Analysis of WiMedia-based UWB Mesh Networks

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Abstract

Regarding maximum transmission rates, Ultra Wideband (UWB) seems to be the wireless technology which could successfully replace most of the data-cables in office and home environments: With up to 480 Mb/s gross data rate, wireless high-definition video streaming and data synchronization become feasible.

Of course, these advantages come at a price: UWB is designed for short-range communication, limited to 10 m. While this suffices for some application, it does not fulfill the vision of ubiquitous wireless access in the fully-connected home.

A straightforward solution to increase the network coverage is given by Wireless Mesh Networks (WMNs). In this paper, we analyze if the combination of UWB and WMN is able to provide the required coverage and the expected data rates. Several different deployment concepts (including ad-hoc networking and dedicated mesh relays) are evaluated with a realistic system model, which is able to compute the resulting network capacity. The results show that under the assumptions of the model, i. e. a MAC which is able to exploit spatial divided frequency reuse, UWB mesh networks are able to provide a stable capacity of more than 100 Mb/s in a typical scenario of up to 250 m^2. Hence, the combination of the two technologies is able to succeed in much more application scenarios in comparison to the current UWB standard.

1. Introduction

In the form of Bluetooth, as standardized by the IEEE 802.15 working group [2], Wireless Personal Area Networks (WPANs) have become an ubiquitous technology. Complimentary to this low-power and low-rate wireless networks, the next generation of WPANs is expected to provide much higher data rates to target at the market of broadband multimedia applications, e. g. High Definition TV (HDTV).

In February 2002, the Federal Communication Comission (FCC) of the United States allocated 7.5 GHz spectrum, ranging from 3.1 to 10.6 GHz, for unlicensed UWB communication applications. The first and only standard which utilizes this huge bandwidth was developed by the WiMedia Alliance [1] and standardized successfully in [3].

As UWB uses the frequency bands of several existing wireless technologies, it has to restrict its transmissions power to -41.3 dBm/MHz. Hence, its range is limited to few meters, and the high-rate Modulation- and Coding Scheme (MCS) are available only in close vicinity of the transmitter.

To increase the coverage range of a transmitter without increasing its transmission power, relays can be used: If the receiver cannot be reached via direct communication, intermediate nodes forward the packets over multiple hops. Hence, it becomes possible to cover the home environment with ubiquitous UWB access.

The enlargement of the covered area and the traffic increase, caused by the multiple transmissions of the same packet by the intermediate relays, introduces new challenges. This paper deals with the question how the current UWB technology is able to face the requirements of a relay operation and how well it performs in a typical indoor scenario. It is structured in the following way: After an introduction to the UWB standard, we define a system model which incorporates the scenario description and an abstraction of the Physical Layer (PHY), Medium Access Control (MAC) and routing layer.

Furthermore, different deployment concepts are introduced: Here, we differentiate between a) a pure ad-hoc approach, where all devices are not only traffic consumers, but can also relay their peer's data, and b) a mesh network approach, where special-equipped mesh points span a backbone which is committed only to the data-forwarding.

Finally, the performance of the deployment concepts is evaluated and compared in different sized scenarios and networks. Here, the system capacity is used as a metric; it is derived using an optimization framework developed in [12] and extended in [8].

1.1. Related Work

In this paper, two important subjects are combined: First, the evaluation of capacity limits for wireless networks, and second the emerging technology of UWB-based networks.

The evaluation of capacity limits is a popular research topic. One of the most cited papers in this area is the seminal paper by Gupta and Kumar [6], where they discuss the asymptotic capacity of random ad-hoc networks. Since the publication, their results have been extended by different researchers who calculated the capacity bounds in other network types, e. g. [7] and [11].

Due to the chosen approach, they have in common that they derive fundamental scaling laws that describe the theoretical capacity under the model assumptions. Hence, one must be careful to apply them to an arbitrary and small network instance with a restricted topology and PHY.

To our best knowledge, the only work for the computation of the throughput capacity in arbitrary network instances which takes into account additive interference and different MCS is presented in [12]. This method is extended by heuristics which allow for the handling of larger networks in [8].

2. WiMedia's UWB Standard

This section introduces the current Multiband OFDM Alliance (MBOA) PHY and MAC. Furthermore, we indicate possible extensions to increase the performance of the MAC in mesh scenarios.

2.1. Multi-band OFDM PHY

The MBOA PHY for WPANs utilizes the unlicensed 3.1-10.6 GHz frequency band, which is divided into 14 bands á 528 MHz. Information is transmitted wit a Multiband OFDM (MB-OFDM) scheme which applies several error protection schemes to ensure a successful reception. We summarize the different settings for the error protection as MCSs.

Each MCS consists of a parameter set which influences the Forward Error Correction (FEC) coding rate, the modulation type (Quarternary Phase Shift Keying (QPSK) or Dual Carrier Modulation (DCM)) and the spreading via Time Domain Spreading (TDS) and Frequency Domain Spreading (FDS). As a result, the PHY layer allow to transmit data at the rates 53.5, 80, 106.7, 160, 200, 320, 400 and 480 Mb/s. Of course, the robustness of the MCS against interference is inversely proportional to the used data rate.

2.2. The Multiband-OFDM Alliance (MBOA) MAC

In contrast to other WPAN MAC protocols, e. g. IEEE 802.15.3, MBOA uses a synchronized distributed MAC. Channel time is organized into fixed-length superframes; each superframes consist of 256 Medium Access Slot (MAS) with 256 μs each.

Each superframe commences with a Beacon Period (BP), in which each device sends its beacon. Beacons are used to synchronize the superframe start time of each device, to learn its neighbors and to coordinate the channel access during the remaining superframe, the Data Transmission Period (DTP). To avoid collisions between beacons, each device includes a map describing its view of the current occupancy. If a device receives several times a map where its beacon is missing it knows that it is part of a beacon collision and selects randomly a different slot.

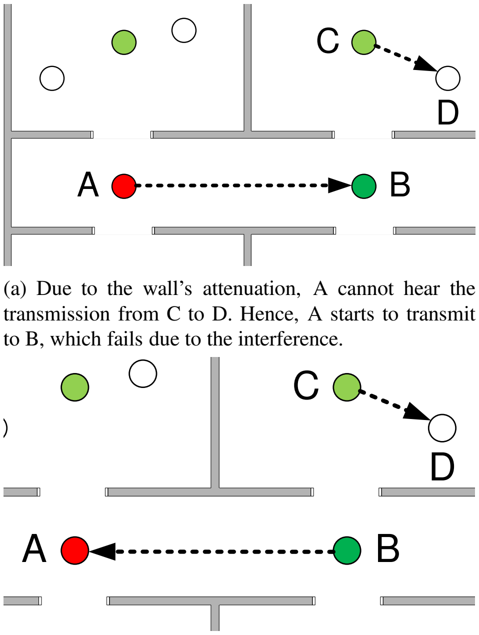
MBOA defines two different medium access schemes during the DTP: The Distributed Reservation Protocol (DRP), which is a reservation-based distributed Time Division Multiple Access (TDMA) and the contention-based Priotized Contention Access (PCA).

Distributed Reservation Protocol (DRP) With the DRP, devices can negotiate the ownership of future MASs. The negotiation information (i. e. the positions of the MASs) is either included into the beacon or send via special command frames. A DRPs session is established after the receiver confirms the indicated MASs, from this moment on both the transmitter and the receiver include this information in their beacon frames.

As every device in the same BP receives this MAS occupation status, it learns of the reservations and refrains from channel access during this time. Hence, the DRP provides a collision free channel access.

Priorized Channel Access (PCA) In contrast to the DRP, PCA uses a randomized listen before talk scheme to prevent possible packet collisions and to share the wireless medium. With its exponential backoff, it is designed very similar to the Enhanced Distributed Channel Access (EDCA) defined by IEEE 802.11e. Similar to this ammendment, priorities are introduced by the definition of different initial waiting times and different backoff window sizes.

Acknowledgment policies MBOA defines three Acknowledgment (ACK) policies: No-ACK, immediate ACK and burst ACK. While the no-ACK generates no frame acknowledgment at all, the immediate ACK demands an acknowledgment after every successfully received data frame. The burst ACK implements a selective-reject



(a) Due to the wall's attenuation, A cannot hear the transmission from C to D. Hence, A starts to transmit to B, which fails due to the interference.

(b) Although C is transmitting to D, B could start a successful concurrent transmission to A. Nevertheless, B refrains from the medium access.

Figure 1: The hidden (1a) and the exposed node problem (1b) decrease the performance of the MAC protocol in typical mesh networks.

acknowledgment scheme with a window size which is negotiated previous to the frame exchange.

2.3. Mesh Networking with the MBOA MAC

The MBOA MAC is well designed for the operation in mesh network topologies. From the MAC point of view, the major challenges in mesh network is the increased occurrence of hidden- and/or exposed-nodes, as given exemplary in Figure 1.

In the MBOA MAC, the hidden node problem is well solved for one-hop networks (i. e. every device can sense every other device) by the reservation information in the beacon for the DRP and the backoff for the PCA. In mesh networks, these methods do not solve the problem: Even with the usage of the most robust transmissions mode, the required Signal to Interference plus Noise Ratio (SINR) level must be reasonable high. Therefore, it does not suffice to notify the neighboring devices of a link, but all devices which could interfere with the transmission.

This becomes possible by introducing second-level DRP announcements: Neighbors of an existing link repeat periodically the reservation information to their neighbors, such that it is known in the two-hop neighborhood. This prevents most hidden node scenarios.

Unfortunately, this enlargement of the blocking area around a link aggravates the exposed node problem, as opportunities for concurrent transmissions are wasted. Several possible mechanism are under discussion which are able to solve this dilemma; nevertheless, currently there is no functionality at all in the current WiMedia standard to handle the exposed node problem and to allow for concurrent transmissions. While this paper does not concentrate the proposed mechanisms, it is analyzed how such a functionality could in principle improve the performance of the standard in a typical indoor mesh scenario. To do so, the potential performance gain assuming a perfect MAC operation is calculated and compared to the current WiMedia MAC. Hence, it becomes possible to judge the applicability of WiMedia's UWB in the given scenario independently from the exact future ammendments.

3. System Model

The performance of WiMedia-based UWB mesh networks in the indoor environment is analyzed using a system model which is build by several sub-models. As a whole, it allows for the computation of the upper bound capacity in the different scenarios under consideration.

In detail, the system model consists of the scenario description, the channel and PHY model, the MAC and finally the routing model.

3.1. Scenario

The performance of a wireless mesh network always depends on the given environment, which includes Line Of Sight (LOS) and non Line Of Sight (non-LOS) conditions, shadowing, the positions of the nodes and their mobility, the assumption of the induced traffic and finally the capabilities of the investigated nodes.

To evaluate the performance in a representative indoor scenario, an abstraction of a typical office floor is used, as displayed in Figure 2. It can be seen from the figure that three different node types a positioned into the scenario:

1. End-*Devices*, which are positioned randomly in the offices. They can be either full-fledged mesh devices, i. e. they are able to forward other device's data, or they are simple one-hop devices which have to connect either directly to the portal or use the service of a mesh point. Any device in the scenario represents a consumer and/or server of a traffic stream.

2. The *portal*, which connects the mesh network to a wired backbone and thus is the sink/source of all outgoing/incoming traffic streams.

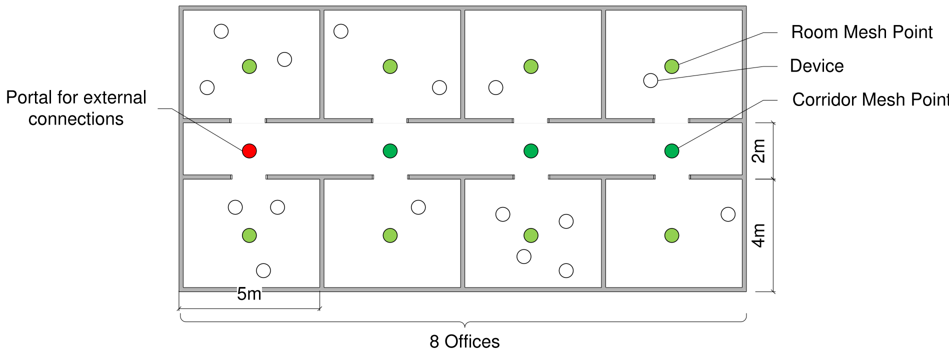


Figure 2: The scenario under consideration, here with eight rooms.

3. Dedicated relays, *mesh points*, fixed either (at the ceiling) in the corridor between two offices or at the center of an office; they are not sinks nor sources, but only intermediate hops. As the mesh points are fixed, it becomes possible to interconnect them with directed antennas; hence, we assume an additional receive antenna gain of 10 dB.

Depending on the capability of the devices and the existence of corridor/office mesh points, three different deployment concepts become possible: Pure ad-hoc networking without any mesh points, mesh points in the corridor and mesh points in the corridor and the offices.

Due to the geometry of the scenario, a variation of the number of offices and thus the average route length becomes possible: Starting from 2 offices directly opposite to each other, the scenario can be enlarged by adding an even number of offices. In the evaluation, scenarios with up to 10 offices are considered.

Throughout the evaluation, the sources and sinks of each route are chosen randomly among the devices and the portal, such that

- the portal is the source of 50% of all routes,
- no device connects multiple times to the portal and
- each route is bidirectional, divided into 90% downlink for the data and 10% uplink traffic for the control information.

3.2. Channel and Physical Layer Submodel

While the channel submodel determines the received signal quality of a transmission, the PHY submodel maps the received signal quality to the resulting Packet Error Rate (PER). The detailed development of this model can be found in [9]; here, only the major characteristics are enumerated.

The path loss between two nodes and the resulting Received Signal Strength (RSS) is calculated according to the equation 1 in [9], taking into account the transmission power, the distance, the wavelength, a path-loss exponent and a random log-Normal shadowing. Additionally, each traversed wall attenuates the signal by 7 dB [10].

The PER in the PHY sub-model depends on a number of factors:

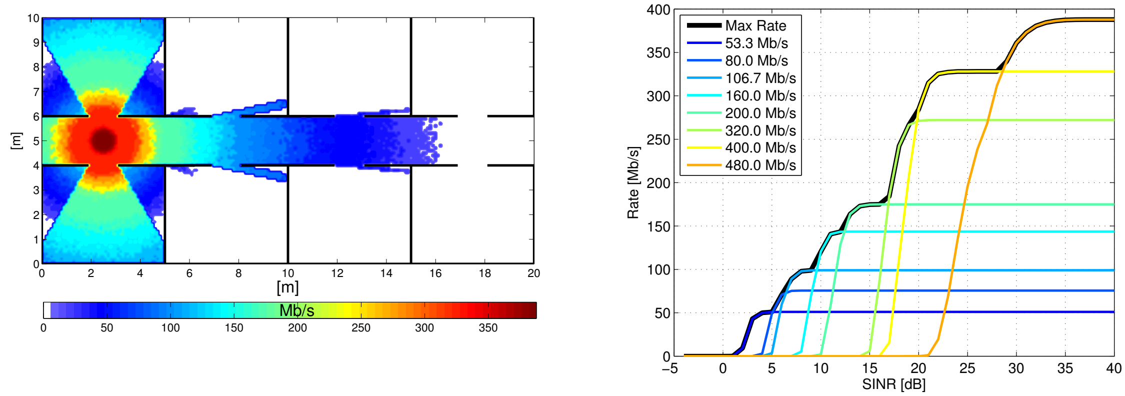
- the RSS has to exceed a threshold which depends on the used MCS; if many bits per symbol are used the receiver required a higher RSS to decode the signal,
- the SINR, which models interfering transmissions as Gaussian noise; again the higher MCSs are more susceptible to interference,
- the frame length and
- the channel condition, which is called in the IEEE 802.15.3a terminology Channel Model (CM) [5]. It defines four different settings, representing the channel in a typical LOS or non-LOS condition with different distances between 1 and 10 m.

Figure 3 shows two different resulting aspects of this model: In 3a, the applicable data rate of a transmission from a node positioned at $(2.5, 5)$ is indicated; assuming that the transmitter selects the optimal MCS depending on the RSS at the receiver; the shown values already include the overhead of the frame headers. Figure 3b complements the description by showing the relation of the SINR an the resulting data rate, depending on the selected MCS.

3.3. The Medium Access Control Model

While the PHY model abstracts the behavior of a single link in the network (under which conditions the link is usable, what is its PER and resulting rate), the Medium Access Control (MAC) model is responsible for the behavior of the multiple channel access. Due to the nature of the wireless channel, transmissions have to be scheduled without collisions.

To estimate the maximum achievable throughput capacity, the evaluation assumes an optimal coordinated DRP.



(a) Data rate versus distance and obstacles

(b) Data rate versus Signal-to-Noise-plus-Interference (here for Channel Model 1 [5])

Figure 3: In the physical layer model, the achievable data rate depends on the distance, attenuating obstacles and the interference by other concurrent transmissions.

This is modeled via an omniscient and omnipotent coordination entity, which

- has full knowledge about the PHY model for each link,
- controls the traffic load on each link, so that the end-to-end requirements are met,
- generates a DRP-schedule for the transmissions and
- disseminates this schedule to the nodes without costs.

All nodes operate under the guidance of this hypothetical controlling entity. This allows for an optimal schedule to be followed by the network, which maximizes the network capacity.

In the used optimization framework, the time is divided into periodic intervals of one superframe in which the same schedule applies. The schedule defines who transmits (concurrently) and how long. Each feasible transmission or combination of concurrent transmissions is called Network State (NS). Thus, a schedule is defined as a list $([NS_1, d_1], [NS_2, d_2], \ldots, [NS_S, d_S])$ of network states and respective transmission durations d_i. A schedule is optimal if no other shorter schedule exists that fulfills all traffic requirements, defined by the routes.

The first step in the optimization is the creation of all feasible NSs. Since this problem is known as NP-Complete [4] we apply the heuristics proposed in [8]. Then, the second step is to find the optimum combination of NSs, creating an optimal schedule. This is done by translating the NS and the conditions for feasibility and optimality into a Linear Programming (LP) instance, which can be solved with the help of a commercially available optimization toolbox. The resulting vector $d^* = (d_1^*, \ldots, d_S^*)$ assigns the optimal durations to all NSs and determines the duration of the optimal schedule. Based on the total amount of transported traffic during this duration, the system capacity can be derived.

3.4. The Routing Model

Wireless mesh networks usually define a routing sublayer between the link layer and the network layer. It is used to incorporate the complexity of the wireless channel (i. e. the path with the lowest number of hops is not always the best one) into the routing protocol and to hide this complexity from the higher layers. From the viewpoint of layer 3, the mesh network is represented as one broadcast domain where any node can be reached in one hop.

Similar to the MAC model, we abstract the capability of the routing protocol and describe its effects on the traffic streams. Path selection among Mesh Points (MPs) and the devices (if they are able to forward data) is driven by the end-to-end cost, measured in the total transmission duration. As it is already known from the PHY model whose links can operate using a given MCS, we can use the Floyd-Warshall algorithm to find the cheapest routes. This algorithm operates on a graph representation of the network topology, where all edges between the nodes are weighted with the maximum transmission rate.

4. Evaluation

Based on the described system model the three deployment concepts from Section 3.1 are analyzed. As the calculation described in Section 3.3 computes the system capacity for one given placement of devices in the scenario, we generate several samples of the to evaluate the mean upper bound capacity. For each sample, the following process is executed:

1. According to the selected number of offices and the deployment concept, the portal and the mesh points are

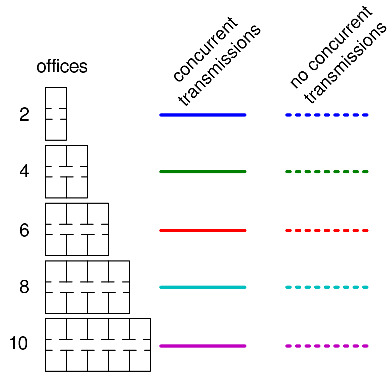


Figure 4: Legend for the Figures 5 to 7.

positioned into the scenario; then, n Devices are distributed randomly into the offices. Sources and sinks are determined according to the traffic model from Section 3.1.

2. Using the routing model, the required routes from each source to its sink are determined.

3. With the use of the optimization algorithm, the required duration to transport 1 Mb is computed. The computation either uses all possible network states or is restricted to those with only one transmission at a time. With the later one, a MAC protocol which is very restrictive is modeled. Finally, the sum of the transported traffic divided by the required time gives the system capacity of the current scenario.

The iterative generation of samples results in the mean value of the system capacity for a certain deployment concept. In the following, the mean values are shown together with their confidence interval using a 95% confidence level.

Throughout the evaluation, the resulting system capacity is shown for

- All three deployment concepts,
- 2, 4, 6, 8 and 10 offices and
- One to 50 devices, with at least one device per office on average.

To distinguish the number of offices (and thus the scenario size), the graphs are colored as given in the legend in Figure 4; furthermore, the capability of the MAC (with or without concurrent transmissions) is coded in the line style.

4.1. Pure Ad-hoc Networking

In the first deployment concept, all mesh points (green in Figure 2) are deactivated and the devices form an ad-hoc network between themselves and the portal. Hence, it is assumed that each devices is capable of forwarding its peer's data frames, which requires a forwarding table and a routing protocol. Furthermore, it becomes much harder for each device to switch into power saving, as other devices might need its services as a forwarder. Of course, this concept provides the most flexible setup for the user, as no additional nodes other than the devices have to be installed.

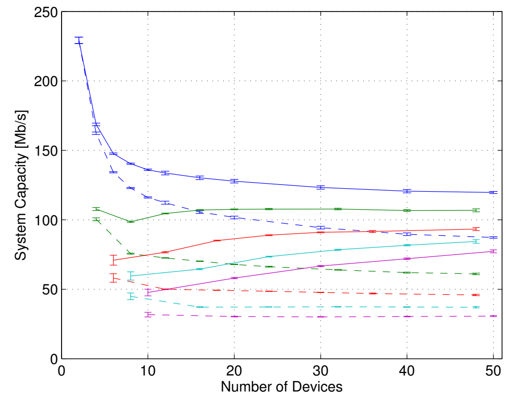


Figure 5: System capacity in the ad-hoc networking concept.

Figure 5 shows the resulting system capacity. Immediately, several trends can be observed:

- For the smallest scenario size (blue graphs), the capacity is maximal (up to 230 Mb/s) with few devices and converges to 90 Mb/s/120 Mb/s (without/with concurrent transmissions). This is rooted in the routing algorithm: With few devices, almost each user connects directly to the portal, which becomes the bottleneck of the network. Hence, almost no concurrent transmissions are used and the data rate is given by the average distance of 2.5 m.

  If the number of devices is increased, the average route length increases, as short, high-rate paths are preferred; this reduces the capacity as the small size reduces the benefit of concurrent transmissions.
- If the scenario size is increased, the capacity is reduced heavily for small network sizes, e. g. from 140 Mb/s to below 50 Mb/s for 10 offices and 10 devices. This is a direct result of the increased path length and the routing overhead.
- In large scenarios with many devices, concurrent transmissions are able to absorb the burden of the longer routes; with 50 devices the difference between the smallest and the largest is halved to 50 Mbs in comparison to the network with only 10 devices. Of course, this result assumes an optimal MAC scheduling, which is hard especially in large scenarios.

From the viewpoint of the user, an UWB network which is based on ad-hoc functionality, i. e. without specialized mesh points, is beneficial in dense networks only. As current users do not expect long transmission ranges from UWB devices, this acceptable for the common WPAN applications, but not for the connected home, which is enriched over time with more and more devices.

4.2. Introduction of Mesh Points

Based on the findings in the previous section, dedicated mesh points are introduced which are connected using directed antennas; they form the mesh backbone which provides the service of data forwarding for the devices.

In this deployment concept, the devices are either equipped with forwarding capability and the mesh is used as additional help, or the devices are limited to be either the source or the destination of a path, but not an intermediate relay. The latter has the advantage that even current devices are able to participate in the network without upgrades for the forwarding functionality.

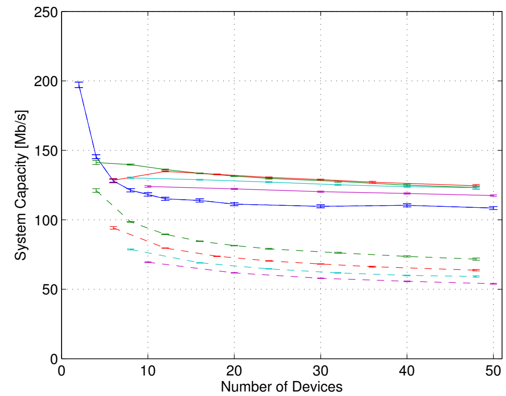
The results in Figure 6 immediately show the advantage of the concept: In comparison with the ad-hoc network, the data rate is independent from the size of the network if a minimum threshold of around 7 devices are present and optimal scheduling is assumed. In this case, a system capacity of 125 Mb/s is obtained.

The comparison with (6a) and without (6b) ad-hoc networking reveals only minor differences. Even if the devices are able to forward their data using their peers, they route over the mesh points if possible, as they provide the highest bandwidth. Hence, the routing functionality is not necessary and can be exchanged against power saving functionality.

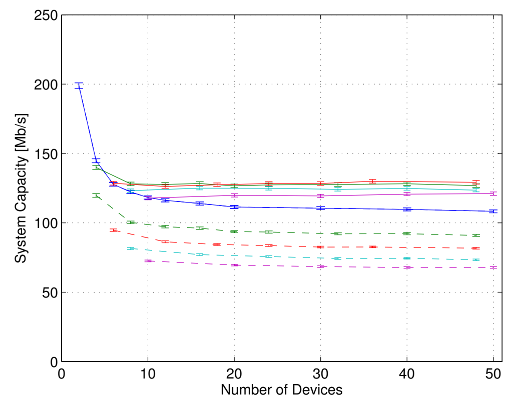
4.3. Full Mesh Point Concept

If the number of mesh points is increased by three times, it becomes possible to place one into each office next to the ones in the corridor. The resulting system capacity, shown in Figure 7, shows the same characteristics as in the deployment concept using few mesh points: Again, the capacity is independent from the scenario size and the number of devices (assuming optimal MAC operation).

In comparison to the previous concept, the capacity can be increased by about 25% to more than 150 Mb/s, as solely the high-performance mesh network is used for each hop besides the first one. Especially in this case, the difference between the optimal scheduling and the worst-case assumption without any concurrent transmissions becomes significantly high.



(a) Ad-Hoc networking and mesh points in the corridor



(b) Mesh points in the corridor, no forwarding functionality in the devices.

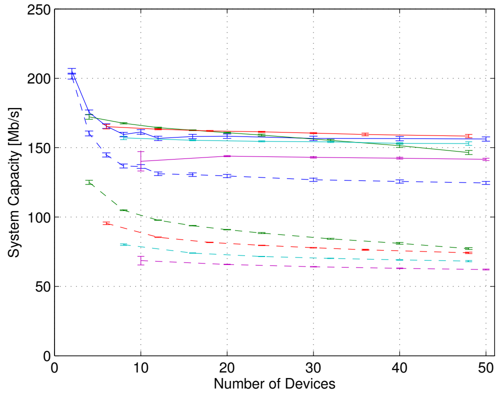
Figure 6: System capacity with mesh points in the corridor.

5. Conclusion

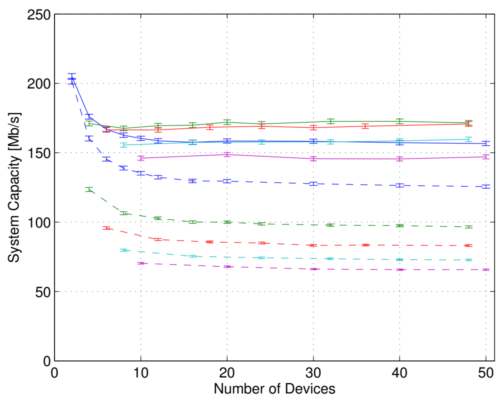
This work performs a feasibility study of the combination of UWB and ad-hoc/mesh networking, based on the average obtainable system capacity. Three different deployment concepts are compared in their ability to cover a small- to large-sized corridor and attached offices with up to 50 devices; these are

1. Purely ad-hoc networks,
2. mesh backbones with few mesh points and
3. mesh backbones with many mesh points.

All evaluations are based on a system model which represents the current standard for UWB networks from WiMedia [3], enhanced by the ability to schedule their transmissions in the optimal way, transmit concurrently and thus solve the exposed node problem.



(a) Ad-Hoc networking and mesh points in the offices and the corridor



(b) Mesh points in the offices and the corridor, no forwarding functionality in the devices.

Figure 7: System capacity with mesh points in the offices and the corridor.

Using the system model, we can show the benefit of a dedicated mesh backbone in comparison to an ad-hoc network: If the network is not dense enough, the performance of the ad-hoc network significantly drops with increasing scenario sizes. Hence, it cannot be applied to cover the usual home environment completely. Even with the installation of few mesh points, the system capacity becomes independent from the area which is covered. Hence, the quality of the user experience becomes independent from the exact position for the average scenario.

Of course, the results are based on the assumption of an optimal resource control, i. e. a MAC which is able to schedule the optimal MCS at the optimal time. In a decentralized system like the WiMedia MAC, this performance is hard to reach. In our future work, we plan to evaluate and decrease the gap between the optimal, omniscient operation and the distributed protocol.

6. Acknowledgments

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References

[1] Wimedia alliance home page. `http://wimedia.org`.

[2] IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs), Sept. 2003.

[3] Standard ECMA-368: High Rate Ultra Wideband PHY and MAC Standard, December 2005.

[4] E. Arikan. Some complexity results about packet radio networks. *IEEE Transactions on Information Theory*, 30(4):681–685, July 1984.

[5] J. R. Foerster, M. Pendergrass, and A. F. Molisch. A channel model for ultrawideband indoor communication. Technical Report TR-2004-074, 2004.

[6] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 46(2):388–404, 2000.

[7] B. Liu, Z. Liu, and D. Towsley. On the capacity of hybrid wireless networks. In *Proc. of the IEEE Conference on Computer Communications (INFOCOM)*, Mar. 2003.

[8] S. Max, G. R. Hiertz, E. Weiss, D. Denteneer, and B. H. Walke. Spectrum sharing in ieee 802.11s wireless mesh networks. *Computer Networks*, 51:2353–2367, June 2007.

[9] S. Max and Y. Zang. Ofdm-uwb physical layer emulation for event-based mac simulation. In *Proceedings of the 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, page 5, Helsinki, Finnland, Sep 2006.

[10] J. Reed et al. *An Introduction to Ultra Wideband Communication Systems*. Prentice Hall, 2005.

[11] S. Toumpis. Capacity bounds for three classes of wireless networks: Asymmetric, cluster and hybrid. In *Proc. of the 5th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc)*, pages 133–144, Roppongi, Japan, May 2004.

[12] S. Toumpis and A. J. Goldsmith. Capacity regions for wireless ad hoc networks. *IEEE Transactions on Wireless Communications*, 2(4):736–748, July 2003.