Interference Awareness in IEEE 802.11 Mesh Networks

Sebastian Max[1], Guido R. Hiertz[1], Thomas Junge[1] and Hans-Jürgen Reumerman[2]

[1]Chair of Communication Networks, Faculty 6, RWTH Aachen University, 52074 Aachen, Germany
(e-mail:{smx,grh,thj}@comnets.rwth-aachen.de)
[2]Philips Research Aachen, 52066 Aachen, Germany
(e-mail:hans-j.reumerman@philips.com)

***Abstract*: With current amendments, transmission rates of 54 Mb/s and more with IEEE 802.11 WLANs become possible. On the one hand, this allows the end user to change from wired to wireless infrastructure in even more application scenarios, on the other hand the sensible transmission modes reduce the maximum distance between the mobile Station (STA) and the Access Point (AP) to few meters in indoor environments. To extend the transmission range transparently, relay APs can form a mesh network to provide wireless connection over large areas.**

The Mesh Network Alliance (MNA) has presented an amendment to the IEEE Task Group "s" with the aim of enhancing the legacy 802.11 medium access protocol to enable efficient mesh operation. In this work we give a short overview of MNA and introduce a possible extension to enhance its frequency reuse in scenarios of mutual interference. The possible throughput of a mesh build upon legacy 802.11, MNA and the enhanced MNA are compared by simulation using the WARP2 simulation engine.

1. Introduction

The Wireless Local Area Network (WLAN) Standard 802.11 of the Institute of Electronics and Electrical Engineering (IEEE) is successful on the market. One of its main applications is the connection of mobile devices to the Internet, provided by the Basic Service Set (BSS) build by a stationary AP. As the distance between an associated STA and its AP is restricted by the propagation loss on the Wireless Medium (WM), complete coverage of a large environment with wirless access requires an Extended Service Set (ESS), consisting of several APs interconnected by the Distribution Service (DS).

A Wireless Distribution System (WDS) between multiple APs is vital if a wired infrastructure is not available and portals cannot be reached wirelessly by the mobile devices due to the distance and/or shielding walls. In this case, it is the duty of the APs to forward packets from their associated STAs via other APs to the portal and back ("multihop"). APs equipped with this technology form a mesh network and are consequently called Mesh Points (MPs).

The enlargement of the covered area and the traffic increase, caused by the multiple transmissions of the same packet by the relaying MPs, introduces new challenges which the legacy 802.11 Medium Access Control (MAC) does not meet successfully [1]. Therefore, the aim of the new-founded IEEE 802.11 Task Group (TG) "s" is to elaborate an amendment to the current standard that enables an efficient mesh-based WDS [2].

An important factor considering possible 802.11s protocols is the constrain that the IEEE 802.11-Physical Layer (PHY) layer must not be changed. Therefore an upgrade of a legacy AP to an MP does not need any radio modifications, and the 802.11s protocol is compatible to all future PHY-standards developed by the 802.11 group. Another important limitation on all proposals is the requirement to support one or more radios, i. e. any mesh point owns only one radio.

In this work we concentrate on the IEEE 802.11s proposal by the Mesh Network Alliance (MNA). A special feature of this proposal is that a single frequency mesh network is suggested, requiring a highly efficient solution for the sharing of the mesh traffic and the legacy 802.11 traffic inside the BSS. After reviewing the proposed mechanisms in section 2. we enhance the protocol with a complementary mechanism that improves the interference awareness, allowing planned concurrent transmission. The protocol with the improvements is evaluated by stochastical event-driven simulation in section 4. by comparison with a mesh network which is solely based upon the legacy 802.11. Throughout this paper all units and abbreviations are defined according to [3].

2. The Base Protocol

In this section, we give a short overview of the basic mechanism and structure of the MNA proposal for IEEE 802.11s. A deeper insight to the protocol can be found in [4]. As mentioned above, the MNA proposal is offers a single-frequency solution, i.e. all MPs and associated legacy STAs transmit and receive on the same frequency. As the contention-based medium access protocol for 802.11 allows a very aggressive occupancy of the wireless channel, a solution for the coexistence of the BSS traffic and the mesh traffic is needed. In this proposal, the legacy 802.11 Contention Free Period (CFP) is used to silence all associated STAs: After the announcement of a CFP, all legacy STAs defer from accessing the medium during the advertised time. Therefore, this period can be used as an exclusive resource for the mesh traffic, which can be structured differently for a more efficient multihop performance.

Time during the complete CFP is divided into equal length Mesh Transmission Opportunitys (MTXOPs), any transmission must begin with the start of a MTXOP. The first few MTXOPs belong to the Beacon Period (BP) which is used for the announcement of the CFP and management issues. The remaining CFP, the Mesh Transfer Period (MTP), is used for data exchange between the MPs. Figure 1 gives an overview of this timing structure, the different periods together with their access protocols

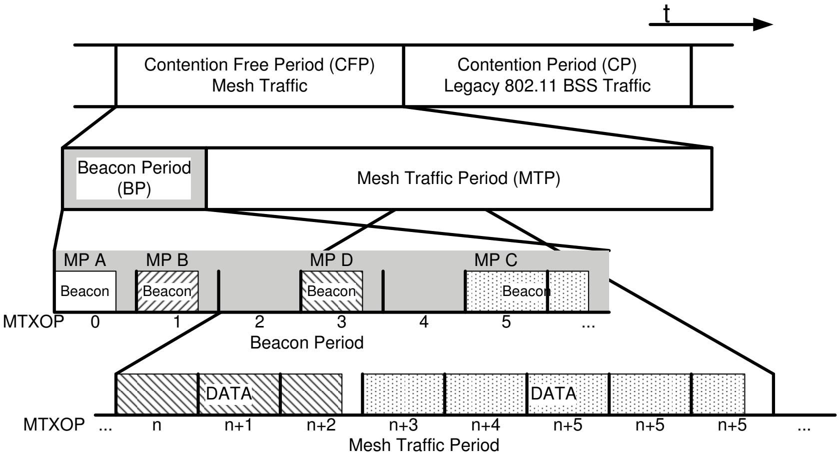


Figure 1: Typical timing structure of the MNA protocol: The CFP and the CP alternate in time, the first one is furthermore subdivided in the Beacon Period (BP) for management and in the Mesh Transfer Period (MTP) for the mesh traffic.

are explained in the next sections.

2.1. Beacon Period Access Protocol

During the first part of the CFP, beacons are transmitted from all MPs. Besides announcing the beginning of a CFP to their associated STAs, the beacon is also used to coordinate the mesh network. In detail, it provides information about the synchronization between MPs, the mesh neighborhood and the occupation of the MTP.

To fulfill these aims, all MPs listen during the BP and the beacons have to be broadcasted collision-free among them. This is provided by the usage of the Beacon Period Access Protocol (BPAP), which disseminates the occupancy of the MTXOPs used for beacon transmission in the network. Therefore, possible collisions can be recognized and resolved by the MPs. A detailed description of the BPAP can be found in [4].

2.2. Distributed Reservation Protocol

The remaining time of the CFP after the (variable-length) BP is used for data transmission between the MPs. In contrast to the contention-based IEEE 802.11 medium access protocol, a reservation protocol is used to negotiate and occupy the MTXOPs. Preferred ones are indicated by the intended transmitter with the inclusion of a Information Element (IE) in its beacon. MTXOPs are regarded as occupied if the intended receiver acknowledges the reservation with the transmission of a IE in its beacon. Neighboring MPs repeat the information within their beacons to support a collision-free access during the occupied MTXOPs.

As the transmitter can rely on the collision freeness, it can start its transmission at the beginning of the reserved MTXOPs, no additional backoff or channel sensing is needed. To allow a predictable channel usage, no other transmissions from other MPs besides the owner are allowed. This holds especially for the transmission of acknowledgments; they have to be send in differed, previously reserved MTXOPs or piggybacked to data transmissions. A possible time flow during a CFP can be seen in Figure 2. Again, a detailed description of the Distributed Reservation Protocol (DRP) can be found in [4].

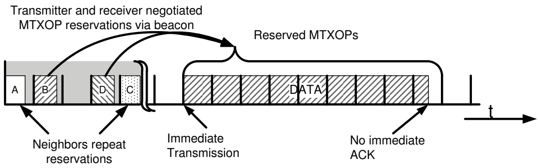


Figure 2: Possible time flow during a CFP: In the BP, some MTXOPs are reserved via the DRP; in those time slots the mesh traffic is exchanged later.

3. Interference Awareness

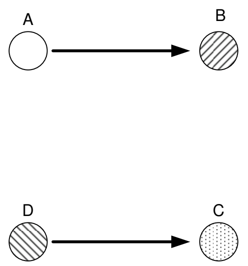
Using the proposed extensions above, the MNA proposal provides an adequate method of providing the WDS. But one of the main disadvantages of the legacy 802.11 still remains: There is no interference awareness included, enabling the MPs to recognize and utilize possibilities for planned concurrent transmission.

Consider the two scenarios if Figure 3: In case (a), the mutual interference between the transmissions of the MPs A and D demand alternating transmissions to the MPs B and C. In contrast to this, a building between the links attenuates the interference in case (b). Therefore, concurrent transmissions would be possible if the MPs are able to differentiate between the case (a).

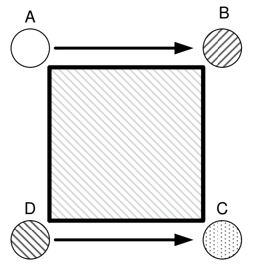
In the following section, we propose a solution that enables exactly this ability. It builds upon the mechanisms of the MNA proposal without changing the protocol structure itself, therefore the extension is optional. An evaluation of the improved MNA mesh technology is given in section 4..

3.1. World Model

In order to take advantage of the enlarged system capacity that results from concurrent transmissions, MPs must first learn a model of the current environment, i. e. the mutual interference situation. This model, called the world model, should be as simple as possible to be feasible and thus abstract from reality as much as possible. Also, it shall be as detailed as needed to produce



(a) The mutual interference demands alternating transmissions from the MPs A and D.



(b) Due to the attenuation of the building, concurrent transmissions would be possible.

Figure 3: An interference aware MP is able to differentiate between the two scenarios and takes advantage of the attenuation of the building.

good estimations for the success probability of a concurrent transmission. A world-model improved MP has the structure as given in Figure 4: Sensors are used to enrich the world model continously with information from the environment, derived from the given mesh protocol. After sufficient information is integrated in the world model, conclusions can be drawn out of it regarding the MTXOPs of further transmissions.

We propose a world model with is derived from the assumption that in wireless networks the success probability of a transmission is mainly determined by the Carrier over Interference (CoI) at the receiver, defined for an MP X as

$$CoI_X = \frac{C_X[\text{mW}]}{N_X[\text{mW}] + \sum_i I_{i,X}[\text{mW}]}$$

With C_X representing the power of the wanted transmission, $I_{i,X}$ the power of the interference by MP i and N_X the background noise; all values are measured at the receiver.

It is important to notice that two different CoI have to be taken into account before a new concurrent transmission can be started:

1. The Receiver Carrier over Interference (CoI$_{Rx}$), measuring the CoI at the receiver of the new Concurrent Transmission.

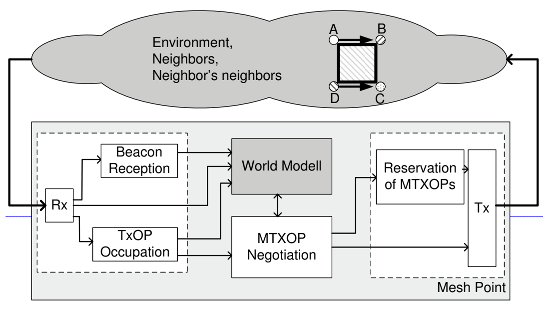


Figure 4: The structure of a learning MP: The world model incorporates the sensor's output and is used for a better judgment of the usability of a MTXOP.

2. The Interferer Carrier over Interference (CoI$_{Int}$) which represents the minimum CoI at the original receiver(s) of the MTXOP.

A sufficient information to compute these CoI values is the implementation of the world model as a signal strength graph. In this complete graph, the vertices represent the MPs in the (known) network. The edge between two vertices is weighted with the estimated signal strength that is measured at one of the represented MP if the other MP is transmitting. An example signal-strength graph for the scenario in Figure 3b is given in Figure 5.

It has to be noticed that the abstraction which is done in the world model incorporates easily all kinds of PHY technologies like directed antennas: If the CoI$_{Rx}$ or the CoI$_{Int}$ is improved, the performance is directly incorporated into the model.

3.2. Learning the Signal Strength

For every new MP that is recognized, the weights to the other MPs have to be estimated, which is done in two ways.

The direct link weights can be learned by using the BPAP together with measurements from the PHY layer: An MP knows the MTXOP occupation during the BP via the dissemination by the BPAP, even if it cannot receive all beacons correctly due to the large distances or attenuating obstacles. Therefore, the measured received power during one beacon transmission can be related to the transmitter and the weight can be estimated by this sample.

The weight for the other, non-direct links is learned as all MP spread their acquired link weights in small IEs which are included in the beacon periodically.

3.3. Concurrent Transmissions

With the learned signal strength graph, all MPs are able to recognize possibilities for concurrent transmissions. During the negotiation of new reservations, the transmitter and the receiver compute the CoI$_{Rx}$ and the CoI$_{Int}$ from the values found in the graph. If both values exceed a preset threshold, the negotiation ends successfully and the MTXOPs can be occupied.

In the example scenario from Figure 3b and the signal strength graph from Figure 5, MP A would compute the values

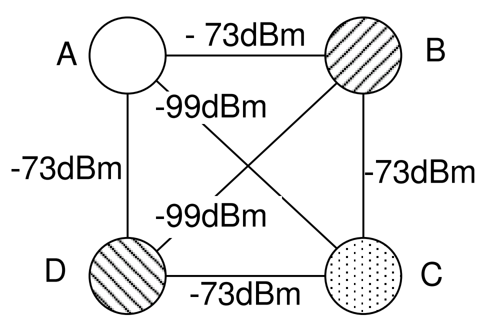


Figure 5: A possible learned Signal Strength Graph for the scenario in Figure 3b.

$$
\begin{aligned}
CoI_{Rx} &= -73\text{dBm} - 10\log_{10}(N\text{mW} + 10^{-9.9}\text{mW}) \\
&= CoI_{Int}(\text{as the scenario is symmetrical}) \\
&\approx 25\text{dB}
\end{aligned}
$$

The assumed background noise N is set here to -95dBm, an increased setting could be used to lessen the probability of concurrent transmissions.

4. Evaluation

We use event-driven stochastic simulations to analyze the performance of the proposed MNA protocol and the enhancements for interference awareness. The simulations were performed using the Wireless Access Radio Protocol 2 (WARP2) simulation environment developed at the Chair of Communication Networks, RWTH Aachen University. It is programmed in the Specification and Description Language (SDL) using Telelogic's TAU SDL suite. The error model used in WARP2 to accurately simulate the WM is presented in [5].

In the two exemplary scenarios presented in this paper, we compare a mesh networks based solely upon IEEE 802.11 with the performance if MNA is used for the mesh traffic and legacy 802.11 for the last hop in the BSS.

4.1. Multihop Route

The first investigated scenario is presented in Figure 6: Four MPs and one STA are connected to a four hop route. Data is transmitted from the STA to the last MP, which acts as a gateway to the Internet, and back from the last MP to the STA. Each link transmits with 12 Mb/s in accordance to the PHY mode defined in IEEE 802.11a [6]. The traffic sources insert packets of 80 B size with a constant bit rate into the mesh network.

Figure 7 shows the system throughput for different offered traffic settings per route. Legacy 802.11 is able to carry the offered traffic up to 300 kb/s, above this point the saturation is reached. In contrast to this, MNA is able to deliver a throughput of up to 500 kb/s per route, solely by the division of the mesh traffic and the BSS traffic and the efficient, multi-hop oriented transmission of the first one.

Furthermore, the behavior of the two different protocols after the saturation point is reached differs significantly: Whereas MNA is able to stay at the maximum level of possible throughput, legacy 802.11 nearly fails to transmit at an offered traffic which is twice the saturated traffic. This is a consequence of the random-based medium access protocol which is not intended for multihop usage: the border STAs of the route keep transmitting their packets although the capacity of the whole route is reached. Therefore, the STAs in the route (which receives interference from both sides, opposing to the two border STAs) defer from accessing the medium and discard new packets as their transmission queue is full.

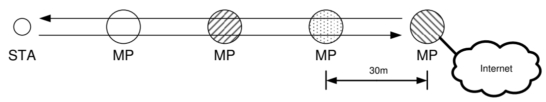


Figure 6: First simulation scenario: Four MPs provide the wirless access for the STA to the Internet via a four-hop route.

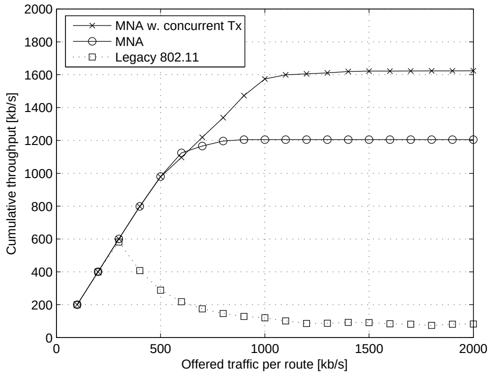


Figure 7: Cumulative throughput for the scenario in Fig. 6, the mesh network is either based on MNA, MNA with concurrent transmissions or legacy 802.11.

The evaluation of the proposed MNA extension, allowing planned concurrent transmissions, outperfOne can do this by modifying the last Latex file forms the basic MNA: Due to the enhanced mechanisms, the outer MPs can recognize the opportunity to transmit concurrently to the inner MPs, the same holds for transmissions from the inner to the outer MPs. Consequently, a system throughput of nearly 1600 kb/s can be reached, which is an improvement by 400 kb/s.

4.2. Outdoor Scenario

The second scenario, displayed in Figure 8, investigates further the possibilities of the proposed extension to the MNA proposal, the planned concurrent transmissions. The mesh network is build around four small buildings, wireless connectivity is provided for the eleven associated legacy 802.11 STAs over routes with one, two and three hops. Only downlink traffic is induced, beginning from the middle MP, with packetsize 80 B. All links in the mesh network operate with QPSK modulation and a coding rate of 3/4, resulting in a PHY rate of 18 Mb/s [6]. The walls in the scenario have an attenuation of 11 dB which represents concrete building walls [7].

The cumulative throughput relative to the offered traffic is given in the Figure 9. All three graphs are furthermore divided to show the fraction of the throughput which is generated by which route. Although the legacy 802.11 does not degrade after the saturation point in this scenario, the reachable system throughput is limited to 200 kb/s per route, whereas with the standard MNA about 300 kb/s can be obtained. Figure 9a shows the possible gain in throughput with concurrent transmissions: Here, up to 500 kb/s are reached until the multihop routes are saturated.

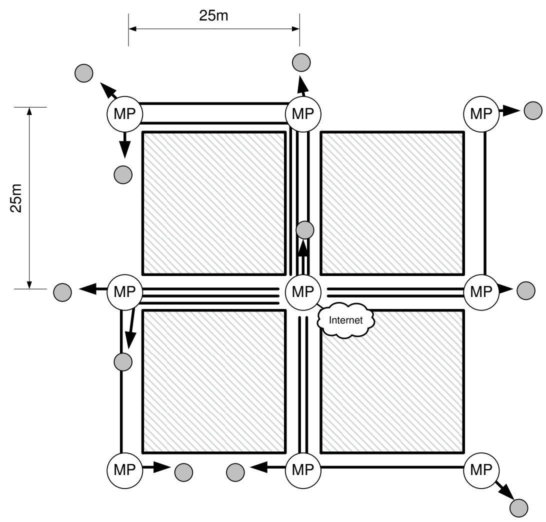
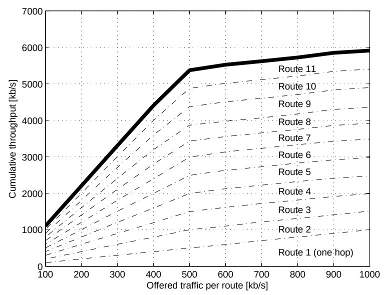
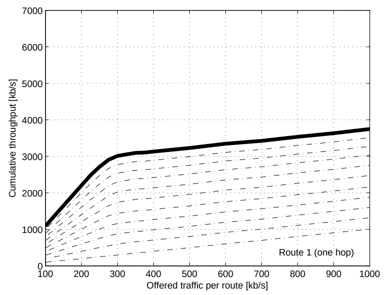


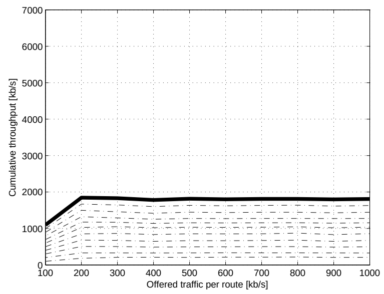
Figure 8: Second simulation scenario: To evaluate concurrent transmissions we assume the mesh network is build around four small buildings. Nine MPs provide the WDS to the associated STA using one-, two- and three-hop routes.



(a) Mesh based on MNA with concurrent transmissions.



(b) Mesh based on standard MNA.



(c) Mesh based on legacy 802.11.

Figure 9: Cumulative throughput for the scenario in Figure 8. Additionally, for each route the corresponding area is marked.

5. Conclusion

In this paper a proposal for the TG “s” of the IEEE 802.11 is presented and enhanced by a mechanism for interference awareness.

Simulation results show that the usage of MNA provides an optimal basis for the interference aware MP. A BP is used to organize the channel access among the MPs. Its design enables an MP to measure the signal strength of its surrounding nodes. Hence, MPs are able to set up an interference graph of their neighborhood. Combined with the deterministic DRP medium access the spatial frequency reuse is increased to the optimum.

While a mesh network build on 802.11 medium access suffers severely from the exposed node problem, our approach increases the achievable throughput significantly. By means of stochastic simulations we show show that our proposed solution enables single transceiver mesh technology, which seamlessly integrates legacy 802.11 devices. This offers a cost effective and extensible solution to enable access to high performance wireless service even at a large number of intermediate relays.

Acknowledgments

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Abbreviations

AP	Access Point
BPAP	Beacon Period Access Protocol
BP	Beacon Period
BSS	Basic Service Set
CFP	Contention Free Period
CoI	Carrier over Interference
CoI$_{Rx}$	Receiver Carrier over Interference
CoI$_{Int}$	Interferer Carrier over Interference
CP	Contention Period
DRP	Distributed Reservation Protocol
DS	Distribution Service
ESS	Extended Service Set
IE	Information Element
IEEE	Institute of Electronics and Electrical Engineering
MAC	Medium Access Control
MNA	Mesh Network Alliance
MP	Mesh Point
MTP	Mesh Transfer Period
MTXOP	Mesh Transmission Opportunity

PHY	Physical Layer
SDL	Specification and Description Language
STA	Station
TG	Task Group
WARP2	Wireless Access Radio Protocol 2
WDS	Wireless Distribution System
WLAN	Wireless Local Area Network
WM	Wireless Medium

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