); see Fig. 2b. Before any transmission, MPs announce their intention to use an MTXOP in the beacon frame. The intended receiver replies to the MP announcement by a response message in its own beacon frame, indicating either to accept or to decline the reservation. Additionally, it may propose a different MTXOP for frame exchange.

Current wireless protocols acknowledge each frame or fragment thereof immediately. As the duration of a data transmission depends on the arbitrary frame length and the MCS in use, it is impossible to predict when an acknowledgment would be sent. Consequently, it becomes impossible to conduct concurrent frame transmissions in the neighborhood of the frame of the sender. Hence, spatial frequency reuse is limited. With the MNA proposal, acknowledgments are delayed. They are sent in a separate MTXOP or optionally piggybacked with data transmissions on the reverse path. Thus, during each MTXOP the transmitter and receiver roles are fixed. The result is a predictable usage of the wireless medium.

Together with the signal-strength graph, the table of its own and neighboring MTXOP reservations forms the world model; see Fig. 4b. Because only the frame transmitting device emits energy to the wireless medium, devices may use the world model to predict possibilities for spatial frequency reuse. With the help of its local world model, an MP calculates whether its own emissions to the wireless medium (frame transmission) would be harmful at the receiver side of an already announced MTXOP reservation. Furthermore, an MP may decline a proposed MTXOP for reception if it calculated that the receiver of a current MTXOP would be interfered by the additional radio transmission. Figure 4a provides an exam-



■ Figure 5. *MDA divides the mesh wide superframe into slots.*

ple: due to shadowing of a wall, device C is inside the reception range of D and B but outside the reception range of A and E. Thus, it can decode beacon frames from B and D. As B informs C about its neighborhood, C can measure the received signal strength of the beacon frames of A and E without being able to decode them. C propagates its measurements results within its beacon frames. The world model helps B and C to identify an opportunity for concurrent transmissions to A and D, respectively. Finally, they use the same MTXOPs during [t_0, t_1]; see Fig. 2b. Thus, MPs have the ability to identify MTXOPs that can be reused.

Efficiency can be further enhanced with frame aggregation. Due to the predictable SINR, transmissions are less interference-prone. Thus, they can be reliably concatenated. Whereas the header indicates the amount of concatenated frames, a frame check sequence separates each element. In case of a transmission error, a frame can be retransmitted independent of others.

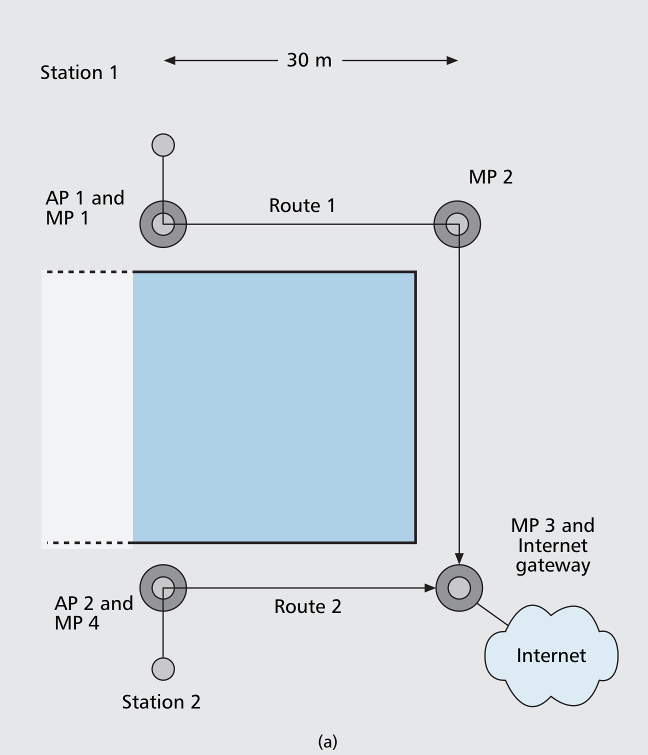
Mesh Deterministic Access — An Optional MAC in the IEEE 802.11s Draft Standard

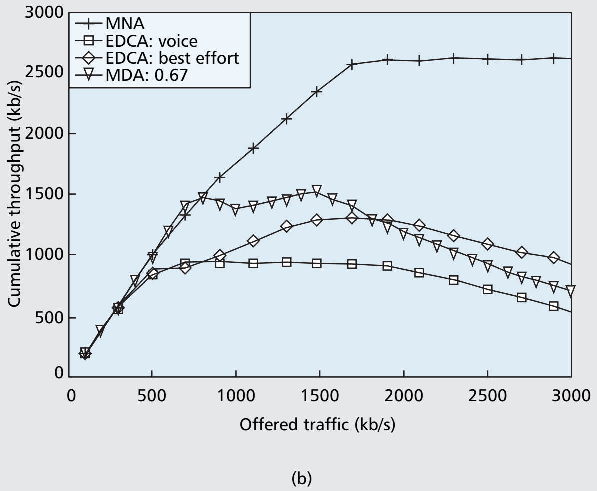
In November 2005, MNA merged with the industry alliance Wi-Mesh. In the following, Wi-Mesh Alliance and the competing SEE-Mesh consortium jointly formed the baseline document that became the current 802.11s draft standard [5]. As an optional MAC scheme, 802.11s provides the mesh deterministic access (MDA). MDA offers a compromise between the MNA proposal and the 802.11s members' desire for a more loosely coupled WLAN mesh operation.

MDA divides the mesh wide super frame into slots of 32 µs duration; see Fig. 5. The periodicity of an MDA reservation defines an amount of subintervals within the super frame. Within each subinterval, an offset value and the duration make the reservation well defined. Such a reservation is referred to as an MDA opportunity (MDAOP). During an MDAOP, its owner has highest priority for medium access. As an example, the MDAOP may access the wireless medium after a zero back off. Furthermore, other MDA-capable devices in the neighborhood defer from medium access during the MDAOP.

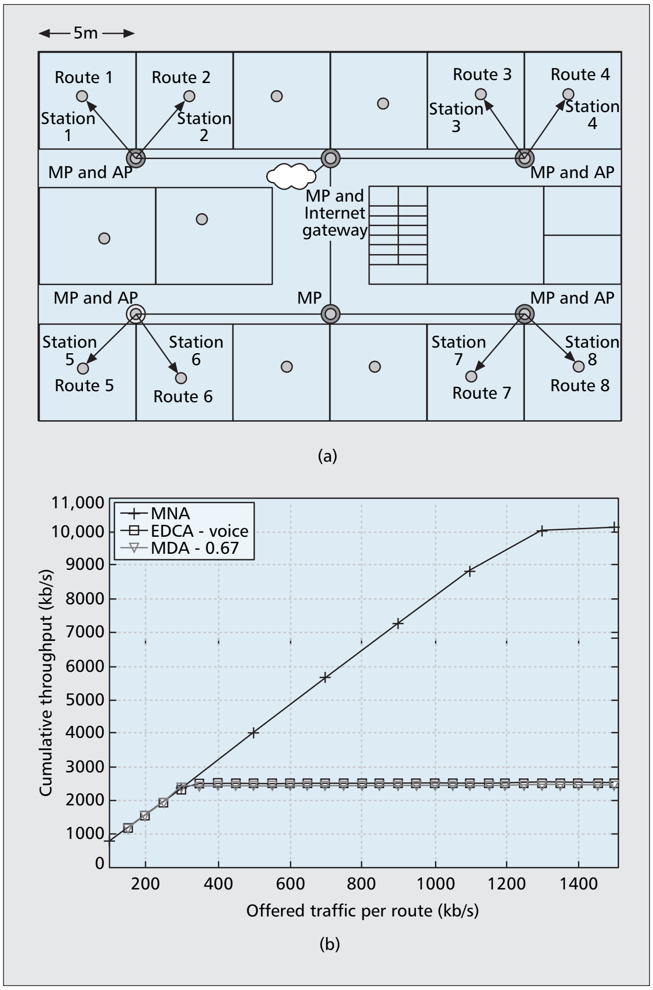
To set up an MDA reservation, the initiating MP uses an MDAOP set-up request message. Depending on its local knowledge about neighboring MDAOPs, the receiver accepts the set up. After the initial handshake, both MPs include the MDAOP in their beacon frame and on request, send the reservation details with unicast frames to neighbors. To further limit interference, surrounding MPs advertise an interfering-times report to their neighbors. Thus, devices in the extended neighborhood learn about slots that are currently in use.

The MDA fraction (MDAF) parameter defines the fraction of the super frame that can be used for MDA. The parameter





■ Figure 6. *a) On both sides of a building, mesh access points provide network access to stations; b) offered traffic vs. system throughput.*



■ Figure 7. *a) In an office environment, a central gateway delivers downlink traffic to the network; b) the MNA approach achieves four times as much throughput.*

is broadcasted in the beacon frame. An MDA-capable device must not accept any further MDA reservation if the total duration of all announced MDA reservations has exhausted the MDAF of the super frame.

MDA replaces the EDCA contention-based medium access by a reservation mechanism. As MDA-unaware devices in the same frequency channel can delay or disable MDA reservations, no performance or QoS guarantee is possible. The frame exchange during an MDAOP is equivalent to a frame exchange during a standard transmission opportunity (TXOP); any kind of acknowledgment scheme may be used.

Simulation

For performance evaluation, we implement 802.11s including the optional MDA and the original MNA concept into the WARP2 platform [10]. The event-driven, stochastic simulation tool implements the 802.11a physical layer [15] that operates in the unlicensed 5-GHz frequency band. The channel model calculates packet error ratios depending on the SINR, MCS, and frame length. According to the regulatory restrictions, each device transmits at 20 dBm output power. Reflecting an indoor environment, at a distance r, the signal power is assumed to decrease to $1/r^{3.5}$. MNA MTXOPs have duration of 256 μs. To provide a worst-case assumption, each MAC service data unit has 80 B size. EDCA access parameters are set to the 802.11 default parameters [1].

MNA operates only during the CFP (50 percent of the super frame). During the CP, stations and APs communicate by use of EDCA. All our simulation results indicate that MNA far outperforms the EDCA-based channel access of 802.11s. Although MNA introduces additional overhead due to the beacon period, its efficient use of the wireless medium more than compensates for this overhead. The increase in efficiency depends on the details of the scenario. The more that shadowing is provided by obstacles, the more likely MNA can detect and exploit possibilities for spatial frequency reuse.

Figure 6a provides a scenario where two stations are separated by a building. It provides sufficient shadowing (100 dB) that separates both sides. Each device transmits at 12 Mb/s radio data rate. Whereas route 1 consists of three hops, route 2 consists of two hops. The stations that send uplink traffic to the gateway have no means of congestion avoidance. Consequently, EDCA system throughput decreases as soon as the network saturates (1.3 Mb/s). The highest EDCA priority performs worse than the best effort category due to its small contention window sizes. With an MDA fraction of 67 percent, MDA carries up to 1.5 Mb/s aggregated end-to-end throughput. As offered traffic increases, MDA suffers from the legacy stations that do not respect MDA reservations. Thus, the achievable throughput drops. With MNA, the wireless medium can be spatially reused, resulting in a system throughput even above the MDA results (2.5 Mb/s); see Fig. 6b.

Figure 7a depicts an office scenario. Walls provide 13 dB of shadowing. A central gateway delivers frames to eight different stations via two and three hops, respectively. Considering the route arrangement, no hidden nodes are present in this scenario. As every device in the downlink routes receives frames only from its predecessor, no node congestion emerges. Applying a 64 QAM3/4 (54 Mb/s) MCS, EDCA, and MDA show exactly the same results (2.5 Mb/s). With MNA, distinct transmission areas can be formed, enabling concurrent transmissions. A total system throughput of almost 10 Mb/s is attained; see Fig. 7b.

Summary and Conclusion

Our studies show that current WLAN mesh performance is limited by the 802.11 MAC. The MDA is a first step toward a mesh-topology aware, distributed medium access coordination. Over multiple hops, its efficiency in medium access is comparable to current single-hop EDCA transmissions. As EDCA has not been designed for mesh topologies, MDA may well replace it in mesh applications.

Future mesh related protocols must incorporate highly efficient spatial frequency reuse to provide reasonable performance over multiple hops with limited frequency bandwidth available. Attenuation and shadowing provide separation and thus increase the network capacity. However, for current MAC design, such topologies are unfavorable. In the future, concepts known from pipelining in modern CPU designs will be applied in WMNs. These concepts enable the independent service of concurrent traffic flows to increase the efficiency of overall spectrum utilization. Our proposed concept — MNA — reveals the possibilities.

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Biographies

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