TECHNISCHE UNIVERSITÄT CHEMNITZ

Faculty of Electrical Engineering and Information Technology
Chair of Communication Networks

Diploma Thesis

Layer 2 Path Selection Protocol for Wireless Mesh Networks with Smart Antennas

Marco Porsch

Chemnitz, 4th April 2011

Student number:	146131
Email address:	marco.porsch@s2005.tu-chemnitz.de
Course of studies:	Informations- und Kommunikationstechnik
Examiner:	Prof. Dr.-Ing. Thomas Bauschert
Advisor:	MSc Muhammad Irfan Rafique

Technische Universität Chemnitz
Fakultät für Elektrotechnik und Informationstechnik
Professur Daten- und Kommunikationstechnik

Aufgabenstellung

für

Diplomarbeit

(Art der wissenschaftlichen Arbeit)

Name, Vorname: Marco Porsch geb. am: 19.12.1985

Studiengang: Informations- und Kommunikationstechnik

Studienrichtung: Informations- und Kommunikationstechnik

Thema: **Layer 2 Path Selection Protocol for Wireless Mesh Networks with Smart Antennas**

(Ausführliche Aufgabenstellung siehe Rückseite)

Die wissenschaftliche Arbeit ist als Einzelarbeit anzufertigen.

Namen der Betreuer: MSc Muhammad Irfan Rafique
(Akadem. Grad und Name)

Betreuer außerhalb der TUC:
(Akadem. Grad und Name)

Tag der Ausgabe: 5.7.2010
Abgabetermin: 4.1.2011

Tag der Abgabe:

Prof. Dr.-Ing. habil. Th. Horstmann
Vorsitzender des Prüfungsausschusses

Prof. Dr.-Ing. Thomas Bauschert
Verantwortlicher Hochschullehrer

Aufgabenstellung:

The IEEE 802.11n amendment (Draft Part 11.0) is the latest addition under development of IEEE 802.11 providing an significant increase in the data rate up to 600 Mbps for traditional one hop WLANs. Smart antennas instead of omnidirectional antennas are assumed in IEEE 802.11n. With that, it is possible to realize high data rates by means of Space Division Multiplexing (SDM), increase the range by diversity transmission/reception and increase the range as well as the overall throughput taking advantage from spatial reuse with beamforming.
In currently deployed Wiresless Mesh Networks (WMN) with legacy physical layer specification (IEEE 802.11a/b/g) the throughput degrades significantly with the number of wireless hops. Therefore, WMNs with smart antennas have been recognized as technology for next generation wireless mesh networks. However, an adaptation of the MAC and routing functions is needed to fully take advantage of the new PHY layer capabilities resulting from the use of smart antennas.

In this Diploma Thesis, primary focus is on the routing layer of WMNs with smart antennas. IEEE 802.11s, a draft for mesh networking, introduces the Hybrid Wireless Mesh Protocol (HWMP) which works on the MAC layer assuming traditional omnidirectional antennas. In the thesis, a literature survey about existing solutions for routing schemes in WMNs with smart antennas and about the recent amendments in the original HWMP draft should be performed. Furthermore, the impacts of the underlying PHY behaviour on the routing and MAC layer should be investigated. Possible routing metrics for HWMP considering spatial multiplexing and adaptive beamforming should be identified and their influence on the routing should be examined and compared. Additional tasks might be performed as agreed with the supervisor of the thesis. Program code development should be done in C++/NS3 and Matlab.

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Vorname: Marco
geb. am: 19.12.1985
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Bibliographic Description

Title:	Layer 2 Path Selection Protocol for Wireless Mesh Networks with Smart Antennas
Author:	Marco Porsch
Document class:	Diploma Thesis
Pages:	95
Figures:	51
Tables:	4
References:	79
Attachments:	1 DVD

Chemnitz University of Technology
Faculty of Electrical Engineering and Information Technology
Chair of Communication Networks

Abstract

In this thesis the possibilities of smart antenna systems in wireless mesh networks are examined. With respect to the individual smart antenna tradeoffs, a routing protocol (Modified HWMP, MHWMP) for IEEE 802.11s mesh networks is presented, that exploits the full range of benefits provided by smart antennas: MHWMP actively switches between the PHY-layer transmission/reception modes (multiplexing, beamforming and diversity) according to the wireless channel conditions. Spatial multiplexing and beamforming are used for unicast data transmissions, while antenna diversity is employed for efficient broadcasts. To adapt to the directional channel environment and to take full benefit of the PHY capabilities, a respective MAC scheme is employed. The presented protocol is tested in extensive simulation and the results are examined.

Keywords - Wireless Mesh Networks; Smart Antennas; Routing; Hybrid Wireless Mesh Protocol (HWMP); Directional MAC (DMAC)

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Abbrevations and Acronyms

ACK	Acknowledgement
AF	Array Factor
AODV	Ad hoc On-demand Distance Vector
BER	Bit Error Rate
BF	Beamforming
BFPREP	Beamforming Path Reply
BFPREQ	Beamforming Path Request
CDMA	Code Division Multiple Access
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
DAM	Density Aware Metric
DCF	Distributed Coordination Function
DMAC	Directional Medium Access Control
DoA	Direction of Arrival
DSR	Dynamic Source Routing
EDCA	Enhanced Distributed Channel Access
FCS	Frame Check Sequence
FDMA	Frequency Division Multiple Access
HWMP	Hybrid Wireless Mesh Protocol
IE	Information Element
IP	Internet Protocol
ISM	Industrial, Scientific and Medical Band
LOS	Line of Sight
MAC	Medium Access Control
MCCA	Mesh Coordinated Channel Access
MCS	Modulation and Coding Scheme
MHWMP	Modified Hybrid Wireless Mesh Protocol
MIMO	Multiple Input Multiple Output
MP	Mesh Point
MPP	Mesh Point Portal
MRC	Maximal Ratio Combining
MUX	Spatial Multiplexing
NAV	Network Allocation Vector
NIC	Network Interface Card

OFDM	Orthogonal Frequency Division Multiplexing
PERR	Path Error
PHY	Physical Layer
PMP	Peer Management Protocol
PPERR	Proactive Path Error
PREP	Path Reply
PREQ	Path Request
QoS	Quality of Service
RTS	Ready to Send
SEL	Selection Combining
SMDA	Spatial Division Multiple Access
SNOI	Signals of no Interest
SNR	Signal to Noise Ratio
SOI	Signals of Interest
STA	Wireless Station
STC	Space Time Coding
TCP	Transmisson Control Protocol
TDMA	Time Division Multiple Access
TTL	Time to Live
UCA	Uniform Circular Array
UDP	User Datagram Protocol
ULA	Uniform Linear Array
URA	Uniform Rectangular Array
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
WSAN	Wireless Sensor and Actuator Network

1 Introduction

Originally wireless communication techniques were focused on low data rate communications, such as voice or text data, while high-rate applications like videostreaming and filetransfer were traditionally associated to wired networks. In the last decade the interest in video streaming and web applications on mobile multimedia devices such as laptops and smartphones shifted these services into the domain of unbound wireless communications, thus enforced the emerging of high throughput wireless standards such as the IEEE 802.11 WLAN. Today there is another shift from wired to wireless ongoing in the scope of backhaul networks.

WMNs (Wireless Mesh Networks) have been recognized as a reliable solution for wireless backbone networks and have been in focus of academic and industrial research for the last decade. They provide high throughput, auto-configuration and robustness against poor channel conditions. In WMNs data forwarding is performed completely on air, without any need for additional wiring except for a power source. WMNs also provide freeedom of choice concerning the connetion type, as they can easily incorporate different wireless techniques such as 3G, WiMax, sensor networks and traditional wired networks. Hence WMNs might integrate various device types into the mesh, ranging from small sensor nodes and handhelds to whole Ethernet subnets.

In WMNs the problematic factor related to limiting capacity and throughput, is the performance degradation over multiple hops, as each hop transmission consumes time and occupies the wireless channel in its coverage area. To avoid severe performance losses, WMNs already rely on high performance wireless interfaces together with progressive channel access and reuse techniques. Well known methods include concepts from FDMA (Frequency Division Multiple Access), CDMA (Code Division Multiple Access), TDMA (Time Division Multiple Access).

One relatively new approach is the dynamic use of SDMA (Spatial Division Multiple Access) provided by smart antennas; it accomodates channel reuse in the same frequency, coding and time. Additionally smart antennas provide abilities to increase robustness and range as well as the data rate. Unfortunately smart antennas do not magically employ all these benefits at once, as there is a tradeoff between the different smart antenna gains. Certain smart antenna features are beneficial under special conditions only, as identified in [10]. Their different characteristics pose problems when used together by different nodes without coordination. For example MUX (Spatial Multiplexing) and diversity transmit omnidirectionally. The former is applied to increase the data rate while the latter decreases the variance in received SNR [11]. BF (Beamforming) transmits directionally and increases received SNR. As the improved SNR through diversity and BF can be used to increase the transmission range, the number of neighbours experienced by a node might be different according to the transmission scheme. Hence MAC (Medium Access Control) and routing schemes have to be aware of the smart antenna features employed at the PHY (Physical) layer to take full advantege of the smart antenna.

A number of routing protocols are proposed for multi-hop networks with smart antennas. But unfortunately most of them consider specific features of smart antennas only, without taking full benefit of all characteristics.

In this thesis a MAC layer routing protocol based on the IEEE 802.11s draft is presented, which employs and actively switches between smart antenna features according to the current network and channel conditions. The designed protocol is called MHWMP as it is based on HWMP (Hybrid Wireless Mesh Protocol), but is modified to consider the PHY layer capabilities of smart antennas. Mesh nodes with smart antennas can choose from different transmission schemes depending on the channel conditions: MUX is used to increase the data rate while BF is applied for range extension as well as to enable interference-reduced parallel communication. Diversity is used to send broadcasts with a range similar to BF, while maintaining the omnidirectional transmission pattern. To accomodate with the directional transmissions, a directional MAC scheme is employed to avoid channel access problems and take benefits of channel reuse possibilities.

In the first two chapters WMNs and smart antennas are explained to give an overview about the basics of both topics. Then the following chapter covers the related work of other authors in the research field of using smart antennas in WMNs. The amendments in channel access and the proposed routing protocol is presented in chapter 6. The system model for validating the designed protocol is explained in chapter 7. Simulation results are presented and discussed in chapter 8. A conclusion and outlook for further work is given in the final chapter 9.

2 Wireless Mesh Networks

WMNs are similar to ad hoc networks, with the difference that they are specially designed to resolve the scalability and performance issues of traditional ad hoc networks. They also enable the integration of various other networks into the formed mesh and include many techniques for self-configuring, -organizing and -healing. In contrast to ad hoc networks, which rely on the contribution of end-user supplied devices with various individual characteristics, WMNs employ powerful dedicated mesh routers which serve as the network backbone. These routers transport most of the mesh traffic and serve as bridges to various other networks. Other mesh-capable devices can join the mesh as mesh clients. These devices are also capable of forwarding data frames on behalf of other mesh nodes, but mostly rely on mesh routers for this task. This reduces the requirements for end-user devices joining the WMN, like cost and power consumption.

Figure 2.1 shows an example WMN. It is formed by mesh routers, which interconnect various connected sub-networks and devices. Some mesh routers perform additional functions as they employ gateway interfaces for connecting different other networks and devices. The mesh provides associated services to all connected devices. For example the sensor nodes in the lower right of the figure are connected to the global internet via the mesh.

All the mentioned features bring a lot of advantages, such as robustness, easy maintenance and low cost deployment. Often WMNs are considered a type of ad hoc networks. But since WMNs employ many additional techniques, that diversify the capabilities of ad hoc networks, it seems more suitable to say that ad hoc networks are a subtype of WMNs [12].

2.1 Mesh Routers

Unlike traditional ad hoc networks WMNs have special focus on scalability. Therefore special dedicated mesh nodes, called mesh routers, serve as a network backbone, transporting most of the networks traffic. These devices rely on a powerful hard- and software for maintaining network connectivity and high forwarding throughput. They are mostly dedicated embedded routers with a powerful hardware basis optimised for routing tasks. Also mesh routers can be equipped with multiple high-performance NICs (Network Interface Card) using special PHYs and/or directional antennas. Using these techniques they provide increased throughput and coverage area. Mesh routers are expected to be only minimally mobile and to have only few power restrictions.

Mesh routers are also capable of using multiple network interfaces with multiple wireless access technologies for integrating a large variety of node types into the mesh network. Of course this ability requires interoperability and compability between the wireless protocols used. So mesh routers must not only avoid collisions with mesh frames but also with interference from all surrounding wireless technologies.

Using a bridging technique different types of networks are integrated into the mesh, such as WSAN (Wireless Sensor and Actuator Network), conventional WLAN, WiMax and cable-bound networks like Ethernet. Thus conventional wireless devices like laptops or PDAs can connect to

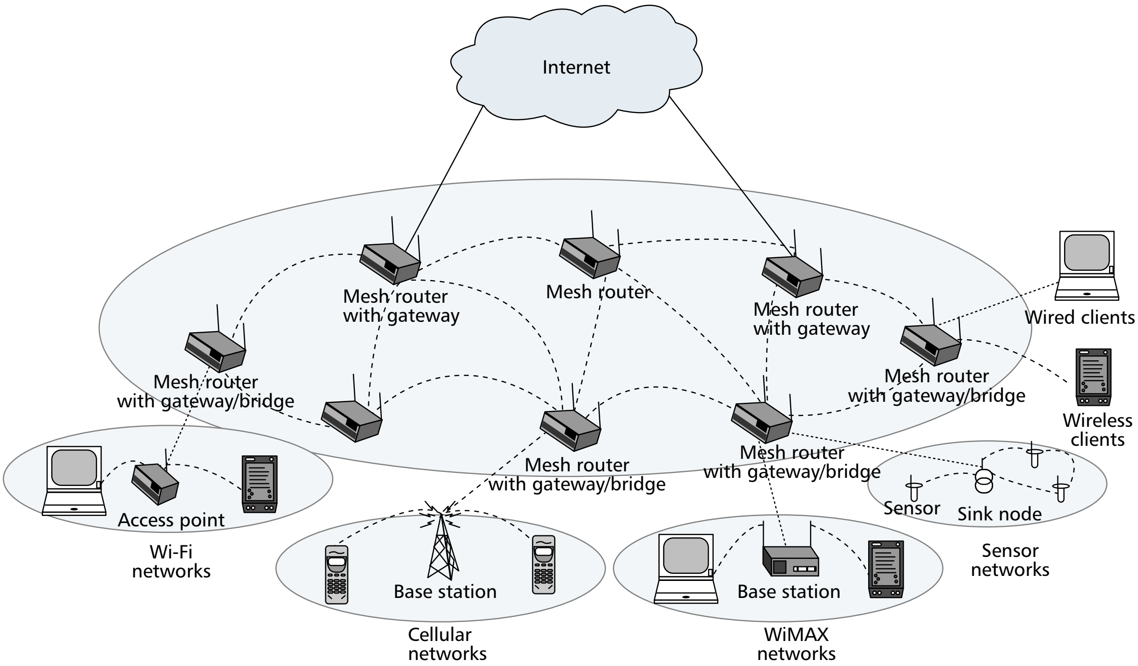


Figure 2.1: Example WMN [1]

WMNs by using the respective gateway functions. For example a mesh router equipped with a WSAN interface card is able to give all nodes of a connected sensor network access to all other mesh patricipants and their connected sub-networks. Similarly all integrated devices may access bigger networks like the global internet, if only a single mesh node is connected to it. Thereby services in a connected network are also availible to all participants of the mesh.

2.2 Mesh Clients

In contrast to mesh routers, mesh clients can be built much simpler, since although they are also capable of traffic forwarding, they mostly rely on the nearest mesh routers for this task. Mesh clients are only expected to have one compatible interface for connecting to mesh routers or other clients. Because of this mesh clients can have a much simpler hardware with only a simple NIC and network stack and may be bound to fullfill strict power restrictions e.g. reduced transmission power for increased battery life. Mesh clients may be much more mobile than mesh routers. A good example for a mesh client is a mobile laptop, equipped with a standard WLAN NIC. Using a software mesh protocol stack, this laptop is able to join any compatible mesh and to communicate with all other attached nodes over the mesh links. Other examples are PDAs or IP-phones, which would benefit from increased network coverage area.

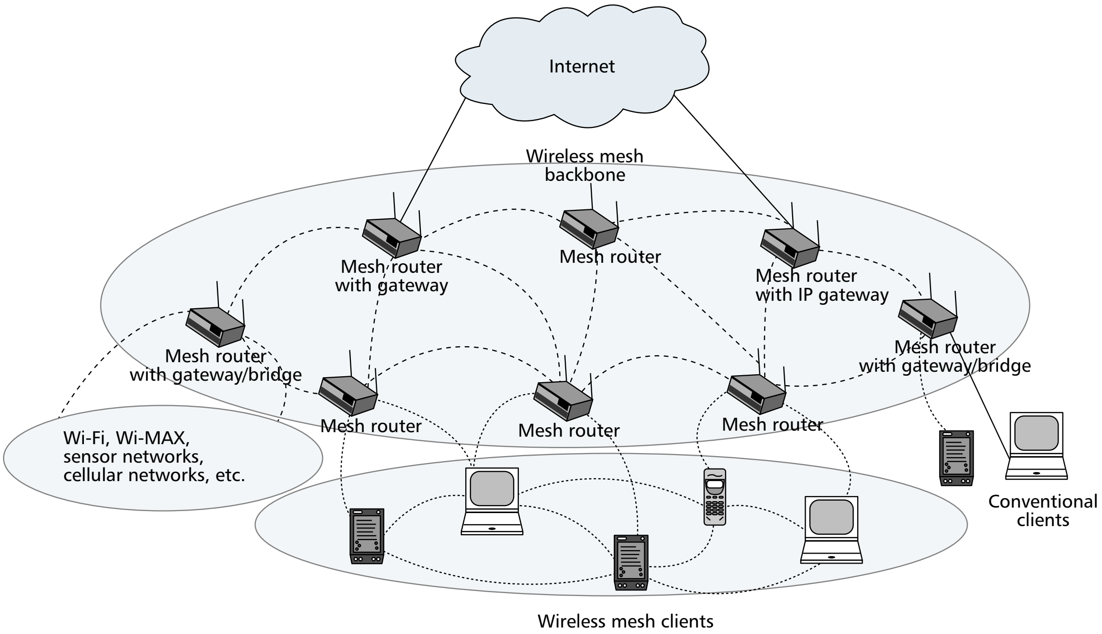


Figure 2.2: Example for WMN Types [1]

2.3 WMN Types

WMNs can be classified into three groups depending on their node composition:

- Client mesh
- Infrastructure mesh
- Hybrid mesh

The client mesh is similar to an ad hoc network and only consists of mesh clients, which need to perform all forwarding operations in this WMN subtype. An infrastructure mesh is a network that only consists of mesh routers, which form a backbone network and serve as gateways to other networks through their bridging interfaces. A hybrid mesh is the combination of infrastructure and client mesh; both mesh routers and mesh clients are part of a network. In Fig. 2.2 an example WMN is shown. An infrastructure mesh in the center serves as the backbone and uses gateways to integrate other networks like the internet on top and different wireless and wired networks in the lower right and left. A client mesh is formed within the clients in the lower center of the picture. As the client mesh is connected with the infrastructure mesh, a hybrid mesh is formed.

2.4 Mesh Applications

Due to the high performance and flexibility of WMNs, many applications are feasible for these kinds of networks. Some examples are given in the following.

- Fast-deployed, mobile emergency networks for fire departments or police:
  In case of a natural disaster local communication and power lines may be destroyed. Range and performance of mobile personal communication devices are strongly restricted by their battery capacity. Whereas a mesh formed with stationary mesh routers equipped with a strong battery together with lightweight client handhelds brings the benefits of both larger coverage area and better performance, even allowing streaming of video data. Also due to self healing and -configuration, the mesh routers can be easily exchanged or the coverage area may be extended by adding more routers.
- Neighborhood community networks:
  Since an internet access availible to a single mesh node is availible to the whole network, a whole neighbourhood community can share a single broadband internet access. Also having the neighbourhood connected in a single network makes distributed file storage and data exchange easy.
- All-wireless networks for home, office or campus:
  Often a single wireless access point is not sufficient to cover a mid-sized office. Current approaches such as WDS (Wireless Distribution System) are not standardized and thus problematic with heterogenous hardware. WMNs are easily deployed by placing routers, which only need a power supply and pose as standard access points to legacy WLAN devices.
- Building automation:
  Similar to the previous scenario the routers are easily deployed and serve a large coverage area. Through the use of corresponding NICs the routers incorporate different other networks such as existing Ethernet-parts, WSAN or cellular networks.
- Last-mile-access solution for providing rural areas with broadband internet access:
  Since mesh routers only rely on a power supply, they can be easily deployed towards rural areas along existing power lines. In case of increasing demand, the mesh may be enhanced step-by-step with more mesh routers.

2.5 PHY Layer Techniques

Mesh routers in WMNs may employ special interfaces and radio techniques for backbone connectivity. Therefpre multiple PHY techniques are already in use or in focus of current research. The purpose of these techniques varies from increasing range and reliability to a special problem of WMNs: throughput and capacity over multi-hop transmissions.

Advanced radio transmission techniques such as OFDM (Orthogonal Frequency Division Multiplexing) have increased the achievable data rate in wireless networks for example the 802.11agn amendments for WLAN. OFDM is a frequency-division multiplexing scheme, which uses multiple sub-carriers for data transmissions. A high-rate bit stream is divided into multiple low-rate sub-streams. Since the signals are transmitted frequency-orthogonal, the different sub-streams can be transmitted in parallel, each using a low symbol rate with a high SNR (Signal to Noise Ratio). Also the multi-carrier system is robust to narrowband noise, since the data of noisy sub-carriers can be disseminated to other untroubled sub-carriers [13]. This technique is different to MUX explained in section 4.6, where spatial multiplexing is used instead of frequency multiplexing.

One commonly used technique for balancing BER (Bit Error Rate) and data rate in wireless networks is multiple rate transmission. A rate control algorithm is responsible for choosing an optimal transmission scheme for each communication partner. For IEEE 802.11n WLAN these schemes are called MCS (Modulation and Coding Schemes). A MCS consists of transmission parameters like modulation, coding rate and code bits per symbol ([14] 20.3.5). The chosen MCS determines the BER, data rate and range of a transmission. Each network node must be capable of using at least a subset of the defined MCS. Example rate control algorithms are the PID and minstrel algorithms implemented in the GNU/Linux kernel.

Multi-channel techniques allow parallel transmissions at different radio channels. Due to their multi-hop nature this is especially interesting for WMNs, as closeby links may use different channels to avoid interference to each other. This technique is useful for both single-radio and multi-radio nodes. For single-radio nodes the use of different channels within a network reduces contention and thus increases the capacity. For multi-radio nodes even multiple concurrent transmission between multiple nodes are possible, which increases the capacity even further. To use multi-channel techniques the MAC layer must be capable of coordinating multiple channels and/or radios for its links, which increases MAC complexity.

Another promising technology is cognitive radio. The motivation for cognitive radio is, that the frequency spectrum availible is used very ineffectively. For example while the unlicensed ISM band (Industrial, Scientific and Medical) is usually very occupied in urban areas, frequencies which are currently reserved for other communication systems may be unused. Cognitive radio aims at solving this imbalance: an intelligent PHY layer is monitoring current spectrum usage and dynamically alters transmission parameters such as frequency and modulation to use the availible spectrum. Of course this spectrum use is bound to legal regulations of the corresponding countries. This technique is also closely related to Software Defined Radio, which allows the network designer to set transmission parameters in software.

A prominent research issue is the use of multiple antenna systems, often called smart antennas. This topic is in focus of this thesis and is covered separately in chapter 4.

2.6 MAC Layer Algorithms

A challenging task for WMN development is the design of appropriate algorithms for the MAC layer. Most standard MAC protocols are designed for single-hop communication. Single-hop techniques managed by the MAC are separated from multi-hop aspects directed by the routing layer. This makes protocol design easier, since the MAC functions are handled transparently to the routing layer. Examples for single-hop MAC are the random access schemes of the 802.11 family based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) (see section 3.1). Since in WMNs multi-hop communication is the dominating aspect, the use of normal MAC protocols brings many drawbacks in scalability and throughput, as each node only focuses on its own traffic delivery rather than the whole network performance.

Different multiple access techniques are availible: FDMA, TDMA, CDMA and SDMA, representing separation by frequency, time, code and space. A nice example for these techniques is a group of people trying to talk in parallel. For understanding the corresponding communication partner in the sourrounding of other speakers, the different pairs may use different voice pitches, different time slots, different languages or may talk specifically in the direction of their partners.

Most current approaches can be divided into two groups: single-channel and multi-channel techniques [12]. For single channel approaches, different multiple access techniques such as TDMA or CDMA may be used to overcome issues of single-hop techniques. These are interesting approaches, but have two major drawbacks: complexity and compatibility due to coordination problems with the random access networks in the distributed nature of WMNs. An example TDMA scheme is MCCA, as defined in the IEEE 802.11s draft ([4] 9.9a.3) and described more vividly in [15]. MCCA is a multi-hop channel access technique with distributed coordination over two-hop distances in cooperation with CSMA/CA. This scheme is explained more in detail in 3.1.

Other MAC algorithms employ advanced PHY techniques together with CSMA/CA. For example the use of dynamic power control to minimize interference to the network while reducing power consumption for battery-driven devices. A promising technique is the use of directional- or smart antennas, which are in focus of the following chapters. These approaches have the benefit, that they are able to cooperate with other CSMA/CA techniques, but require additional MAC complexity to avoid hidden and exposed node situations.

Multi-channel MAC techniques employ FDMA to benefit from multiple non-interfering channels. Multiple radios transmitting on different channels enable communication with multiple MP (Mesh Points) at once. This is able to highly increase the capacity of WMNs at the expense of hardware cost and increased MAC complexity to manage multiple channels and radios. Example algorithms are [16] and [17].

2.7 Network Layer Algorithms

2.7.1 Routing Protocols

Routing protocols rely on the distribution of information about the connectivity between nodes. With this information an optimal route to any other node within the network may be determined for packet forwarding. Various routing protocols are known for mobile ad hoc networks. Most of these routing protocols are also applicable to WMNs. These routing protocols can be classified into different categories by their routing information distribution [18]:

- Proactive protocols
  These routing protocols rely on periodic exchange of routing information between all nodes to maintain the optimality of routes stored in each node at all times. This scheme is well known from traditional IP and Ethernet routing. Examples for proactive protocols are OLSR (Optimized Link State Routing Protocol) or DSDV (Highly Dynamic Destination-Sequenced Distance Vector routing protocol). The benefits of this approach are up-to-date routes, which result in a low latency, since after an initial startup phase routes to all known destinations are always availible. Of course these benefits are only availible at the cost of continuous routing overhead for distributing the routing information, even in a inactive section of the network. Therefore proactive protocols are best used in highly dynamic networks, where the constant overhead allows to cope with frequent topology changes.

- Reactive Protocols
  In reactive routing protocols: paths are only resolved and maintained, when they are actually needed. For example if a packet is addressed to a destination and there is currently no active path stored. In this case the node will queue the packet and start a path discovery to resolve an up-to-date path to the desired destination. After a path has been resolved, the packet is sent according to the resolved routing information. This approach reduces routing overhead at the cost of latency, when there is currently no path stored. Reactive protocols are beneficial in relatively static network environments without frequent route changes, since the overhead is dependent on the network dynamics. Examples for reactive routing protocols are DSR (Dynamic Source Routing) and AODV (Ad hoc On-demand Distance Vector).

- Hybrid Protocols
  Both of the previous schemes are beneficial in very different kind of network scenarios with respect to mobility, link failures and different traffic patterns. This is the motivation to combine both approaches into one routing philosophy: the hybrid routing protocols. This approach uses elements of reactive and proactive schemes to adapt to the network conditions and traffic needs. An example hybrid routing protocol is HWMP. This protocol is employed in the focused IEEE 802.11s mesh protocol and further explained in section 3.3. It combines aspects of AODV [19] and tree-based proactive routing [20]. This gives the option to announce important often used destinations - such as mesh gateways - to all MP, while for seldom used destinations a reactive on-demand path discovery is a better choice.

- Position-assisted Protocols
  These protocols rely on information about the geographic position of the nodes, additionally to commonly measurable network parameters such as BER or data rate. Advantages of these approaches are the intelligent distribution of routing information only into parts of the network, where they are actually needed and the ability to cope with highly dynamic networks. This reduces delay and overhead and increases the scalability of networks. The drawback of these protocols is their need for position information, gained either through individual techniques - such as GPS - or in collaboration with other nodes through complex position finding protocols. Example protocols are LAR and DREAM.

Another approach for classification is the separation into distance vector protocols and link state protocols as known from traditional IP routing. The difference between these two is the nodes knowledge of the network.

- Link state routing
  In these protocols a node knows of all links between all nodes in the network. Hence, the routers distribute their entire routing table information to the whole network. In link state routing a node has a path table containing a complete path description over all neccessary hops and is thus able to select different, non-overlapping routes for a packet to a distant destination. Examples of link state routing are OSPF and IS-IS.

- Distance vector protocols
  In distance vector routing a node only propagates information about its links to its direct neighbours. This also applies to the case of a link failure. In distance vector routing a node only has a short routing table with entries containing only the next hop the packet should be forwarded to. This results in an inavailibility to choose multiple non-overlapping

routes, since the forwarding node is unaware, how the route continues after the next hop. Examples for distance vector routing are RIP and BGP.

2.7.2 Routing Metrics

An important tool for finding optimal paths through the mesh are the routing metrics. Criteria for good paths are for example throughput, end-to-end delay, reliability and load balancing.

Metrics should depict characteristics of the current link, such as interference from either the own or other data flows within the mesh and also interference from out of the mesh. Other characteristics are the current load on the link, throughput and reliability. All these factors are highly dynamic in WMNs, depending on the position within the mesh and the current data streams. For example close to a mesh gateway, the traffic can be highly increased due to multiple streams passing this node. Another important factor of metric design is isotonicity. A metric is isotonic, if the order of two weights $w_1 < w_2$ is preserved, if they are concatenated to a third path w_3, thus $w_{3\otimes1} < w_{3\otimes2}$ and $w_{1\otimes3} < w_{2\otimes3}$. This is important for designing metrics for which routes may be calculated with reasonable calculation effort, using algorithms like Bellman-Ford or Dijkstra algorithm.

Due to the common nature of ad hoc networks and WMNs, many routing protocols as well as metrics used in ad hoc networks are also applicable to WMNs. Multiple metrics have been proposed in the literature [21]:

- Hop count
  is the simplest metric for multi-hop networks, which only indirectly represents path characteristics, as it treats all links equally.
- ETX
  represents the expected number of retransmissions on a link, judged by the packet loss probability e_f to the corresponding neighbour. This loss probability takes into account the loss of any frame needed for a successful frame exchange, including the data frame and ACK (Acknowledgement) as well as optional RTS/CTS (Ready to Send / Clear to Send).

  $$ETX = \frac{1}{1 - e_f}$$

- ETT
  is the Expected Transmission Time, which also takes into account the different possible transmission rates used for each link.

  $$ETT_l = \frac{r}{O} ETX$$

  O denotes the frame size and r the data rate used on this link.
- WCETT
  also takes into account multi-channel paths and focuses on using paths with orthogonal non-interfering channels.

  $$WCETT_p = (1 - \alpha) \sum ETT + \alpha \cdot max_{i \leq j \leq k}(X_j),$$

  where X_j is the sum of all ETT of links on channel j, and $0 \leq \alpha \leq 1$ is a tunable parameter.

- MIC [22]
  the Metric of Interference and Channel switching also takes into account load balancing from the own and other data streams.

  $$MIC_p = \frac{1}{N \cdot min(ETT)_{link}} \sum IRU_l + \sum CSC_l$$

  $$IRU_l = ETT \cdot N_l$$

  $$CSC_l = \begin{cases} w_1, & \text{if same channel as previous hop} \\ w_2, & \text{if other channel than previous hop} \end{cases}$$

  In these equations N_l is the number of neighbours of that corresponding link, w_1 and w_2 are weights given for the use of the same channel or channel switching.

- LAETT
  uses information about current flows and remaining capacity on each node along the path.

  $$LAETT_{ij} = ETX \frac{O}{\frac{RC_i + RC_j}{2\gamma_{ij}}}$$

  RC is the remaining capacity of either node i and j, γ_{i_j} is a link quality factor.

- EETT
  incorporates all paths, that interfere with the current path

  $$EETT_l = \sum_{IS_l} ETT$$

  IS_l refers to the interference set of link l, which includes any links, that interfere with the current path, including the current path itself.

- ILA
  is similar to MIC metric, with the difference that it also incorporates knowledge about the average load of neighbours along the link.

- iAWARE
  is similar to the WCETT metric with the addition, that it employs interference ratio factors, which directly correspond to SNR and SINR values instead of relying on derived factors like ETT.

3 IEEE 802.11s

IEEE 802.11s is a draft for WMNs based on the large family of 802.11 networks. It uses PHY layer technologies as defined in the IEEE 802.11abgn amendment, IEEE 802.11e for channel access procedures and IEEE 802.11i for security means. 802.11s uses HWMP as mandatory default routing protocol together with the radio aware airtime metric. HWMP combines approaches from AODV [19] and tree based routing for the use of reactive and proactive path discovery procedures respectively [23]. In contrast to other WMN types using routing on layer 3 (IP routing), 802.11s uses routing with layer 2 MAC addresses. This reduces the complexity and power consumption of mesh router implementations.

802.11s is designed with an interchangable path selection protocol and metric. An IEEE 802.11s node must implement the mandatory path selection protocol HWMP and the mandatory airtime metric. Apart from these conventions a node may use any other path selection protocol and metric in the corresponding networks. In this case the current protocol and metrics are announced in the MP beacons.

As 802.11s uses the same radio technology as other widespread WLAN devices, IEEE 802.11s routers can easily serve as gateways - or mesh access points - for these devices by providing a virtual access point interface using the same PHY.

3.1 Channel Access

The channel access schemes of IEEE 802.11 rely on two main techniques: sensing the channel and random backoff.

In 802.11 carrier sensing is performed in two variants. Physical carrier sensing relies on information from the PHY layer about the current channel state. The PHY usually determines the channel as busy, if the currently received energy is higher than a predefined threshold. To avoid hidden node situations virtual carrier sensing is performed. Virtual carrier sensing relies on duration information included in the 802.11 frame headers. Since frames may only be decoded after complete receipt and FCS (Frame Check Sequence) check, the duration field contains the duration of channel usage excluding the current frame. Thus data frames contain only the duration of a inter-frame space and the follwing ACK frame. When a node receives any type of frame not addressed to its MAC address, it checks the duration field and notes the duration in its NAV (Network Allocation Vector). This NAV may be implemented as a decrementing counter or timestamp. As long as the NAV indicates an ongoing channel reservation, the indication is treated equally to a busy notification from PHY carrier sensing.

It is problematic that the virtual carrier sensing is only applied after the transmission of the data frame. Thus the vital data frame is the only frame, which is not protected this scheme. Therefore the RTS/CTS scheme is employed: RTS and CTS frames are short MAC control packets, which are exchanged beforehand and contain the duration of the following data and ACK frame. Through the use of RTS/CTS the virtual carrier sensing of all uninvolved nodes in transmitter/receiver range is nofified about a following frame exchange. Also both transmitter and intended receiver check the channel condition before sending a longer data frame in vain. If the receiver finds the channel busy at its position, it will not answer back with a CTS. The procedure is illustrated in figure 3.1 for two nodes S and D. After sensing the channel S sends a RTS to D. After receipt D also senses the channel and answers with a CTS. As S receives the CTS, it is made shure that the channel is idle and the transmission of the data frame may start.

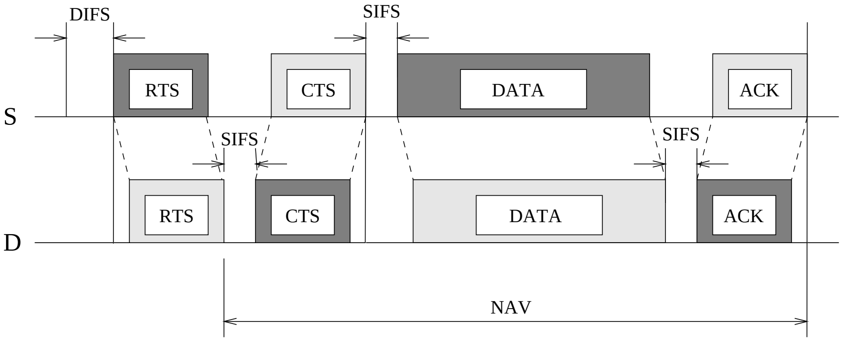


Figure 3.1: RTS/CTS Procedure (based on [2])

The random backoff procedure is used to avoid multiple STA beginning to send right after the channel is sensed idle for longer than the defined timeouts. After a transmission is complete the random backoff timer is set to a random value between zero and CW (contention window). This timer is decremented every slot time after the channel is sensed idle for longer than the corresponding timeout. If the medium is sensed busy, the backoff timer is suspended. Decrementing continues only after the channel is sensed idle for longer than the timeout again. For example in figure 3.2 STA D already has a backoff timer value at the beginning. While A accesses the medium the timer is suspended. One timeout after A is finished, D starts to decrement its timer. As C accesses the medium, D again suspends its timer. Once again after the medium is sensed idle for longer than a timeout D continues decrementing its timer. As the medium is still idle as the timer reaches zero, D can access the channel and reset its timer to a value between zero and CW_{min}. The CW is used to increase backoff duration after each transmission failure, to avoid increased contention in cases of multiple collisions.

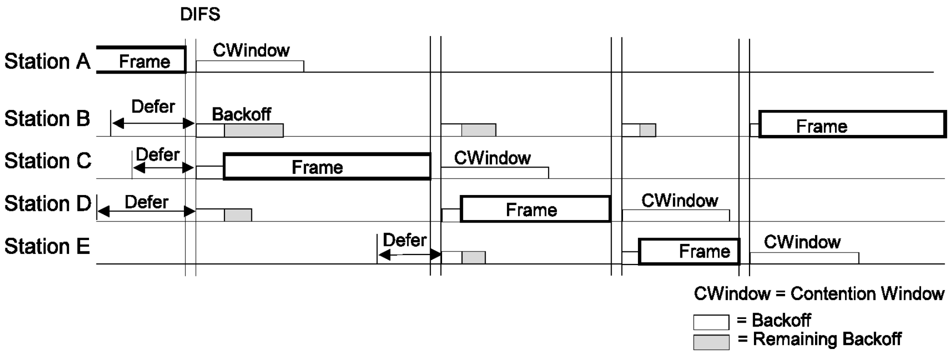


Figure 3.2: Backoff Timer Usage [3]

This access scheme is implemented for each packet queue a STA maintains. In legacy 802.11 devices this scheme is called DCF with only one mandatory queue, while 802.11e defines EDCA. EDCA uses at least four queues for different QoS classes, which are assigned different parameters for channel sensing and random backoff. Also in EDCA channel access is gained for a specified duration instead of per-packet access.

MCCA

IEEE 802.11s introduces a coordinated channel access scheme to increase reliability and scalability with respect to a certain QoS. Similar to IEEE 802.11e the 802.11s MAC layer channel access functions, which are referred to as MCF, use a contention-based access period and a period with reduced contention.

The contention based channel access method in IEEE 802.11s is EDCA as defined in IEEE 802.11e. The channel access technique for the contention-free period is called MCCA (Multi-user Polling Controlled Channel Access). The fundamental difference to PCF and HCCA - the coordinated channel access schemes in AP WLANs ([3] 9.3, 9.9.2) - is its decentralized manner, because in WMNs there is no AP or other priorized control entity for scheduling the medium access times for all STA. Since the extent of the network may be far bigger than a single STA transmission range, the transmission opportunities are coordinated for a two-hop neighborhood. In MCCA management frames are used to reserve transmission opportunities (MCCAOP) in advance. These MCCAOP are advertised around the intended sender and receiver by being rebroadcasted one time. All STA within a two-hop range of the MCCAOP shall refrain from accessing the wireless medium during the specified time. During the MCCAOP only the involved STA access the channel using the EDCA channel access procedures. The implementation of MCCA is not mandatory for all IEEE 802.11s STA. Since this TDMA-inspired channel access scheme is not in scope of this thesis, the interested reader is referred to the current 802.11s draft ([4] 9.9a).

3.2 Peer Management Protocol

The PMP (Peer Management Protocol) serves as the basis for the routing abilities by providing an overview of all MP belonging to the same network, which are in direct transmission range ([4] 11C.1). Possible peer MP are nodes, which have the same Mesh ID, share the same mesh configuration and use the same basic transmission rates. A single node wishing to join a mesh, may simply adopt the mesh configuration of the canidate network. The nodes to whom an active peering link is established may be used for frame forwarding. All incoming frames exept peering frames from non-peer nodes are dropped.

Peer management can either be performed securely by using Authenicated Mesh Peering Exchange or unsecured with Mesh Peering Management Protocol ([4] 11C.4). Since network security is out of the scope of this thesis, when talking about mesh peering instances the latter, unsecured peering functions are referenced.

Mesh peering relations are triggered by the receipt of beacon frames, which are periodically broadcasted by all MP. These beacon frames contain all information about a mesh nodes capabilities and the configuration of the mesh network it belongs to. If a node receives a beacon of a possible peering canidate, it will send a Mesh Peering Open frame to the beacons transmitter. Upon receiving the Mesh Peering Open frame, the node will perform the same checks as the beacons receiver beforehand and will - if all conditions are fulfilled - send a Mesh Peering Confirm frame back. Also it will send a Mesh Peering Open frame itself, to perform the same operations as the initial opening frame sender. Thereby the peering link is bidirectionally established when both nodes have successfully sent and received a Mesh Peering Open frame and a Mesh Peering Confirm frame. The link can be cancelled at any time by sending a Mesh Peering Close frame. The behaviour of each peer link is specified by a finite state machine model, where state transitions are triggered by peering management frame receipts or timeouts as seen in figure 3.3.

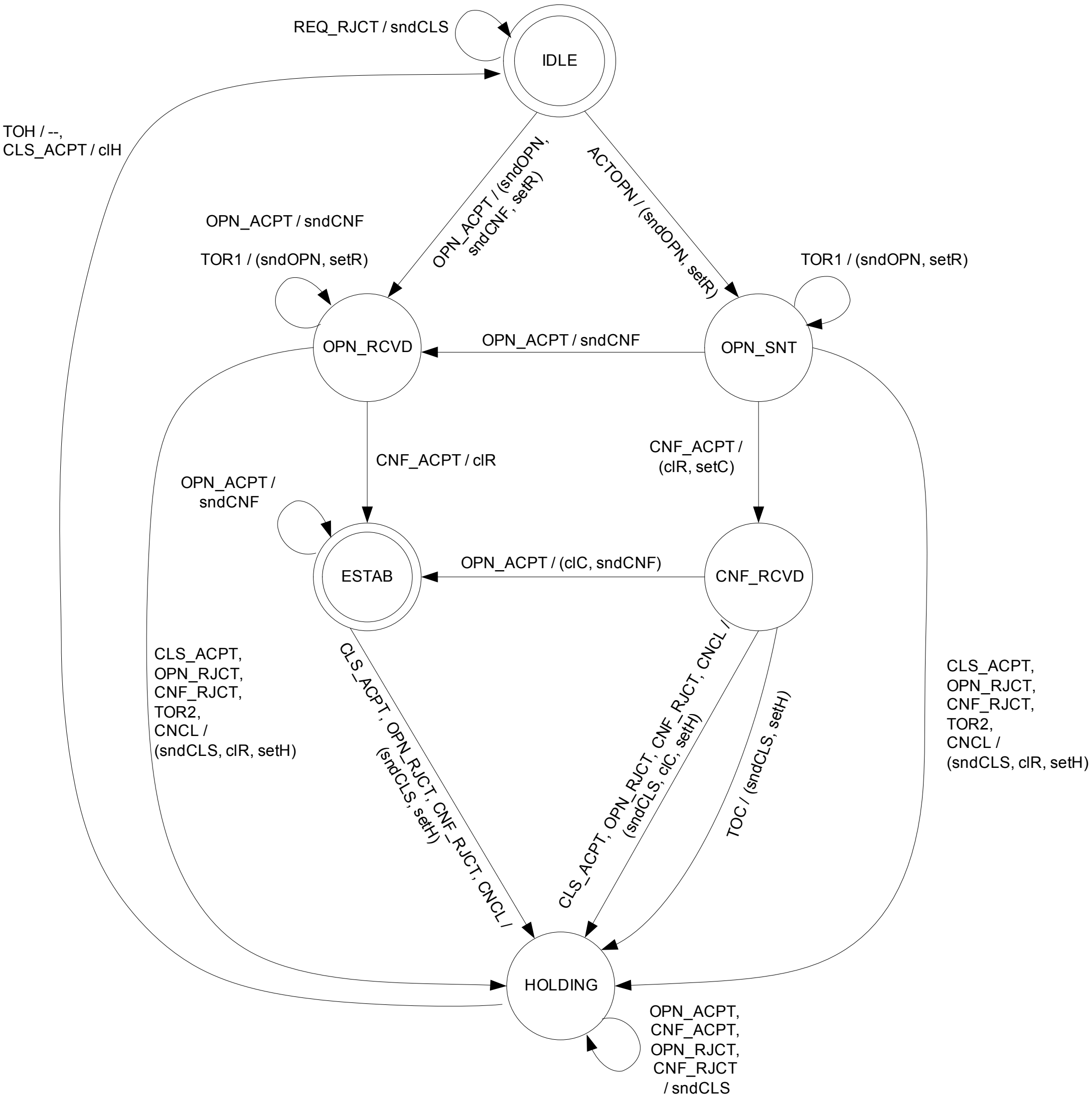


Figure 3.3: PMP Finite State Machine ([4] 11C.4.3.4)

3.3 Routing Protocol HWMP

HWMP is a hybrid routing scheme as explained in 2.7.1, which uses reactive and proactive schemes for distributing routing information. HWMP is based on the well known AODV routing protocol [19], but works on layer 2 with MAC addresses instead of layer 3 addresses as most traditional routing schemes. Being based on AODV, HWMP is also a distance vector routing protocol, where each MP stores a path table containing a next hop MP for each known destination. The next hop can be the destination itself, if the they are direct neighbours, or an intermediate MP, if the destination is out of transmission range of the originator MP.

3.3.1 Link Metric

The airtime metric used in IEEE 802.11s reflects the time, which is needed to transmit a packet over the channel. So end-to-end delay and throughput are reflected in the metric as well as contention to the network. The data rate and frame error rate towards the specific communication partner serve as inputs for metric calculation. These values, which may be obtained by the MP either analytically or experimentally, reflect critical channel parameters such as the BER and SNR depending on distance, LOS condition, channel noise and previous collisions, fading, mobility, etc. The calculataion is given by

$$C_a = [O + \frac{B_t}{r}]\frac{1}{1-e_f}$$

where O is the channel access overhead corresponding to frame headers, training sequences, access protocol frames, etc. It depends on the current PHY implementation ([4] 11C.9). B_t is the size of a test frame, fixed to 8192 bytes and r is the data rate chosen by the rate control algorithm for a specific neighbour node. e_f is the frame error rate for the neighbour, which is monitored by the rate control algorithm and/or the PMP. This value reflects the reliability of a link and thus enforces the use of reliable, long-lasting links.

The airtime metric is a member of the commonly used ETT metrics, as described previously in section 2.7.2.

3.3.2 Path Discovery

The reactive path discovery procedure is ususally triggered by a data packet, destined to a MAC address differing from the own MP address to whom no path is stored in the local path table. To resolve a path to the destination, the node increases its sequence number (also mind [4] 11C.10.5.6 Limiting the rate of HWMP sequence number increments) and creates a PREQ IE (Path Request Information Element) with the metric initialized to zero and filled with one or more targets the MP wants to establish a path to. The sequence number is an incrementing number, which is used as a tool to identify stale routing information. The management frame containing the PREQ is broadcasted. Until the path is resolved data packets are queued and will be sent as a path becomes availible.

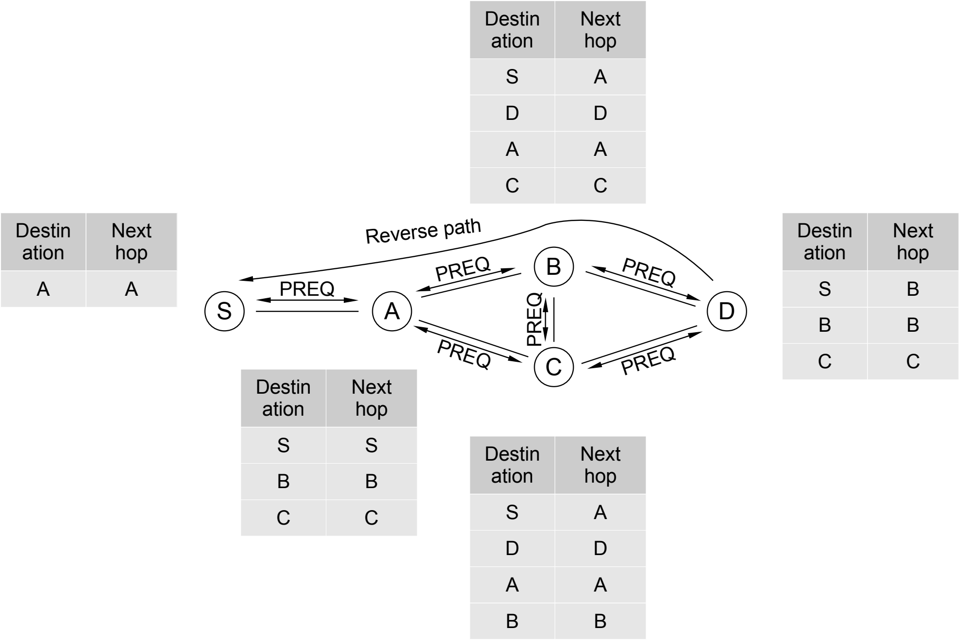
All MPs receiving the PREQ, will check whether the PREQ fulfills the acceptance criteria:

- the remaining TTL is greater than 1
- the sequence number of the originator is greater than the last known sequence number or the sequence number is equal and the PREQ metric is better than the last known metric

If these criteria are fullfilled, the receving node will update the metric and TTL fields of the PREQ IE, and will add or update a path table entry to the originator and the retransmitter of the PREQ. If the receiving node is one of the targets specified in the PREQ, it will remove its target entry from the PREQ and will answer with a PREP (Path Reply) to the originator after incrementing its sequence number. If there are target entries left, the MP will rebroadcast the frame. The airtime metric C_a is incremented hop by hop along the different possible paths towards the destination.

Since the PREQ is broadcasted and rebroadcasted through the mesh, it forms a path to its originator in all receiving nodes and thus forms the backward path between originator and target, as seen in an example network in figure 3.4. The source S wants to establish a path to destination D and thus sends out a management frame containing a PREQ. The depicted path table entries refer to the time, after all nodes have received the PREQ and D is about to answer back to S. The double arrows refer to the broadcast nature of the PREQ.

To reduce the delay of an initial path discovery, the DO and RF flags may be used. If the DO flag (Destination Only) is not set, all intermediate nodes having a valid path to the target in their path table, may answer with a PREP to the originator. In this situation the RF flag (Reply and Forward) will decide, whether the PREQ should still be forwarded towards the target after answering with the PREP. In case of a set RF flag the PREQ will be forwarded, in case of unset RF the PREQ will be dropped.



Destin ation	Next hop
S	A
D	D
A	A
C	C

Destin ation	Next hop
A	A

Destin ation	Next hop
S	B
B	B
C	C

Destin ation	Next hop
S	S
B	B
C	C

Destin ation	Next hop
S	A
D	D
A	A
B	B

Figure 3.4: Path Discovery Example: PREQ

A PREP contains the address and HWMP sequence number of the targeted node and is forwarded with unicasts along the optimal reverse path generated by the PREQ. All receiving nodes will update the frames metric and TTL field and update their path table entries for the PREP originator and retransmitter. If the acceptance criteria (same as for PREQ) are fulfilled, the frame will be forwarded. With this technique a forward path is formed between the source and destination, which completes the bidirectional path between source and destination as shown for the previously used example network in figure 3.5. Here the path via intermediate nodes A and B had the lowest metric and is thus chosen by D for the PREP unicast. The path table entries depicted refer to the time after S has received the PREP.

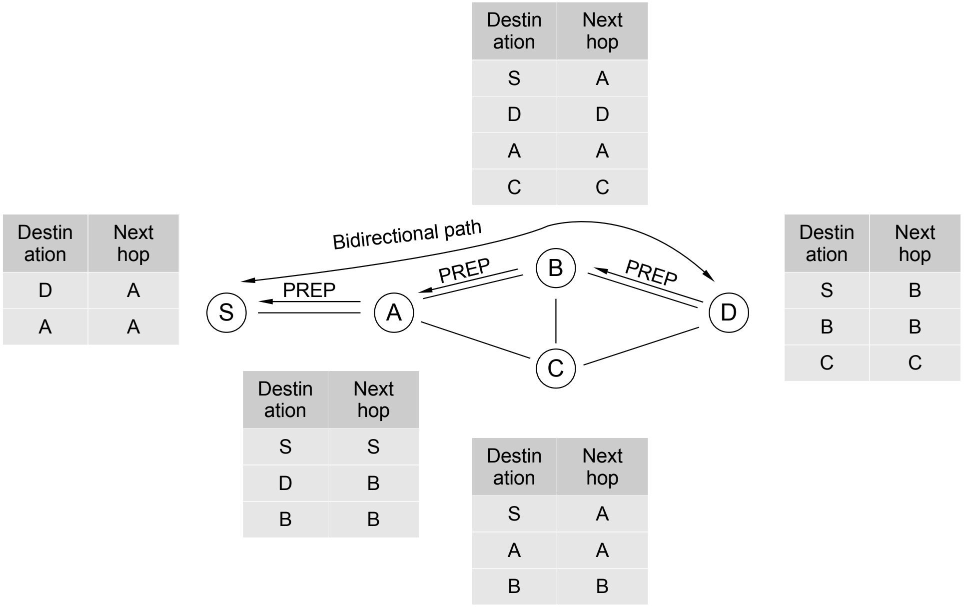


Figure 3.5: Path Discovery Example: PREP

HWMP also provides a proactive path discovery procedure, which relies on the same IE and rules as the reactive scheme. A node which is configured to announce itself in proactive fashion will periodically generate PREQ targeted at the broadcast address with DO and RF flag set. These proactive PREQ are handled just like normal PREQ: all mesh nodes receiving these IE will increment the metric field and add or update their paths to the proactive PREQ originator and retransmitter according to the previously mentioned acceptance criteria. Additionally a node wishing bidirectional connectivity with the originator of the proactive PREQ may answer with a PREP. This technique is for example useful for a MPP (Mesh Point Portal) - or gateway - that mostly forwards data out of the mesh. If bidirectional connectivity is wished to all nodes in the mesh, there is a special flag called 'Proactive PREP' in all PREQ IE, that will be set in this situation. A node receiving a proactive PREQ with this flag set, must answer with a PREP to the PREQ originator. This is useful for a MPP which handles incoming and outgoing traffic of a mesh, since the MPP is now able to immediately forward a packet from outside the mesh to the addressed MP.

HWMP also incorporates the additional proactive procedures Root Announcement (RANN) and Portal Announcement (PANN), as well as proxy information for associated non-mesh STA. These topics are out of the scope of this thesis and the interested reader is referred to the current 802.11s draft ([4] 11C.10.9, 11C.8.5).

3.3.3 Path Failure

In error conditions, which are

- a neighbour is no longer reachable, while trying to transmit frames to it,
- a node which is configured not to forward, has received a frame addressed to another node,
- a frame was received and should be forwarded to another node to which no path table entry exists (optional, see [4] 11C.7.5.2.2),

a PERR (Path Error) is generated to notify all precursors about the invalid route used. For this reason precursor lists are maintained, which note all packet sources that rely on a path for forwarding. Therefore a list of receivers, which should be notified, is generated. Depending on this list, a broadcast or multiple unicasts are sent to these nodes. The PERR IE is filled with information about the destinations which are no longer reachable through the error condition. In case of an unreachable neighbour, these destinations consist of all path table entries, which use the broken link as next hop entry to the destination. Also any other path table entries, which rely on the unusable next hop, are invalidated.

All nodes receiving the PERR will invalidate all path table entries the PERR notified as unavailible and which use the PERR (re-)transmitter as next hop. Then the node will remove entries from the PERR, which did not apply to its path table. If entries are left, the node will forward the PERR to all precursors of the unreachable destinations after incrementing the TTL field.

For clarification see figure 3.6 depicting the known example network. A bidirectional path was established through a path discovery from S to D as explained in the previous section 3.3.2. As the link between B and D breaks, for example due to multiple failed transmissions to D, B will generate a PERR, addressed to the precursors of D, which is only node A in the example network. Since D is the only destination using D as next hop, this will be the only entry of the PERR. After receiving the PERR frame, node A will check its path table for entries affected by the PERR. One path fulfilling this condition is the path to D using B, which is then invalidated and the corresponding PERR entry will be forwarded to its known precursor S. After receiving the PERR, S will invalidate its path to D, but will not forward it, since no precursors for D are known. If S has any packets to forward to D after the PERR receipt, it will have to establish a new path, by starting a path discovery as described previously in section 3.3.2. If node D also realizes the broken link, for example as it misses multiple expected beacon frames from B, it will invalidate its path table entry to B and S, but will not generate a PERR, unless it receives any data frames to forward to these destinations.

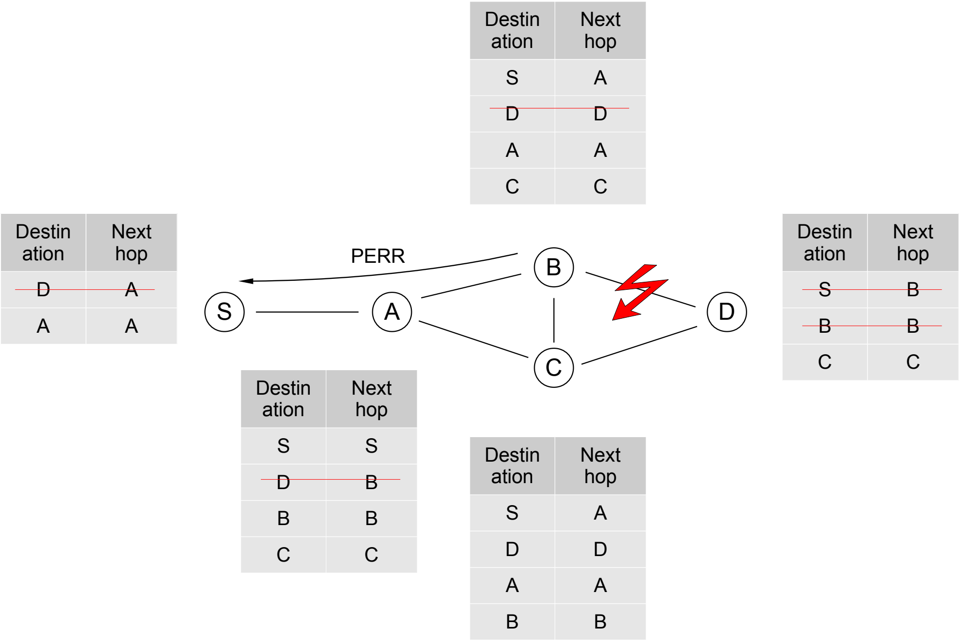


Figure 3.6: Path Error Example

3.3.4 Frame Forwarding

The source of a data frame will set its own MAC address as source address and the destination MAC address as destination in the frame header, which is depicted in figure 3.7 and explained in table 3.1. A MP receiving or starting a frame, which which is not destined to itself, will lookup the destination MAC address in its path table. If the corresponding path table entry is found, the frames receiver address is set to the entries next hop address and the frame is (re-)transmitted after decrementing its TTL. If the node does not have a valid path to the destination address and in case it started the frame, it will perform a path discovery as described previously in section 3.3.2. Otherwise, in case it received the frame from another MP, it may discard the frame, perform a path discovery or may send a PERR to the source of the frame, depending on its configuration ([4] 11C.7.5.2.2).

The standard format of frames transported through the mesh is depicted in figure 3.7. Mind that this is a standard IEEE 802.11 frame, with the addition, that the mesh header is added to the head of the payload section. The addresses contain the entries described in table 3.1.

If the flags for address extension are set in the Mesh Flags field of the mesh header, addresses 5 and 6 contain the MAC address of non-mesh destination and source, which use the MP referenced by addresses 3 and 4 as mesh proxies. These addresses are used for STA, which are connected to the mesh via MPP or gatweways. If a frame has been received by its intra-mesh destination - the MPP or gateway - and address extension is used, the MP will check its proxy table entries, whether the node referenced by address 5 is known. In this case the MP will forward the frame via the specified interface to the non-mesh destination, using the correct frame format for the non-mesh network.

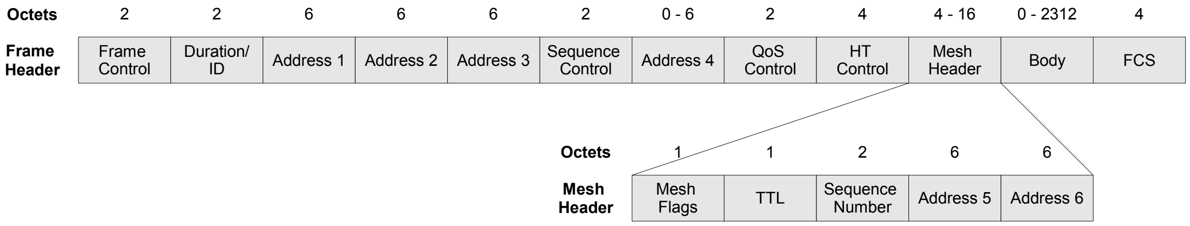


Figure 3.7: IEEE 802.11s Data Frame Format

Address 1	Address of the next-hop mesh STA
Address 2	Address of the transmitter mesh STA
Address 3	Address of the destination mesh STA
Address 4	Address of the source mesh STA
Address 5	Address of the destination end point (may be the same as Address 3 if the destination is the mesh STA at the end of the mesh path)
Address 6	Address of the source end point (may be the same as Address 4 if the source is the mesh STA at the beginning of the mesh path)

Table 3.1: Contents of Mesh Frame Address Fields

Group addressed frames are are handed to the MPs upper layers upon receipt and are forwarded after decrementing the header TTL field. These group addressed frames may also be transmitted using multiple acknowledged unicasts for increased reliability ([4] 11C.7.5.3).

4 Smart Antenna Concepts

Multiple antenna techniques have been a widespread research issue for a long time in military and scientific use for naval acoustic signal processing, Radar or radio astronomy. In recent years due to newly availible low-cost DSP and ASIC, these techniques are also availible for commercial use. While traditional approaches employ channel coding, FDMA or TDMA, multiple antenna systems use the benefits of spatial domain multiplexing. Thereby multiple antenna techniques are able to provide multiplexing gain, diversity gain or antenna gain, depending on the current tansmission scheme, as depicted in figure 4.1. All of these gains are good tools to increase transmission quality, either through increasing the reliability in difficult channel conditions or through increasing the overall throughput. Since these gains may not be applied at the same time, there is a tradeoff between the availible transmission modes and gains.

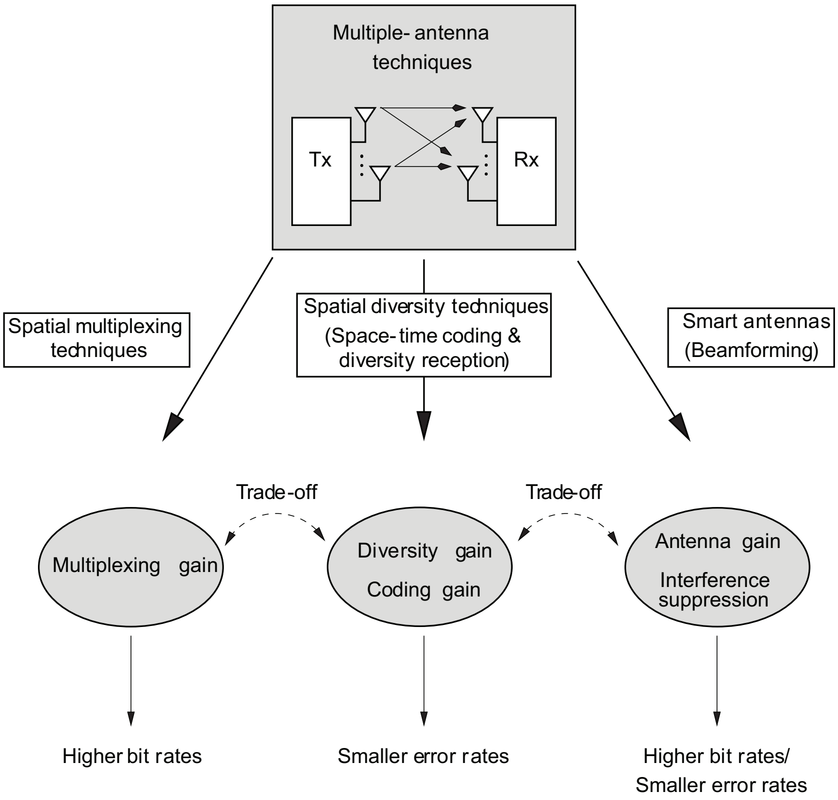


Figure 4.1: Overview of Smart Antenna Gains [5]

In this thesis the term smart antenna, which is often used for adaptive BF features, also covers spatial multiplexing and antenna diversity. Smart antennas employ the abilities to identify wanted and unwanted signals and adapt their antenna pattern to these conditions accordingly. On one hand they can determine the DoA (Direction of Arrival) of signals and coherently add delayed copies of the same signal to improve the reliability. On the other hand they can send and receive multiple signals in parallel to increase throughput. Difficult channel conditions caused by fading, which is highly problematic for traditional communication systems, are not only avoided; instead diversity and multiplexing are actively taking benefit by using individual independent paths. In this concept it is not namely the antenna, which is smart. Rather it is the sophisticated signal processing connected to the antennas, which employs multiple algorithms explained in the following sections.

4.1 Motivation for Smart Antennas

In wireless channels the link quality depends on the SNR of the received signal. A typical IEEE 802.11a packet is transmitted with 50mW, and received with 50pW of power on a good link, which corresponds to a 90dB loss. Since the noise floor is about 0.1pW, this results in a good SNR of about 27dB, which enables a high bit rate [9]. This SNR at the receiver is affected by many factors, some influenced by the transmitter, while others are caused by the wireless channel. Influences of the transmitter are: transmission power, modulation, coding and data rate.

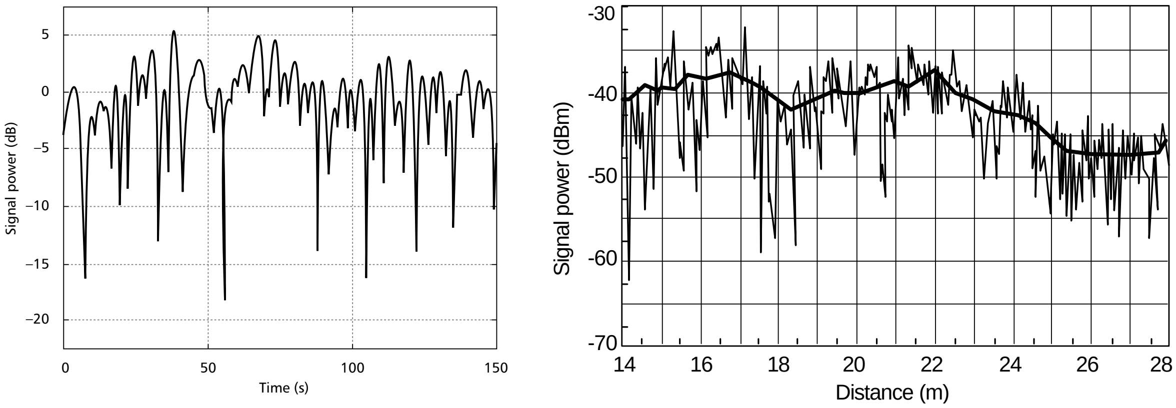
The channel conditions depend on a variety of different factors, such as noise and the channel geometry, which may enable a LOS (Line of Sight) link, cause occlusion or multiple reflections and interferences.

Path loss is caused through the spread of the transmitted electromagnetic field in the shape of an extending sphere in the freespace environment. Depending on the transmission pattern, path loss causes the signal power to drop with at least square magnitude. Additionally the positions of objects between the transmitter and receiver and their mobility might prevent a direct LOS transmission. This effect is called shadowing and is characterized by a signficant drop of SNR.

Fading is a characteristic of wireless channels, which is most significant in highly scattering indoor environments. It occurs in multipath environments, where multiple reflections and scattering of signals on object surfaces result in multiple sequentially overlapped receptions of the same signal. These received signals are delayed, phase-shifted and attenuated and thus cause interference to each other resulting in a loss of SNR as high as 15-20dB [24].

Fading is highly affected by mobility or changes in environmental conditions. Small changes in path length in the magnitude of the signal wavelength may cause a significant change of SNR. Environmental changes could be related to opened doors or moved furniture. This fading variation over time and space caused by node mobility and the environment respectively is depicted in figure 4.2. Fading is highly frequency selective, which means that single channels or OFDM sub-channels may experience deep fades, while others are unaffected.

The channel conditions normally cannot be influenced by the communication partners. Therefore it is vital to adapt the transmissions to these conditions in an optimal fashion. This adaption is performed with variable rate, modulation and coding by the rate control algorithms employed



(a) Fading over Time (based on [25])

(b) Fading with changing Position (based on [26])

Figure 4.2: Examples of Fading Effects

in many wireless transmission systems. Another adaption is often performed with variable transmission power. An interesting approach to adapt to the channel conditions, is to optimize the last element in the transmitter and receiver system chain: the antenna.

4.2 Antenna Arrays

Before explaining the different techniques of smart antennas, this section gives a short overview of the antenna arrays employed. These antenna arrays consist of multiple antenna elements placed in a fashion, which enables special radiation patterns, that apply certain characteristics to the transmitted signal. These characteristics may be modified by electronically steerable amplifiers and phase shifters, which control each antenna element independently according to its assigned weight factor w. BF, diversity and MUX apply different weights to the antenna elements, as described in the respective sections.

Uniform Linear Array

The simplest, well known antenna array geometry is the Uniform Linear Array (ULA). It consists of N antenna elements all placed in a linear fashion with equal distance. By applying a phase shift, a directional beampattern in direction Θ can be achieved.

The AF (Array Factor) is given by:

$$AF(\Theta, \Phi) = \sum_{n=0}^{N} w_n e^{jn\pi sin\Theta}[27] \tag{4.1}$$

The complex weight coefficients for a beam direction Θ_0 are given by:

$$w_n = e^{j2\pi f n \frac{d}{c} sin\Theta_0}[28]$$

As seen in equation 4.1, the AF is independent of Φ. This means that the antenna pattern is rotationally symetric concerning Φ, which is a big problem of ULA. The problem is more clear in the two dimensional case: A beam in a specific direction has a mirror beam flipped along the antenna axis, which transmits the same amount of energy in an unwanted direction. This brings interference into the network and wastes transmitter energy. Another problem is that the field of view of ULA is restricted to to 120° because the beam widens for an azimuth larger than 60° [28]. This would reduce range as well as beam sharpness and thus increase interference to other nodes. For this reason multiple ULA are needed to cover an azimuthal range of 360°. On the other hand, these arrays are well known and most algorithms are applicable to them, for example the Dolph Tschebysheff algorithm to minimize sidelobes.

A great tool for visualizing ULA antenna patterns is availible online at [29].

Uniform Rectangular Array

A Uniform Rectangular Array (URA) consists of $M \times N$ antenna elements, placed in a rectangular fashion with distance d_x along the x-axis and d_y along the y-axis as depicted in figure 4.3.

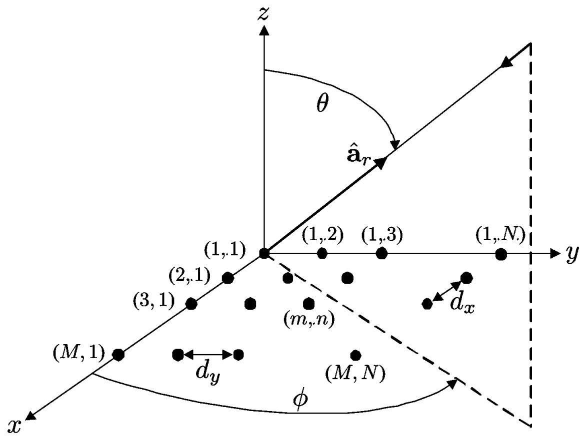


Figure 4.3: URA Geometry [6]

The URA antenna factor is given by:

$$AF(\Theta,\Phi)_{M\times N} = \sum_{m=1}^{M}\sum_{n=1}^{N} w_{mn} e^{j[(m-1)\psi_x+(n-1)\psi_y]} [6]$$

$$\psi_x = kd_x sin\Theta cos\Phi$$

$$\psi_y = kd_y sin\Theta cos\Phi$$

The complex weights w_{mn} for a beam in direction Θ_0, Φ_0 are given by:

$$w_{mn} = e^{-jk[(m-1)d_x sin\Theta_0 cos\Phi_0+(n-1)d_y sin\Theta_0 sin\Phi_0]} [6]$$

The URA allows better three-dimensional BF than ULA, because the formed beam pattern is only symetric to the x-y plane, instead of being rotationally symetric. A drawback of the URA is that the formed beam width is not constant for neither changing Θ nor changing Φ.

Uniform Circular Array

An antenna array, that overcomes most of the problems of ULA and URA is the Uniform Circular Array (UCA) or planar UCA. A UCA consists of N antanna elements placed on the x-y plane in a circular fashion on radius R with angular distance Θ_i as seen in figure 4.4.

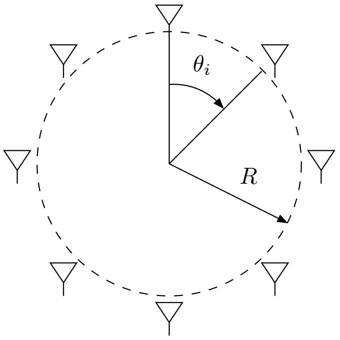


Figure 4.4: UCA Geometry [6]

The AF is given by:

$$AF(\Theta, \Phi) = \sum_{i=1}^{N} w_i e^{jkRsin\Phi cos(\Theta - \Theta_i)}[30]$$

The weights for a beam in direction Θ_0, Φ_0 are given by:

$$w_i = A_i e^{-jkRsin\Phi_0 cos(\Theta_0 - \Theta_i)}[30]$$

UCA antennas only have a single main lobe and the beamwidth is independent of the direction Θ [31]. Also compared to ULA and URA they are able to form the deepest nulls and the narrowest main beams. One of the drawbacks of UCA is that not all algorithms for antenna arrays are applicable to them, since the equations for UCA are not in Vandermonde form. This excludes for example the Dolph-Chebychev method [28]. Also UCA are problematic in multipath environments concerning multiple access interference and computationally intensive algorithms are needed to overcome this problem [28].

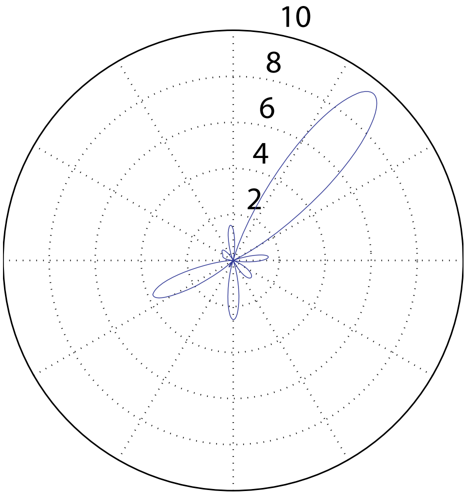


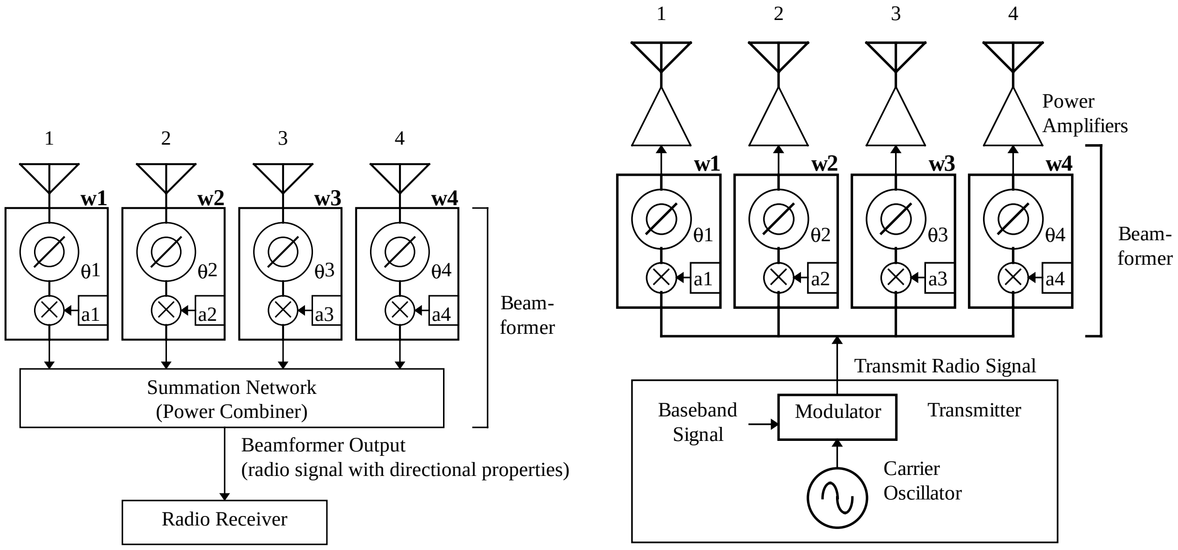
Figure 4.5: Example Gain Pattern of a UCA with 10 elements [7]

4.3 Antenna Weights

To control transmission characteristics smart antennas use multiple antenna elements, that transmit the same signal with changed phase and amplitude. These phase and amplitude shifts are called weights. Figure 4.6 depicts smart antenna implementations in a transmitter and receiver model with four antenna elements. The figure depicts an implementation for BF but is also suitable for diversity. MUX is more complicated as it uses multiple data streams (see section 4.6). In the figures it is visible, that each antenna element is assigned a complex weight w, defined by a phaseshift Θ and change of amplitude a. In a transmitter the weights will be applied to the outgoing signal for each antenna element independently. Through this coding in the time-doimain certain characteristics are applied to the transmitted signal. While diversity and MUX achieve increased robustness by delaying the signals, a beamformer forms a pattern of constructive interference to increase antenna gain. In a receiver the weights will be applied to the received signal of each antenna before being totalized in a Power Combiner, or separated in a Detector for MUX respectively. Thus received signals are shifted to a common phase and received with increased SNR.

4.4 Beamforming

BF is a signal processing technique, which can be highly useful in WMNs. Omnidirectional transmissions send a large part of the transmitted energy into directions, where it will never reach the intended receiver. Using beamforming the transmitted energy is more or less exactly pointed in the direction of the receiver, thus less transmitter energy is wasted. With the same amount of energy transmitted on a smaller coverage area, the electromagnetic field intensity is increased, resulting in a higher SNR at the receiver or same SNR at a receiver wich is further away from the transmitter. This either increases the robustness and rate through less BER or the transmission range. Also since network interference is reduced for all directions except



(a) Receiver (b) Transmitter

Figure 4.6: Beamformer Block Diagram [8]

the transmission direction, parallel transmissions are possible, where omnidirectional interference would prohibit this for traditional antennas.

4.4.1 Terminology and Classification

BF can be accomplished with multiple approaches. Traditional *static BF* uses a single fixed antenna or an antenna array with fixed weights. Thus a single direction may be covered with increased range and quality, while other directions are not accessible at all.

Switched BF relies on multiple antennas or antenna arrays, each pointing in a different fixed direction, enabling a 360° coverage. Using this antenna array, each direction is accessible, when the transmitter switches to the respective antenna for the intended direction.

Electronically steerable antenna arrays, make it possible to transmit in multiple directions with a single antenna array. Phase and amplitude shifts are applied to the incoming signal for each antenna element, resulting in a coherent addition of the incoming signals. This resembles a directional antenna pattern. This *dynamic BF* gives the most flexibility. Depending on the number of antenna elements M, $M-1$ degrees of freedom are availible to be used as main lobes toward SOI (Signals of Interest) or as nulls toward SNOI (Signals of no Interest) [5]. Nulls are directions in the antenna pattern, where the antenna gain is very low.

The term *adaptive BF* is used for an antenna array, which uses information about the current channel condition and/or current statistical knowledge about signals and interference, to adapt the antenna pattern to SOI and SNOI. This identification, location and tracking of incoming signals is done continuously, thus the antenna system is able to adapt to the channel conditions on-the-fly [30]. Such an antenna will be able to direct the main lobe as well as steering nulls towards SNOI. Note that these SNOI also include co-channel interferenc from any source. An adaptive BF antenna is able to provide an additional antenna gain of up to M, when focusing on a single SOI [32]. Adaptive beamformer also have the ability to listen omnidirectionally and employ BF upon packet receiption [32].

An example beam pattern of an adaptive BF antenna array is given in figure 4.7. In this scenario the adaptive algorithm tracks a SOI located at 100°, while pointing nulls into directions 15°, 180° and 285° where SNOI are located.

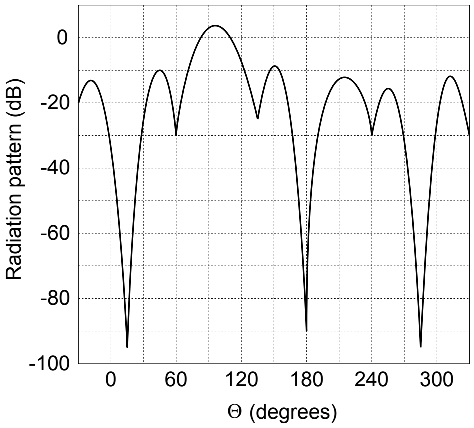


Figure 4.7: Example Adaptive BF Antenna Pattern

Adaptive BF may also be classified into two groups with respect to the higher level functions controlling the BF [7]: Communication based BF and Random BF. Communication based BF will gather informations about all communication partners from DoA estimation. These informations are then used to point the antenna into the direction of the desired communication partner. This approach may be further divided, whether the antenna is steered per packet or per communication stream. Random BF instead brings much less complexity to the MAC layer: no DoA estimation is needed, since the antenna will be steered only rarely. The direction is chosen randomly or by less complex factors like the number of neighbours in a specific direction, which is estimated by sweeping the antenna direction and counting the number of beacon sources for each direction, as described in [7].

4.4.2 Beamforming Algorithms

There are different algorithms proposed in the literature for choosing an optimal set of weights.

- Schelkunoff Polynomial- [33] or Dolph-Tschebysheff-method [34],
  also called data independent beamformers [35], can be used to steer the main beam while minimizing sidelobes, depending on antenna geometry and the desired directions [36].
- Minimum Mean-Square Error-, Maximum Signal-to-Interference Ratio- and Minimum Variance method
  are known as Statistically Optimum Beamformers [35], are also able to point the nulls towards interferers and to dynamically adapt to the conditions using second order statistical knowledge about the desired signal [8]. These algorithms use cost functions at the array output, related to the quality of the desired signal, which are then optimised to maximize

the output signal quality. Through the use of constraints in Linearly Constrained Minimum Variance Beamforming [37], it is also possible to define directions of interest, while maintaining the adaptive features within these constraints [35].

A main lobe will be formed together with sidelobes and nulls. In case of a transmitter antenna array, the main lobe will be pointed at the communication partner, while the nulls are useful to avoid interference from the rest of the network. In case of a receiver antenna array the main lobe will be pointed in the DoA of an incoming signal, while nulls are directed towards sources of interference [38].

4.4.3 DoA Estimation

DoA algorithms are needed to detect the directions of incoming signals, which are needed as input to the adaptive beamformer for tracking SOI and SNOI. DoA methods use multiple inputs such as signal delays, correlation analysis, eigen analysis and signal/noise subspace formation [30].

The author of [30] classifies four methods of DoA estimation:

- Conventional methods
  These algorithms employ sweeping the antenna in all possible directions. Afterwards they determine the DoA by the direction with the maximum signal energy without use of statistical knowledge of the incoming signal.
- Subspace-based methods
  Employing characteristics of the incoming signal and the fact that signal vectors are orthogonal to the noise subspace [28], these algorithms show greatly better results than the conventional methods for estimating the DoA. Examples are MUSIC [39] and its derivates and ESPRIT [40]
- Maximum likelyhood methods
  These methods rely on the computationally expensive Maximum Likelyhood calculation methods and show better results in low SNR and correlated signal scenarios.
- Integrated methods
  These methods combine property-restoring techniques, such as Iterative Least Squares Projection Based Constant Modulus Algorithm [41] and subspace-based approaches. These algorithms are able to track more DoA - direct and multipath - than the previous methods.

4.4.4 Benefits and Drawbacks

BF brings multiple benefits. Most obvious is the increased range, that enables communication to nodes, which are unreachable using omnidirectional transmissions. For close receivers the SNR is increased, allowing the use of less redundant coding and increased symbol rate, since the BER is lower. It is also feasible to reduce transmission power, which is especially interesting for battery powered devices. Adaptive arrays are able to provide an array gain of up to M, being the number of transmitter antennas, if mutual coupling of the antenna elements is avoided [32]. A great improvement is the smaller area interfered by a transmission. This allows multiple parallel transmissions in a network section, provided that the communication partners antenna patterns are not overlapping with the antenna patterns of other transmitters. Through the ability of adaptive BF antennas to point nulls in the direction of interferers, interference to other nodes may be actively avoided. Since up to $M-1$ sources of interference may be nulled, adaptive BF is beneficial in outdoor LOS conditions as well as in multipath indoor conditions. Also diversity gain of up to $M-n$ can be achieved if all signal paths fade independently and n degrees of freedom are used to suppress interference [32]. Another benefit is the security issue: it is harder to tap a directional transmission, where the listener needs to be in the same direction as the user. Also the knowledge of the position of a user has wide-spread use scenarios, from emergency cases to general location-based services [30].

Of course all these benefits come with a price: the hardware and software of both transmitter and receiver are much more complex and cost intensive than traditional approaches. Each radio has multiple transmit/receive chains while algorithms for calibration and signal tracking result in higher computational complexity, bringing the need for powerful processing hardware [30]. Also BF brings many new issues to the MAC and Routing layer. For example the hidden node problem is highly increased in networks using BF, as shown in figure 4.8. Nodes A and B are communicating using BF. As node C is completely unaware of the ongoing communication, it starts transmitting to A in this scenario, resulting in a packet collision.

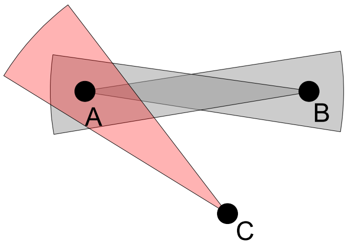


Figure 4.8: Hidden Node Situation in a Directional Scenario

4.5 Antenna Diversity

The fundamental principle of antenna diversity is that multiple antennas provide multiple independently fading paths, even if these antennas are placed only less than a wavelength away from each other [5]. If the same signal is transmitted using multiple antennas, it is unlikely that all possible paths between all transmitter and receiver antennas are experiencing bad channel conditions. Also multiple receive antennas receive a multiple of signal energy which is beneficial for signal detection and processing. This technique increases the SNR without reducing the effective data rate, which is referred to as spatial diversity gain. It can be used to increase transmission range or for reducing transmission power at constant SNR at the receiving node. At constant range it increases the receiver SNR, which enables using higher data rates or increases transmission reliability.

4.5.1 Selection Combining

The simplest diversity technique is SEL (Selection Combining). SEL determines the signal strength at each antenna and uses the antenna with the highest signal SNR as the single receive or transmit antenna. This technique is used in many legacy 802.11abg access points with multiple antennas. It mitigates fading effects, because it is less likely that all antennas experience bad channel conditions to the same extent. On the other hand, since only one antenna is receiving at a time, the antennas which are not chosen are unused and their received energy is wasted.

4.5.2 Receive Diversity: Maximal Ratio Combining

To benefit from the received signal energy of all antennas, the signals should be superimposed. But since the received signals of different antennas are out of phase, this would again suffer from fading effects. Therefore the multipath effects of different attenuation and phase shift have to be revoked before superimposing. The signals are shifted to a common phase and combined coherently. Further they are weighted by their specific SNR to give signals with few noise a higher impact than noisy signals. The amplitude- and phase shifts are represented in complex weights, which are applied to the individual antenna elements of the antenna array as depicted for BF in figure 4.6. This technique is called MRC (Maximal Ratio Combining).

This receiver-side diversity technique is suitable for systems with a single transmitter antenna as well as for full MIMO (Multiple Input Multiple Output) communication. As this scheme requires perfect channel knowledge, channel estimation is needed to adjust the receiver weights [5]. MRC is employed in IEEE 802.11n devices with multiple antennas. To determine the weights special training fields in frame preambles are used.

With the use of MRC, the BER may be reduced to:

$$BER = \frac{1}{SNR^d} \text{ [10]}$$

where d corresponds to the diversity order, which may be as high as $M \cdot N$ for a system using M transmitter and N receiver antennas.

Figure 4.9 serves as an example for MRC and SEL. A receiving node has three antennas: A, B and C, which are all affected by fading effects. In frequency selective fading different OFDM subchannels are affected differently. The SEL algorithm chooses antenna B, since overall it has the highest SNR. Thereby some subchannels suffer a power loss of over -10dB. Using MRC most deep fades can be mitigated, since rarely all received signals experience a deep fade, resulting in only -5dB power decrease for some subchannels.

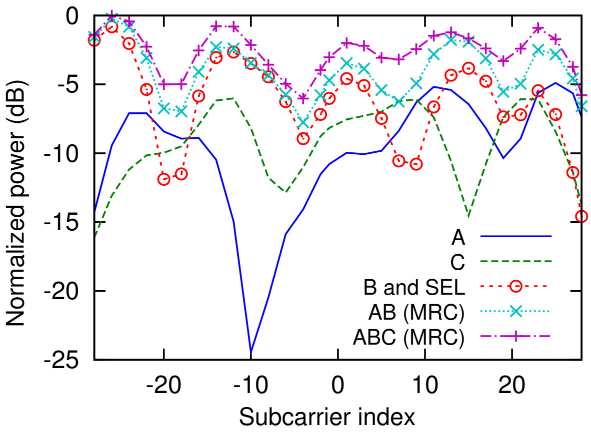


Figure 4.9: Comparison of SEL and MRC Diversity [9]

MRC also has a transmitter side equivalent, which is closely related to BF. The transmitter uses the weights to delay the signals individually in a fashion, that they add up constructively at the receivers antenna. To estimate the weights, a channel estimation is needed beforehand, which can be done with a designated packet exchange or by using received packets and assuming the channel to be reciprocal.

4.5.3 Transmit Diversity: Space Time Coding

An advanced form of transmitter diversity are space time codes. These coding schemes transmit the same signal on all transmit antennas, but with different coding over space (different antennas) and time (delayed transmission). These delays are represented by complex weight factors, which are applied to the corresponding antenna as depicted for BF in figure 4.6. STC (Space Time Codes) do not need any channel knowledge and thus no feedback from the receiver. Since the same symbol is transmitted multiple times with different antennas and at different time points, it is more likely to be independently faded, and thus successfully received at the receiver.

Well known coding techniques are Space-Time Trellis Codes (STTC) [42] and Alamouti Scheme codes [43]. STTC also employ coding gain in addition to the diversity gain, at the cost of high computational complexity for decoding. Alamouti Scheme codes allow full diversity gain at full rate through their orthogonal code design with relatively simple processing.

Alamouti scheme transmits two signal symbols s_0 and s_1 at times t_0 and t_1 with two antennas as shown in table 4.1. This technique increases diversity gain at the receiver up to 2M, where M is the number of receiver antennas [43]. Although STC may be applied to MISO systems, where the receiver has only a single antenna, multiple receiver antennas are advisable to avoid problems due to fading.

The drawback of Alamouti Scheme as well as all other orthogonal STC, which employ full diversity gain without rate reduction, is that they are only applicable to systems using two transmitter antennas. Therefore systems using more than two transmit antennas either take a rate reduction of up to 50% when orthogonal codes are used or use non- or quasi-orthogonal STC with reduced diversity gain [44]. There are also diversity coding schemes that combine multiplexing schemes like BLAST (see section 4.6.1) with STC, to achieve a flexible tradeoff between diversity and multiplexing [5].

	antenna 0	antenna 1
time t_0	s_0	s_1
time t_1	$-s_1^*$	s_0^*

Table 4.1: Alamouti Encoding and Transmission Scheme

4.6 Spatial Multiplexing

MUX uses the multipath environment to transmit and receive multiple data streams in parallel. Thereby the overall bit rate is increased by factor $min(M, N)$, for a system using M transmit antennas and N receive antennas. The achieved gain, in terms of data rate in comparision to a single antenna system, is called multiplexing gain.

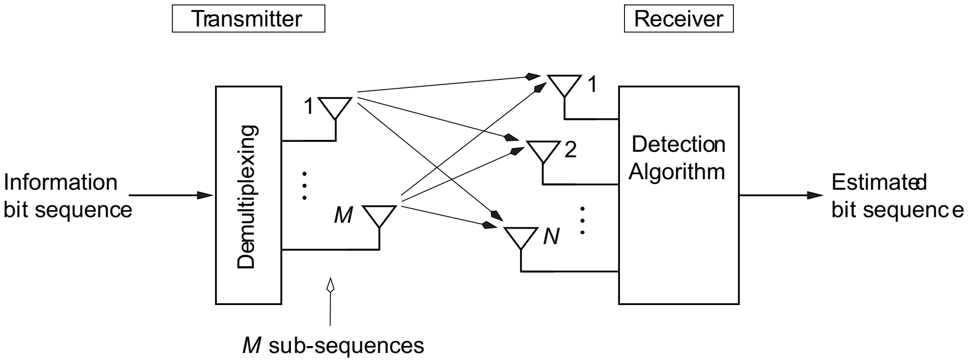


Figure 4.10: MUX Communication System Model [5]

As depicted in figure 4.10, first the transmitter splits the to-be transmitted data stream into $min(M, N)$ sub-streams. Then it modulates them individually and transmits them at same time and frequency using different antennas. After receiving the superimposed signals with N antennas, the receiver must be able to separate them into their corresponding sub-streams again. This is done using an 'interference cancellation type of algorithm' [5] like the BLAST algorithm. This separation is possible because in a rich multipath scenario the different paths fade independently. Thus there is a high chance, that each of the individual antennas receives a portion of a sub-stream, such that the sub-stream can be reassembled over all antennas. Therefore there is also a high probability that all sub-streams are received successfully, spread over multiple antennas, and the receiver is able to fully reassemble the overall transmission.

The MUX transmission is characterized by the following formula for signal vector $\vec{x}$, consisting of the transmitted sub-streams, received signal vector $\vec{y}$, noise $\vec{n}$ and channel matrix H.

$$\vec{y} = H\vec{x} + \vec{n}$$

$$H = \begin{vmatrix} h_{11} & \cdots & h_{1N} \\ \vdots & \ddots & \vdots \\ h_{M1} & \cdots & h_{MN} \end{vmatrix}$$

H has dimensions $M \times N$ and the coefficients represent the amplitude and phase shifts in complex variables, where h_{mn} represents the signal path between transmitter antenna m and receiver antenna n.

For completely independent paths between transmitter and receiver, a theoretical capacity gain of $min(M, N)$ can be achieved through the use of spatial multiplexing techniques, where M and N are the numbers of transmitter and receiver antennas. In practical systems non-linear gains are achieved due to spatial correlation and thus reduced SNR at the receiver through imperfect signal separation.

4.6.1 Direct Mapped MUX

When no CSI (Channel State Information) is availible at the transmitter, the signals have to be transmitted without directed preparation through channel coding. Instead the signals are coded blindly with best effort. This is also called receiver-sided equalization techniques [5], as the most effort of separating the individual sub-streams is spent at the receiver.

Since the different data signals are superimposed during tranmission, the receiver needs the ability to separate all signals again to their respective data streams. This is done using different detector techniques. The simplest approach is the zero-forcing detector, which is prone to errors for imperfect channel conditions [5]. This detectors uses the assumption that H can be inverted and thus the signal vector $\vec{x}$ may be easily recovered.

$$H^{-1}\vec{y} = \vec{x} + H^{-1}\vec{n} \text{ [9]}$$

In this equation $H^{-1}\vec{n}$ represents the error, distorting the received sub-streams and thus the overall data stream. If the paths are uncorrelated and thus H is close to a diagonal matrix, the influence of H^{-1} will be small and thus the magnitude of the error term will be small. Otherwise if the paths are correlated, the error term will become dominant, resulting in degrading performance, since a larger rate of redundancy is needed to recover the losses.

An improvement to the zero-forcing receiver is the Minimum Mean-Square Error Receiver. Using this technique better results at low SNR can be obtained at moderate complexity. Maximum Likelihood Detectors yield better results at the cost of exponentional growing complexity with increasing number of antennas and more complex modulation.

A famous spatial multiplexing scheme is the BLAST algortithms as described in [45]. BLAST and its modifications provide good results at moderate complexity. The BLAST scheme operates sequentially: the incoming superimposed signals are successively separated, starting by the sub-stream - called layers - with the highest SNR. The signal bits are then estimated and the corresponding ideal signal is substracted from the other signals. This process is repeated until all layers are detected [5].

These schemes rely on many assumptions of complete sub-stream receiption. For a certain error performance additional channel coding is employed [5]. Different coding schemes exist: horizontal coding, vertical coding and combinations of both. Horizontal coding is performed in the time domain, meaning that each sub-stream is assigned to one antenna element only and is encoded independently using the antenna weight vectors as depicted for BF in figure 4.6. Since a-priori CSI is unavailible, usually all signals are transmitted using the same amplitude. In vertical coding the individual sub-streams are also distributed over the antenna elements. Vertical coding thus - similar to STC - offers an additional diversity gain at the cost of increased receiver complexity. Therefore multiple BLAST modifications exist, named according to their channel coding scheme V-BLAST or D-BLAST. D-BLAST means diagonal BLAST and is a relatively simple scheme employing vertical and horizontal coding, where the sub-streams are rotary and periodically switched over the antenna elements.

4.6.2 Precoded MUX

In precoded MUX, or transmitter-sided predistortion [5], the transmitter applies channel-coding to the individual sub-streams, that enables the receiver to easily separate them. This requires

CSI at the transmitter. For the principles and methods for acquiring this CSI the interested reader is refered to [46]. These approaches are comparable to BF schemes, where the transmitter also employs CSI to form a pattern of constructive interference at the receiver to increase the gain. Precoded MUX is an optional feature in IEEE 802.11n radios, as it increases complexity and cost.

The principle behind precoded MUX is that every matrix can be separated by Singular Value Decomposition.

$$H = USV^*$$

H represents the channel matrix and $(.)^*$ is the hermitian or conjugate transpose operation. Using this scheme, S is a diagonal matrix representing a completely uncorrelated channel, which enables easy signal separation at the receiver [9]. Note that these diagonal factors also represent the strength of the independent paths and thus their relative capacity. The unitary matrices V^* and U represent coding operations performed at transmitter and receiver. In this scheme unitary means the total power of the signals will be unchanged. For precoding V^* and U have to be known at transmitter and receiver. The matrix coefficients of V^* and U are similar to the known antenna element weights, except that the previously used weight vectors are matrices of weights now, meaning that each antenna element transmits multiple individually weighted and superimposed sub-streams.

The transmitter will precode the data signals with V

$$\vec{x} = V\tilde{x}$$

In this notation $\tilde{x}$ is the actual vector of data signals, while $\vec{x}$ is the signals transmitted over the wireless channel.

After traversing the channel, the receiver will receive the following signal vector, which is influenced by the channel matrix (USV^*) and noise $\vec{n}$:

$$\vec{y} = (USV^*)V\tilde{x} + \vec{n}$$

The receiver will then perform the shaping operation using U^* on the received signal vector:

$$\tilde{y} = U^*\vec{y}$$

$$\tilde{y} = U^*[(USV^*)V\tilde{x} + \vec{n}]$$

$$\tilde{y} = S\tilde{x} + U^*\vec{n}$$

As explained earlier, since the matrix S is diagonal, the receiver is able to separate the different signals without any interference between the sub-streams.

A comparision of direct mapped MUX and precoded MUX is depicted in figure 4.11 for a 3x3 MIMO testbed link. It is visible that the overall performance of all precoded sub-streams is higher, resulting in higher overall throughput, since higher individual rates may be used. It is also visible, that this precoded MUX scheme assigns different power to the individual streams depending on their capacity according to the diagonal channel matrix S coefficients. To use the low-SNR sub-streams reduced rate, modulation and redundant coding should be applied.

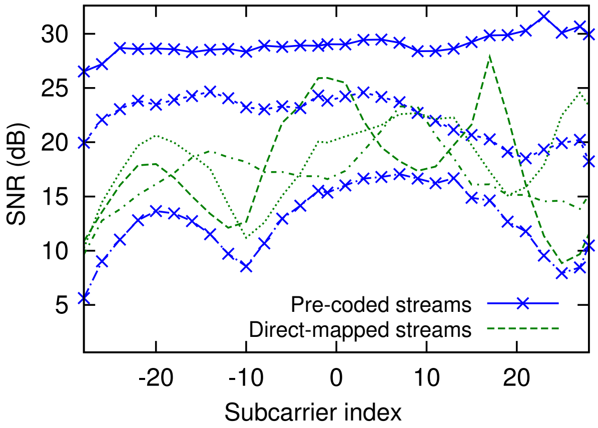


Figure 4.11: Performance Comparison of Direct Mapped and Precoded MUX [9]

5 State of the Art: Wireless Mesh Networks with Smart Antennas

The use of smart antennas in WMNs provides multiple interesting aspects, which may be used to overcome the scalability and performance issues of WMNs or ad hoc networks [32].

Concerning BF, crucially useful to improve capacity and scalability is spatial channel reuse through parallel communication as depicted in figure 5.1. Of course this feature requires a MAC layer, which detects situations when a parallel communication is possible without interfering busy neighbours. Thus the network capacity may be highly increased in the 'hot zones' of the mesh. For example areas close to often used mesh gateways or MPP are highly contended, and the use of interference-free concurrent communications would greatly increase throughput. Theoretical analysis in [47] yield a capacity gain of $2\pi\sqrt{\alpha\beta}$, with α and β being the beamwidths of transmitter and receiver. [48] collects different simulation results, which yield an increase of throughput ranging from 28% to 118%.

A second highly beneficial property of BF is the extended transmission range for constant receiver SNR. Through the increased coverage area, it allows to connect clustered networks and isolated nodes. Thereby mesh cost is reduced, as less mesh routers are needed to cover an area. BF is also highly useful for multi-hop routes, as the number of transmissions needed for end-to-end connectivity is lower, which reduces packet delay and contention effects.

For constant range the BF antenna gain decreases the receiver BER. This increases the stability and throughput of WMN links and allows more reliable and performant end-to-end connections. Since the transmitters energy is focused on its destination, battery powered devices gain benefit from reduced energy consumption. According to [49] a node employing a four-element antenna only consumes approximately 1% of the power of an omnidirectional node.

Smart antennas also increase scalability and reliability by pointing nulls towards interference from any source - intra-mesh or from out of the mesh. This decreases the BER and allows the use of higher PHY data rates as well as avoiding delays because of retransmissions and link breaks. Cancellation of interference is especially useful for WMNs operating in the highly crowded ISM band, which is shared by WLAN, Bluetooth and WSAN. Upon transmission nulls are pointed at known interferers, which reduces interference to the mesh as well as surrounding wireless devices.

Further benefits are the possible use of BF for topology control and user localisation, which proves highly resourceful for providing location-based services. BF is also very useful for communication with legacy 802.11 devices as explained in [50]. There are already commercially availible 802.11 AP using BF for communication with clients, for example the Ruckus ZoneFlex™ 7962.

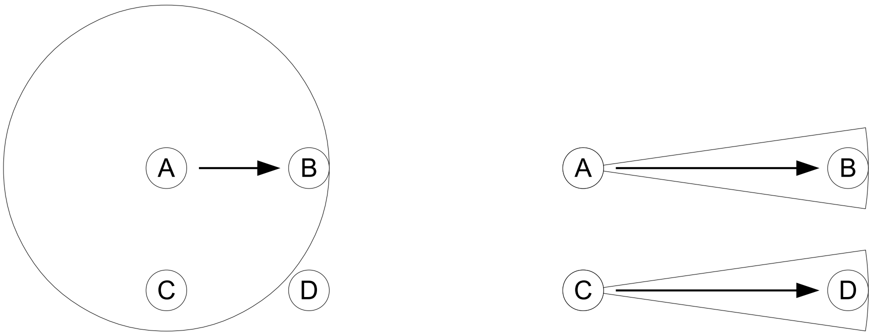
BF is most useful in LOS channels. While traditional directional antennas suffer from multipath signals or interference, adaptive arrays are well suitable for multipath environments [32].

Similar to the use of BF, diversity enables higher transmission range, and thus decreases the end-to-end delay for multi-hop routes and increases the mesh coverage area. Also effects of high mobility are reduced, as nodes stay in the coverage area of a single mesh router longer. At unchanged range the reliability and robustness against link failure is highly increased. A benefit of diversity, that BF is lacking, is its use for efficient broadcasts with long range, reducing the management overhead for the whole network. Also the fact that no CSI is needed at the transmitter makes diversity highly suitable for broadcast transmissions. So diversity may be used to cope with the drawbacks of BF, as it is able to provide a long range notification for the protection of BF transmissions. This may solve the highly critical hidden and exposed node problems in networks employing directional antennas.

Diversity is useful in LOS channels as well as in multipath scenarios. Also since no CSI is needed, diversity is robust to highly dynamic channel conditions.

The use of MUX is able to provide high throughput on heavily used links. For example IEEE 802.11n provides up to 600Mbits of PHY data rate through the use of 4x4 MUX. This is highly useful since end-to-end delay is decreased and the availible throughput provided to clients is increased (e.g. for video streaming). As each transmission occupies the channel for a shorter amount of time, surrounding nodes benefit from reduced contention, which is again useful close to gateways.

Since MUX relies on independed paths, it benefits from multi-path channels. Under LOS conditions with correlated paths the possible data rate is reduced.



(a) Omnidirectional Transmission (b) Directional Transmission

Figure 5.1: Comparision of Omnidirectional and Directional MAC Possibilities

Each of the aforementioned benefits of smart antennas is able to increase the capacity and performance of WMNs. When used together, the individual benefits cover the drawbacks of others, resulting in highly increased performance, capacity and scalability.

Of course all these benefits come with a price. The use of BF increases hidden node problems together with exposed node situations in a network, employing both directional and omnidirectional transmissions. Modified MAC and routing schemes are needed to overcome these problems, which may need knowledge about BF parameters such as the number and proportions of beams and sidelobes together with their directions. Also the knowledge of the direction to a neighbouring node may be time dependent in a non-static mesh.

The use of diversity techniques increases the interference area. This reduces the capacity of dense networks, as the channel reuse distance is increased. MUX might impose problems, since multiple transmitted sub-streams pose as multiple sources of interference to neighbours. Thus neighbours have to spend multiple degrees of freedom for interference cancellation. This may reduce network scalability gained by the higher throughput.

A main problem for the employment of smart antenna features in ad hoc networks is the cost of the additional hard- and software needed for smart antennas. But in WMNs this problem is not a crucial drawback, since mesh routers are expected to rely on a strong hard- and software basis, while end-user devices may employ more simple and cost-efficient transmission schemes.

The previous problems imply that the use of smart antennas in a transparent fashion - with unchanged MAC and routing protocols - is not beneficial or may even reduce performance of WMNs. MAC and routing schemes need to be modified for actively taking benefit of smart antenna features. For example neighbour positions need to be stored in routing tables, for focusing nodes with BF or to avoid interference to them. Knowledge of the smart antenna capabilities and properties of neighbours, the number of antennas, the ratio of interference, the possible beam width etc., is needed in higher layer functions. Therefore cross layer optimization is crucially needed in WMNs employing smart antennas.

The use of smart antenna aspects has been a widespread research issue, especially since the ASICs needed for the smart features have become affordable for commercial and end-user devices. Many authors have proposed techniques for employing smart antennas in WMNs and mobile ad hoc networks. A short overview will be given in the following section.

5.1 Related Work

The authors of [32] outlined, that the sophisticated PHY layer techniques may be highly useful in ad hoc networks, but only with modified or completely new MAC and routing schemes. If these aspects keep unchanged, many possible gains are unaccomplished or even a performance loss may be encountered. Smart antenna techniques provide a M-fold link capacity at PHY layer, with M being the number of antennas employed. If all higher layer schemes are able to take full advantage of the smart antenna features, this should linearly result in a M-fold network capacity. The authors also outlined, that it is not possible to benefit from all smart antenna gains at once. The higher layers need to take into account the network and channel situation for choosing the appropriate transmission mode.

[48] explains many possibilities and problems of WMNs employing directional antennas. Concerning channel access, it outlines hidden and deaf node problems and points out possible solutions by using variants of directional and omnidirectional RTS/CTS. For routing it covers different ideas of neighbour discovery and metric design for paths taking benefit of directional transmission. Also the authors explain different directional antenna models. Possible benefits in network throughput and capacity are quantified..

In [51, 52, 53] the authors employ switching between MUX, BF and STC in the PHY context only, without taking into account the higher layer functions. The mode decision is based on channel correlation together with SNR thresholds, to use the scheme which yields highest channel capacity.

5.1.1 MAC Layer

In the directional environment standard channel sensing is not sufficient, to avoid collisions due to hidden node situations previously depicted in figure 4.8. Thus most of the publications employing BF schemes in random access networks agree, that neighbouring nodes have to be notified of an ongoing BF transmission. While some authors rely on out-of-band transmissions or pilot tones, most publication employ broadcasted notification frames. These enhance the virtual carrier sensing - as explained in section 3.1 - by announcing BF transmissions beforehand.

Many authors have proposed the use of RTS/CTS mechanisms to annonce BF transmissions and to allow the communication partners to locate each other. RTS and CTS are transmitted omnidirectionally and/or directional, while the data and ACK are transmitted using BF. This concept is often called DMAC (Directional Medium Access Control). Since the omnidirectional transmission range is lower than the range of BF, many of these algorithms suffer from reduced overall range, for example [54]. The authors of [55] try to benefit from this range reduction by reducing the BF transmission power, thus decreasing interference for the network.

The omnidirectional exchange of RTS/CTS allows to update the communication partners latest DoA and CSI for possible PHY precoding. This is especially useful in highly dynamic channel environments. Drawbacks of this scheme are an additional delay to all BF data transmissions and increased channel overhead due to the additional frames.

Also variations of the omnidirectional RTS/CTS have been described. Long range omnidirectional RTS by sweeping followed by a directional CTS is used in [56], while directional RTS and omnidirectional CTS have been used in [57]. Of course the latter approach requires beforehand knowledge about the neighbours position.

BF transmissions only cover an area defined by the current antenna pattern. To cover the complete sourrounding of the sender, multiple BF transmissions in all directions, consecutively in a sweeping style are needed. This increases the complexity and duration of many MAC and routing functions relying on broadcast frames. Also it aggravates the problem of node deafness and increases the channel overhead. Achieving a range similar to BF with an omnidirectional tranmission pattern is a common research topic often called the 'gain asymetry problem'.

The most promising approach for solving the gain asymetry problem was proposed in [58, 59, 60]: STC is used for broadcast transmissions as a counterpart to BF unicasts. Although STC maintaints the omnidirectional transmission characteristic, a range similar to BF is achieved for low-rate transmission, especially since the receivers adaptive beamformers are still able to point their main beam into the direction of an incoming omnidirectional tranmission [32]. This transmission mode is most useful for channel reservation. Both RTS and CTS are transmitted omnidirectionally with high-range using STC. Thus all nodes within the maximum availible transmission range may be notified. The enhanced DMAC scheme is depicted in figure 5.2.

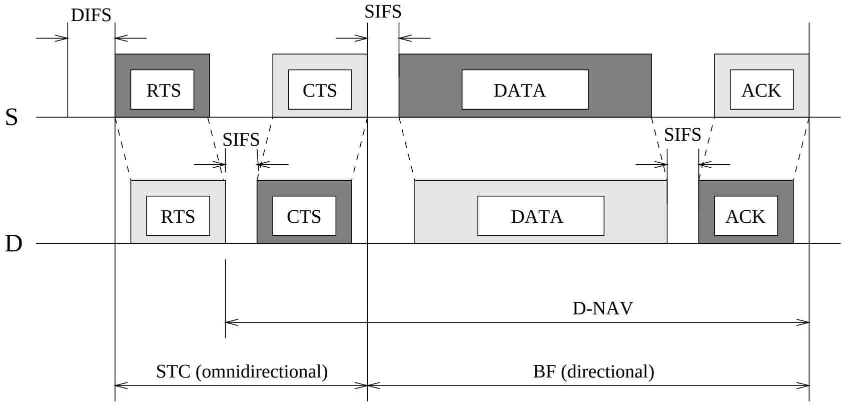


Figure 5.2: DMAC with Omnidirectional RTS/CTS [2]

When a standard NAV as described in section 3.1 is used in directional environments, the RTS/CTS would block all surrounding nodes from channel use, irrespective of their intended transmission mode and direction. This would waste the benefit of parallel BF transmissions.

To avoid this, the DNAV procedure is used, which was proposed in [57] and extended to dynamic BF in [61]. In contrast to the standard NAV, which monitors only the duration the channel is blocked in a singular fashion, the DNAV stores multiple elements of channel busy times with starting time, duration and direction. This gives the MAC the possibility to decide, whether the current active DNAV entries block channel access for a specic desired communication, or if channel access is still possible and the entry may be overrided. The DNAV scheme is used in multiple publications including [62, 63, 55, 56, 2].

A scenario to show the benefits of this scheme is depicted in figure 5.3: nodes A and B are communicating using BF, after announcing their transmission with RTS/CTS, marked in green. Nodes C and D both noted the transmission in their DNAV, illustrated as green sectors. In case C wants to transmit to D using BF, it is able to override the DNAV entries, because none of them covers the intended transmission direction.

As a sidenote: the RTS/CTS exchange also incorporates any legacy 802.11 devices, since the standard RTS/CTS frames are used. While these legacy nodes defer from channel access, the modified MP will be able to override their DNAV entries for parallel directional frame exchanges.

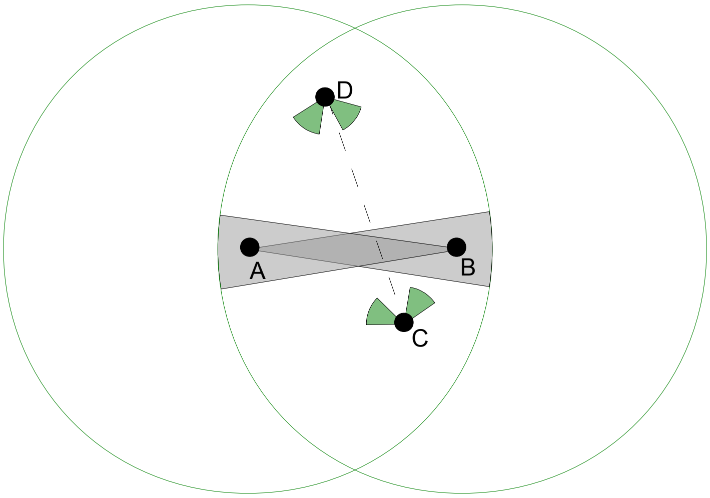


Figure 5.3: DNAV Example Scenario

[63] uses the concepts of DMAC and DNAV as basis for an extended MAC protocol, which aims at solving the range differences of omnidirectional and directional transmissions by employing multi-hop RTS/CTS. This handshake with the help of intermediate nodes is used to allow nodes, which may only communicate when both pointing their antennas together, to prepare for a data exchange. In this protocol different classes of neighbours are distinguished depending on the antenna pattern needed for communication.

Since the PHY layer uses receiver-side BF to focus on incoming signals, these receipts are well protected once the antenna is focused on the incoming SOI. Problematic is the situation, when the receiver antenna is being distracted beforehand by interfering transmissions. This is difficult to avoid, since the PHY is not able to distinguish incoming IEEE 802.11 packets into SOI and SNOI and the MAC may only examine the packets after complete receipt.

This problem is reduced by MAC-controllable receiver-side BF as proposed in [61]. This scheme points the antenna into the direction of an anticipated signal, directed by the MAC. In this context the MAC dictates a direction to the PHY and locks it in this state. This is explained with the example of a RTS/CTS exchange before a BF transmission: after receiving a RTS and answering with a CTS, a node will point its antenna into the direction of the anticipated data frame. Equally after receiving a CTS, the communication partner will decree the PHY to point its antenna into the direction of the transmission destination, before sending the data frame. After the frame exchange is completed successfully, the MAC allows the PHY to reset the antenna to omnidirectional mode. After transmission failures the MAC layer also resets the antenna after the corresponding timeouts for lacking CTS, data or ACK receipt. Still, if not dictated by the MAC layer, the PHY is able to point its antenna in the direction of incoming transmissions freely.

While being locked the PHY is still able to point nulls in directions of interferers with respect to the remaining degrees of freedom. Thus interference from other directions is avoided, which makes BF transmissions less prone to errors in general. This may be used for all but MUX receipt, since MUX employs its degrees of freedom for its multiple spatial streams.

5.1.2 Routing Protocols

Multiple Routing protocols employing BF have been proposed in the literature. [64] adapted DSR for switched beam antennas. Control frame broadcasts have to be performed by antenna sweeping.

Two on demand routing protocols using switched beam antennas are introduced in [65]. Both apply optimized sweeping to broadcast route recovery control frames after link failures. The first proposed protocol starts a new route discovery in the direction the neighbour was last seen, to reduce the overhead after link failures. The second protocol uses DoA information to inform its neighbours after a link failure by broadcasting control frames in their respective directions.

The authors of [66] propose a directional routing protocol called DRP for switched beam antennas. It uses optimized flooding, by forwarding broadcasts in all directions except the direction they have been received from. Further it employs different queues for each antenna segment to reduce end-to-end delay.

The mentioned algorithms take advantages of higher transmission range of BF but suffer from increased network overhead and deafness issues due to sweeping for broadcasts.

[67] compares AODV and DSR in ad hoc networks with adaptive BF antennas at the PHY layer. To avoid the sweeping overhead, these protocols use standard omnidirectional transmissions for broadcast frames. Thus the advantages of larger transmission range possible with BF are not exploited.

A DSR based routing protocol employing dynamic BF antennas is introduced in [68]. The primary objective of this protocol is to overcome mobility effects and network partitions. Therefore route requests are initially sent omnidirectional with short range. If no path is found the route request will be retransmitted with additional power. Capacity improvement possible with interference cancellation and parallel directional communication is not taken into account.

Roy et. al. [69] introduce a routing protocol for ad hoc networks with ESPAR antennas (Electronically Steerable Passive Array Radiator). Control frames are broadcasted omnidirectionally after a notification tone to enable receiver-side BF only. Nodes which receive this tone, rotate their beams around 360° and afterwards focus their antenna in the direction, the highest energy was received from. Maximum disjoint routes are used for each data stream in the network, to balance network load equally.

All previous protocols take benefit of BF antenna gain only, while MUX and diversity are not utilized.

The authors of [10] propose a routing protocol called MIR for ad hoc networks based on DSR, which actively switches between MUX and diversity, based on its two-tupel metric. This metric focuses on minimum network interference and maximum throughput. Therefore it selects routes with many MUX links while keeping the number of diversity links to the minimum needed to bridge sparse network parts. A single path table is employed, containing a single route to each destination. In case of link degradation, a node will increase the diversity order after four unsuccessful RTS transmissions. If a link has degraded permanently a proactive route error will be sent to the source, advising a new path discovery to get better and accurate path metrics again. One possible weakness of this approach is the use of a singular type of path request frames, transmitted using maximum diversity order. The authors use preambles with training fields of reducing diversity order, to determine the minimum diversity order needed for a link. It remains untested, whether links established using diversity may be reliably used for MUX transmissions in practical channel scenarios. The authors did not employ BF and interference cancellation features.

In [70] a routing protocol is presented, that combines the advantages of spatial multiplexing and interference cancellation. A 'service curve' is derived on the network layer, which maps the required number of transmitted bits to meet the QoS requirements. According to the difference of the current mapping and the current bit rate of a data stream to the service curve, more or less degrees of freedom are used for nulling and BF with the aim of reduced power consumption. Thus a stream with less rate is assigned more degrees of freedom for nulling. The proposed scheme does not exploit the advantages of larger transmission rage availible for BF communications.

Similarly in [71] MUX is used together with interference nulling, without using the increased range BF is able to provide.

[72] enhances an AODV-based routing protocol to consider spatial multiplexing at the PHY layer and focuses on the minimization of the route establishment time. A multi-group queueing strategy is employed, where routing and data packets use different queues assigned to the MUX sub-streams. Therefore a routing packet arriving at the node will be immediately forwarded together with the current top-queued data frame.

The authors of [73] presented a locally centralized algorithm for scheduling, routing and power control. It decomposes the network into multiple MIMO broadcast subsystems, where subsystem is defined by number of MIMO neighbors of a transmitter. Then common receivers of different subsystems are identified with the help of broadcasts. Each node sends pilot signals from each antenna and the common receiver grants access to the antenna that has less interference on other antenna streams.

[62] proposes an extension of the IEEE 802.11 based MAC protocol, to be aware of spatial diversity and analyzes its impact on routing. An optimal hop distance with respect to delay is calculated and the deviation from this distance is used as routing metric.

TDMA based routing protocols for MIMO links are also introduced in the litrature in [74] [75] and [76].

5.2 Motivation of the Thesis

Lots of publications aim at employing BF and the corresponding channel access techniques in ad hoc or mesh networks. Whereas only few authors cover the topic of employing multiple or all smart antenna features in a single mesh protocol. As mentioned previously, due to the tradeoff between the different smart antenna gains, such a protocol might overcome the individual drawbacks of one technique with benefits of others.

For example the authors of [10] advised, that the use of diversity has a critical drawback, as its high interference range reduces the channel reuse. Therefore one feature that may solve these issues, is the use of BF together with multiplexing and diversity. For unicast transmissions BF solves these channel reuse issues; first as its interference area is much smaller, second as its directed nature makes even parallel concurrent transmissions possible. For broadcasts diversity is best used, since it preserves the omnidirectional transmission pattern while providing a high range. For short-range and high-rate transmissions MUX increases the possible throughput. To our best knowledge this research topic that has not been covered yet.

6 New Concepts

This chapter describes the amendments of this thesis to the IEEE 802.11s protocol stack for actively using smart antennas. The first section covers the assumptions which were acted upon. In the following sections first the channel access techniques used are described. Second the PMP will be examined, which serves as the foundation for the routing protocol MHWMP, which is described last.

6.1 Preliminaries

The protocol described in the following sections employs the previously described smart antenna tranmission modes BF, diversity and MUX. STC diversity is used for all broadcasts with the range of BF as proposed in [58, 59, 60]. Additionally for broadcasts using the range of MUX transmissions, the legacy omnidirectional transmission mode is used, which is referred to as SEL in this thesis. This separation is used for two reasons: precoded MUX may not be applicable to broadcasts with uncertain receivers and also for symmetry reasons with the long range transmissions. This is summarized in table 6.1. Broadcast transmissions include management frames, such as beacons, RTS/CTS and PREQ action frames, as well as data frames, for example ARP requests.

	Short range	Long range
Broadcast	SEL	STC
Unicast	MUX	BF

Table 6.1: Transmission Mode Use Cases

6.1.1 Assumptions

Concerning the PHY, different capabilities are assumed. Vital for all BF transmission is the ability to detect the DoA of incoming transmissions. As explained in section 4.4 this is possible using multiple possible detector techniques. Also the receiver is assumed to detect the transmission mode of an incoming signal. This may be achieved either with a corresponding ability of the PHY or with modified frame headers or preambles, which may reduce compatibility to lagacy nodes. Concerning the used transmission range, STC is assumed to provide the same range as BF, as it is also assumed in [58], while MUX should provide the same range as the standard omnidirectional transmission mode SEL. Also nodes employing omnidirectional listening are expected to be sensitive to incoming BF transmissions and immediately point their antenna in the direction of the incoming signal as described in [32]. An assumption concerning PHY and MAC is that the receiver-side BF can be set and reset by the MAC at the beginning and end of a frame exchange. This is used for robustness in communications consisting of multiple frames.

Concerning the formed mesh as a whole, it is assumed that all MP provide the same antenna characteristic or employ an algorithm for exchanging information about the availible transmission patterns, such as beam width and range.

6.2 Channel Access Amendments

6.2.1 Motivation

The use of directional transmissions in a wireless network increases hidden node problems drastically. Since in our case BF is used in coexistence with ommnidirectional transmissions with varying range, the problem is even more serious. For example in figure 6.1 node A and B are communicating using BF in parallel with nodes C and D. Since node E is unaware of this, it could start transmitting to either one of them in omnidirectional transmission mode, which would interfere with all ongoing transmissions.

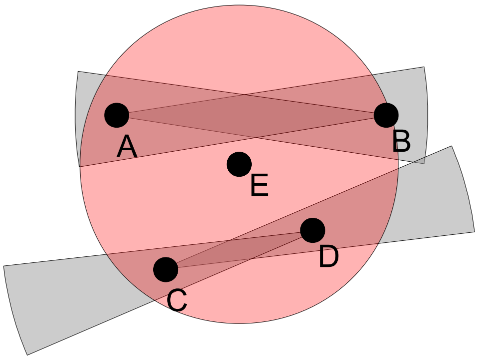


Figure 6.1: Hidden Node Situation in a mixed Directional and Omnidirectional Scenario

The consequence of collisions are packet losses. In IEEE 802.11s the severity of a lost packet depends whether it was sent as unicast or broadcast. In case of a lost unicast transmission, the sender will retransmit it, when no ACK is received after a specified duration. It also triggers the reduction of PHY layer transmission rate in the rate control algorithm of the sender node. Additionally the average factor of packet losses to the neighbouring node is monitored. This factor influences metric calculation (see section 3.3.1) and triggers a link break after exceeding a threshold. This may trigger a path error and a following new path discovery, which adds delay to current data packets. The case of lost broadcast packets is more severe: the packet is completely lost, since the sender will be unaware of the collision. Since many valuable management packets - including PREQ - are transmitted as broadcasts, routing information in the network may be outdated or incomplete.

Therefore collisions have to be generally avoided using a suitable channel access scheme, which is described in the following.

6.2.2 DMAC

As seen in the previous section, the main problem of concurrent directional and omnidirectional channel access are deafness and hidden node situations. To overcome these issues, an omnidirectional long-range RTS/CTS exchange using STC is used prior to every BF transmission as described in section 5.1.1.

To maintain the abilities of parallel BF transmissions, the DNAV scheme for dynamic BF described in section 5.1.1 is used. Additionally by monitoring the angle of incoming RTS/CTS, it is also possible to detect the situation, when a node is directly in between and in the antenna scope of two to-be transmitting nodes and to defer from channel access in this case. Further problematic cases are, when a node is within the antenna pattern of only one of the communication partners. These are not detectable, since the distances between the nodes are unknown, while only the DoA are availible.

Additional to the explained DNAV concept, a node also notes the MAC address of the RTS and CTS transmitters in its DNAV entries. This is used for a further amandment to increase the scalability and throughput of mixed directional and omnidirectional networks: the MAC can override DNAV entries from neighbours, which are out of transmission range for MUX and SEL. The knowledge to distinguish between BF neighbours and MUX neighbours is taken from the PMP, as described in section 6.3. This technique assumes, that the interference range of a transmission is not greatly larger than the range for sucessful receipt of peering frames.

In figure 6.2 this technique is illustrated: after a RTS/CTS exchange nodes A and B are communicating using BF, while nodes C and D have set their DNAV accordingly. As C intends to transmit do D using MUX, it checks its DNAV and is able to override both entries, since A and B are only BF neighbours and should therefore not be disturbed by a MUX transmission.

As a side note; it is a bit tricky, to get the MAC address of the CTS transmitter, since the CTS frame only contains a receiver address. The RTS frame although contains receiver and transmitter address. Therefore both addresses from RTS frames are stored to connect it to a following CTS. This uses the timings described in the IEEE 802.11 standard ([3] 9.2.5.4). Other MAC layer tasks are the transmissions of RTS/CTS beforehand- and ACK after a data frame transmission, as well as maintaining the respective timers. RTS/CTS are transmitted as broadcasts with the range corresponding to the data frame transmission mode. Therefore RTS/CTS for BF are transmitted using STC while optional RTS/CTS for MUX are transmitted using SEL. ACK are transmitted with the same unicast transmission mode as the corresponding data frame.

The receiver-side BF scheme as described in 5.1.1 is employed. To further increase BF transmission reliability, the scheme is modified thus the communication partners point their antennas at each other earlier. After sending an RTS a node will point its antenna into the direction of the anticipated CTS. Equally, sending a CTS in response, a node will decree the PHY to point its antenna into the direction of the RTS sender, awaiting the incoming data frame. Locking the antenna direction earlier avoids further situations when the nodes are being distracted by interfering signals.

DMAC issues

One remaining problem, that may not be completely avoided currently, is when nodes are distracted by interfering signals before a transmission starts. This resembles the known exposed node problem. An example situation is depicted in figure 6.3. In this scenario node A is currently

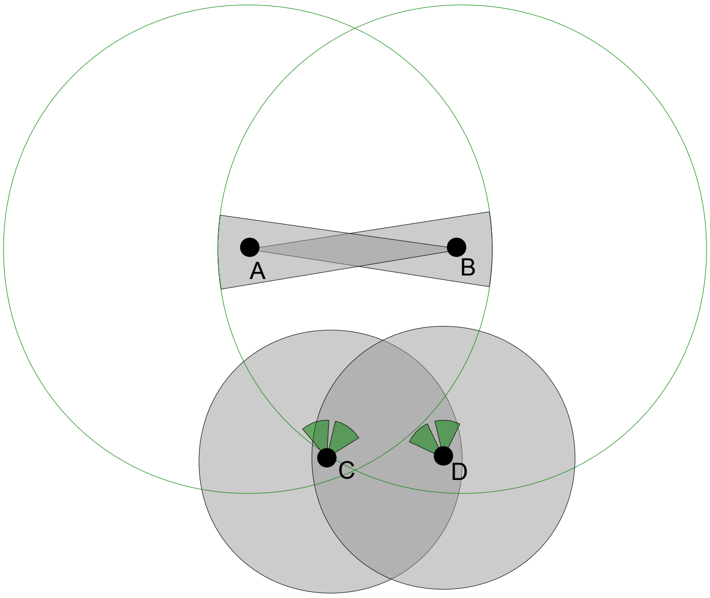


Figure 6.2: Example Scenario for DNAV with Omnidirectional Transmissions

transmitting to B using an omnidirectional transmission mode. Node C is exposed to this transmission. It may not cancel the stream as interference, since it is unaware of the transmissions intended receiver until the frame is received completely. Node D wants to transmit to C using BF and thus sends a RTS. As node C is busy receiving the frame from A to B, it cannot receive the RTS from D and does not answer back with a CTS. In this situation node D will repeat the RTS attempt and will eventually drop the current data frame. This causes packet losses and link breaks. The situation also works the other way around: as C is exposed to the transmission, it physically senses the channel as busy and may not start a transmission to D.

This situation occurs in scenarios with mixed directional and omnidirectional channel acces. It is problematic, as it blocks the BF capability of parallel transmissions.

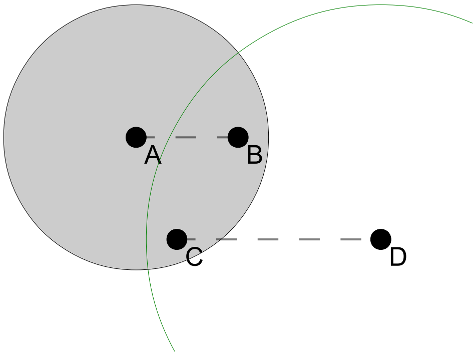


Figure 6.3: Exposed Node Situation in a mixed Directional and Omnidirectional Scenario

6.3 Peer Management Protocol

The PMP is modified to enable a separate handling of BF links and MUX links. This knowledge is used for the channel access scheme as described in the previous section 6.2.2 as well as the path error procedure described in section 6.4.3. Therefore two different path tables are employed: BF neighbour table containing all BF neighbours and the MUX neighbour table containing all MUX neighbours. In case a MP is a neighbour using BF transmission mode as well with MUX, it will be noted in both tables.

To reliably distinguish both types without additional assumptions, it is neccessary to completely separate BF neighbour discovery and MUX neighbour discovery. Therefore beacons are sent, alternating between STC and SEL transmission mode. Upon receiving these beacons, neighbouring nodes lookup the senders MAC address in their BF or MUX neighbour table according to the transmission mode of the received beacon. If currently no peering relationship is established with the neighbour, a peer management frame exchange is performed as described in section 3.2. Differences are, that the transmission mode of the received beacon is used for the peering frame exchange and that the neighbour is added to the corresponding neighbour table.

Of course this procedure results in doubled overhead for PMP of nodes, which receive both STC and SEL beacons. But the benefit is, that since the management frames were successfilly exchanged, bidirectional connectivity is proven. An alternative scheme with one type of beacons would only assume MUX connectivity depending on properties of a received STC frame. Also since the frame exchange is only performed upon discovery of a new peer and the backbone mesh network is assumed rather static, the overall overhead is kept low.

6.4 Routing Amandments: MHWMP

Since BF and MUX have greatly different transmission characteristics and range, a node which is directly reachable with BF is often out of range using MUX. Thus a mesh routing protocol using either MUX or BF only would resolve very different paths. This is visible for an example network in figure 6.6.

To overcome this mismatch, MHWMP uses two independent path tables: one containing MUX paths, the other for BF paths. Thus MP will in most situations be able to choose between two paths to a destination. The transmission mode of the chosen path is then used for the data packet transmission. As decision criterion, which path is more suitable, a common metric is needed. So the airtime metric is also calculated for the BF path as second metric in addition to the primarily used DAM (Density Aware Metric). Both metrics are explained in the following sections. Figure 6.4 shows the structure of MUX and BF path table entries. In two separate path tables also two possibly independent paths are stored. If one path is unavailible, the node will be able to forward data packets using the other, and will try to resolve the missing path type later. This redundancy is very useful to avoid delays under varying channel conditions, since the other path serves as an immediate backup avoiding the delay of a path discovery.

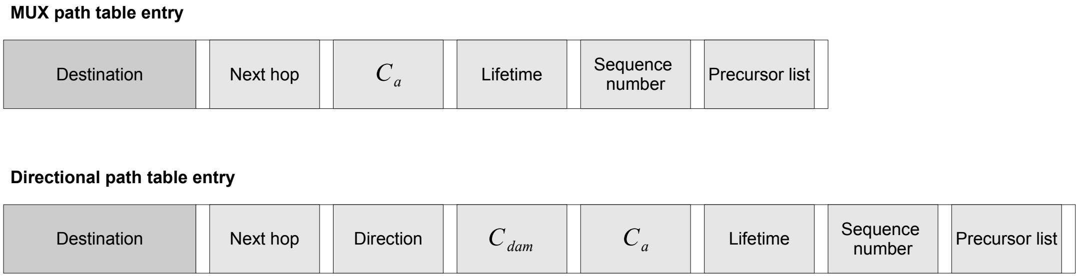


Figure 6.4: Comparison of MUX and BF Path Table Entries

The MUX path uses the standard HWMP metric - the airtime metric - and provides higher throughput using the higher MUX data rates with an omnidirectional transmission pattern. On the other hand, the caracteristic of the BF path is differenth for two reasons: it consists of long range transmission hops and it is generated using a modified metric. This metric prefers a path, which causes only minimal interference to other MP. The purpose of this path is to allow communication over longer distances within the mesh with only minimal interference to other MP. Over longer distances the MUX path would consist of multiple hops, which all cause interference to itself and to all nodes in interference range, while the BF path consists of less hops and avoids links, which cause unneccessary interference, as seen idealized in figure 6.5.

Using these rules all data transported through the mesh gains from the benefits of longer transmission range and thus reduced hop count and delay as well as reduced contention. Traffic transported over short distances additionally benefits from increased data rate and reduced delay using the MUX path.

To propagate the metrics along the path, the IE containing the metrics - named BFPREQ and BFPREP (Beamforming Path Request and Beamforming Path Reply) - must provide two fields for transporting both metrics.

6.4.1 Metrics

The ad hoc network metrics introduced in section 2.7.2 show multiple opportunities concerning metric design for the two path types. Some of these aspects are not applicable to MHWMP: load balancing, the use of information about the nodes remaining capacity as well as information about current interferers are unfavourable, since this information is very time-critical. These aspects are not fitting well to the reactive path discovery procedures of IEEE 802.11s, where a path discovery is usually performed once in multiple seconds. Therefore channel state characteristics are taken into account, which do have a more static nature. These are for example characteristics derived from the topology, which is more suitable for relatively static mesh backhaul networks. The use of multi-channel paths is out of the scope of this thesis.

To find good metrics for MHWMP, we focus on the purpose of the transmission modes as explained in section 6.1: for MUX a metric focusing on throughput is most fitting, while BF paths should provide throughput as well as minimal interference.

MUX Metric

To ensure that paths formed for MUX allow maximum throughput with minimal delay, the airtime metric defined in the IEEE draft for 802.11s ([4] 11C.9) is used. The airtime metric is described in detail in section 3.3.1. The airtime metric is chosen, since it focuses on optimal throughput and delay as well as reducing network channel contention. Therefore it fits best to the characteristics of the MUX path, which is expected to allow maximal throughput over short links.

It is important to note here, that for MUX the rate control algorithm uses the corresponding MUX data rates. For IEEE 802.11 these are the IEEE 802.11 MCS rates up to 600Mbit/s defined in the IEEE 802.11n amendment ([14] 20.6). On the other hand BF communications may only use the legacy data rates up to 54Mbit/s. Thus the higher throughput of MUX transmissions result in a better metric value assigned to a MUX link to a closeby neighbour.

BF Metric

For the longer BF paths a different characteristic favoured: the packets shall reach their destination with reasonable throughput and delay but the interference to the rest of the network should be kept to a minimum. Since the duration of the omnidirectional RTS and CTS is minimal, the directional data and ACK frames are the primary source of network interference. To reduce this interference, knowledge of the network topology is used to choose paths with minimum number of interfered nodes. This concept is depicted in figure 6.5. The topology is partially known by the PHY layer ability of estimating the DoA from incoming transmissions. Combined with information about the own antenna pattern, the number of nodes, which will be interfered by a transmission in a specific direction, can be determined. The number of neighbours is also used for the MIC metric described in section 2.7.2.

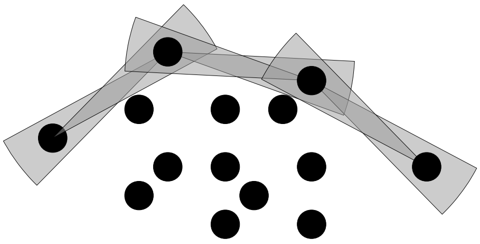


Figure 6.5: BF Path Concept

To consider throughput and delay as well, the airtime metric is also applied to the calculation of the BF link metric. This metric is called Density Aware Metric:

$$C_{dam} = C_a \cdot N_{neighbours}(\varphi, \vartheta)$$

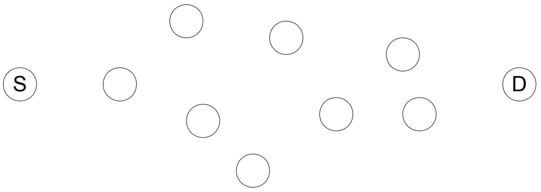
6.4.2 Path Discovery Procedure

The path discovery procedure differs, depening on whether a BF path should be discovered or a MUX path.

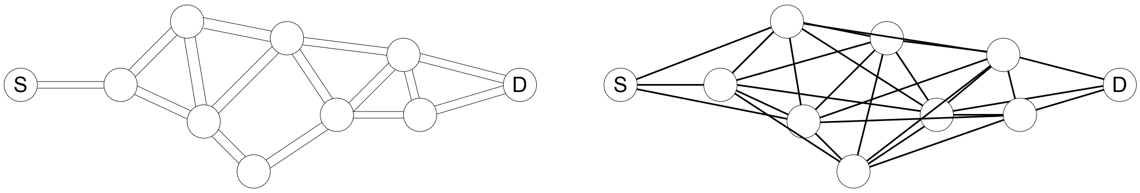
To obtain a MUX path, the same procedures as described in section 3.3.2 are used almost unchanged. A PREQ is broadcasted with SEL transmission mode and the airtime metric C_a is incremented hop by hop. The destination answers with a unicast PREP transmitted with MUX to the source for each received PREQ containing newer or better routing information. For PREQ and PREP each node along the path will store or update its MUX path table to source and destination, as well as to its neighbours according to the acceptance criteria.

The procedure for a BF path slightly differs, as it uses two metrics. To transport two metrics, modified IE are used: BFPREQ and BFPREP. These bear two changes in comparision to their standard 802.11s couterparts: two instead of one metric field and different IE identifier to distinguish them from other IE. These IE are transmitted with STC for BFPREQ broadcasts and BF for BFPREP unicasts. BFPREQ and BFPREP are processed like their MUX counterparts, with the difference, that the DAM is used for the acceptance criteria, while the airtime metric is only updated and recorded together with C_{dam}.

Because of the higher transmission range and the different metric, the established paths may be completely different to MUX paths. This is illustrated for an example network in figure 6.6. Also the BF metric calculations use only standard data rates as mentioned in section 6.4.1.

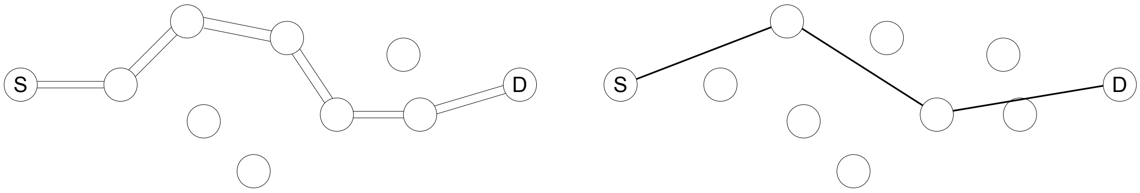


(a) Example Network Scenario



(b) Network Connectivity using SEL/MUX

(c) Network Connectivity using STC/BF



(d) Possible Path for MUX

(e) Possible Path for BF

Figure 6.6: Comparison of BF and MUX Neighbourhood and Paths

A path discovery for either transmission mode may be triggered by the following conditions:

a) a data packet is started, and no path is availible (this will cause two consecutive path discovery procedures)

b) a data packet is started, and only one path type is availible

c) path maintenance for an active path (optional)

d) proactive PREQ (if a nodes is configured as root MP)

6.4.3 Path Failure

In standard HWMP in case of consecutive unsuccessful transmissions to a neighbour, the corresponding peer link is closed and a PERR may be generated as explained in section 3.3.3. For MHWMP this approach is modified to distinguish between BF and MUX transmission modes.

To accommodate with the two separate path tables, a path error could either invalidate both or one specific path. For the first case the new PPERR (Proactive Path Error) IE is used. This IE deletes only the table entry with the mode indicated by an additional flag. The PPERR IE is defined with a new IE identifier and a flag that determines, which path should be deleted. This IE is useful to notify the precursors, that the requested transmission mode is unavailible, while the backup path may be used instead. On the other hand in a situation where a link breaks completely, the node generates a standard PERR to invalidate all paths towards the precursors along its way. To ensure reliable transmission of PERR and PPERR IE, the containing frames are sent using STC for broadcasts and BF for unicasts.

Figure 6.7 shows an example situation for the PPERR meshanism. Node S sends data to D using MUX via intermediate node A. As D moves away, the BER of the MUX link increases. After multiple consecutive losses A closes the MUX peer link to its neighbour D. Also A generates a PPERR, because the BF link to D persists as it is influenced less by increasing distance. The PPERR contains D as unreachable destination and is sent to its precursor S. Upon receiving the PPERR, S deletes the specified MUX path to D only. Now S can fall back on using its BF path and perform a path discovery for MUX later. This scheme avoids the queueing delay inferred, when no path is availible.

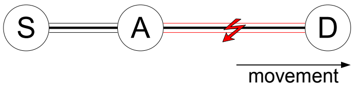


Figure 6.7: PPERR Example Scenario

6.4.4 Frame Forwarding

If a node starts or forwards a data packet within the mesh, it looks into its path table to get the MAC address of the node, which is the next hop along the way towards the packets destination. In MHWMP the procedure differs, whether the node is starting or forwarding the frame.

If a node starts a frame, a path lookup is performed in BF and MUX path table. The following conditions may occur:

a) neither BF nor MUX path are availible
   In this case the node sends a PREQ for resolving a MUX path, and queues a BFPREQ for resolving a BF path. Meanwhile the data packet is queued until either path is availible. Sending both path requests back to back is vital, since in case of a partitioned network the BF path could be the only possibility to reach the destination, while in a close neighbourhood to the destination a MUX path may be resolved with minimal delay.

b) only one path type is availible
   In this case the node uses the availible path together with the respective transmission mode for frame forwarding. Afterwards it tries to establish a backup path to the destination with the corresponding path request IE. If these requests keep unanswered, e.g. due to a sparse network, the node repeats the attempt with respect to the limits described in the 802.11s draft ([4] 11C.10.5.5).

c) both entries are availible
   In this situation the paths are compared by their common airtime metric. The path with better metric is used together with the corresponding transmission mode. In case of equal metric values, the BF path is chosen to reduce interference.

If a node has received a data frame not addressed to its MAC address, it forwards the frame on behalf of another MP. In this situation the processing is different:

a) neither BF nor MUX path are availible
   The 802.11s draft provides different possibilities for the case, that no path is found to the destination of the mesh data frame ([4] 11C.7.5.2.2). In the current MHWMP implementation a PERR is broadcasted using STC, which traverses the path back to the sender of the data frame and deletes all corresponding path table entries. If needed, the source performs a new path discovery as described in section 6.4.2.

b) only one path type is availible
   When the intermediate node only contains either one of the path types, it silently forwards the data frame using the availible path and transmission mode without notifying the source. This is crucial, since the protocol in some cases relies on this behaviour (e.g. in figure 6.7) and many nodes along a path notifying the source would cause a flood of management frames blocking the mesh.

c) both entries are availible
   The same procedure is performed as in the node that started the mesh data frame. This can lead to a situation, that while the starting node used one mode, an intermediate node chooses the other. Since these decisions rely on the airtime metric, which reflects multiple channel parameters, the path chosen has optimal properties for frame forwarding. This is for example used by node B in figure 6.8. Since only the BF path is able to bridge the long gap between A and B, A will choose BF transmission mode. But upon receiving a data frame to D, B has the opportunity to choose the MUX path, even though it received the frame from A using BF. This is beneficial, since due to the higher data rate of MUX the end to end delay and channel occupation is reduced.

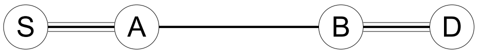


Figure 6.8: Example Scenario for Partition Bridging

7 System Model

7.1 The Network Simulator ns-3

The central simulation tool used to verify the amendments presented in this thesis is ns-3; the open source 'network simulator' in its current version 3.8. ns-3 is a decendant of the famous ns-2 simulator. It has been developed since July 2006 [77] as part of the INRIA Planete research group work on implementing an IEEE 802.11a/e MAC model for the ns-2 simulator [78] and was released in June 2008. Like most simulation software suites it is a discrete event simulator, where events are scheduled and processed on a discrete timescale. Its main field of application lies in the academic environment in the simulation of ad hoc wireless networks.

The network simulator is an open source project for simulating network environments, either cable-connected or wireless. The project is licensed under the GNU general public license version 2 and is availible for use and participation at `www.nsnam.org`. Unlike its predecessor ns-2, which was written in a mixture of C/C++ and the scripting language OTcl, ns-3 is completely realized in object oriented C++. This enables high performance simulation as well as easy code extension and reuse. Python is used for the integrated build system, which handles compilation and linking as well as passing command-line arguments. At the time of writing ns-3 provides no native GUI for simulation design. Instead simulations are prepared in a C++ source code file, where the nodes and their network stack are created and interconnected using the provided classes. For extracting information from the simulation run, callbacks from the network stack classes into the users simulation source code, called trace sources, are used. These trace sources contain different information about the current simulator status and network parameters. In the user simulation code these informations may be processed for statistics or visualization.

7.1.1 Benefits and Drawbacks

ns-3 provides detailed models for various network protocols. TCP/IP is modeled for transport/network layer, while different MAC/PHY specifications are availible such as IEEE 802.11, Ethernet, Point to Point and WiMax. For 802.11, ns-3 implements a MAC and a PHY layer according to the 802.11a specification. For channel modeling the YANS channel model [78] is used. Most crucial for the use in this thesis is the complete implementation of the IEEE 802.11s model, which is used as basis for the presented protocol amendments.

A drawbacks of the ns-3 simulator is, that it is currently lacking some aspects of wireless communication, which are albeit needed for the implementation of MHWMP.

First, ns-3 is lacking a suitable channel and PHY model, since the employed IEEE 802.11 channel model includes neither multipath and fading effects nor BF, MUX and diversity transmissions. For these aspects workarounds were used, because the implementation of an accurate PHY model, as for example the IEEE task group N channel model [79], would exceed the scope of this thesis. Instead the already implemented IEEE 802.11a channel model of ns-3 is employed and extended as described in section 7.2.1. This channel model provides an omnidirectional LOS Friis propagation model [78]. Therefore multipath effects such as fading and variable MIMO SNR due to signal separation problems in LOS channels are not taken into account.

ns-3 does not provide a MAC layer model capable of directional channel access. Since these model aspects are vital for the simulation of MHWMP, these features were implemented in the ns-3 wireless stack. Thus the amendments of DMAC, DNAV and MAC-controllable receiver-side BF as described in 5.1.1 are employed. The implementational changes needed therefore are outlined in section 7.2.2.

Ns-3 contains a model of the IEEE 802.11 MAC, which implements both IEEE 802.11 DCF and IEEE 802.11e EDCA channel access schemes. Unfortunately the IEEE 802.11s model uses DCF channel access procedures, instead of EDCA as defined in the draft ([4] 9.1.3.1). Therefore the amendments of IEEE 802.11e, such as TXOP and channel access according to QoS priority are not implemented, which result in increased channel access overhead for all communications and missing channel access priorisation for QoS data.

7.1.2 The ns-3 Mesh Stack

With respect to the protocol amendments presented in this thesis, the mesh and wireless models implemented in ns-3 are in focus. An overview of the transmit/receive path of the IEEE 802.11s model in the simulator implementation is depicted in figure 7.1.

A packet or stream of packets is created by a simulated application and forwarded to the MeshPointDevice class. This class hands the packets to the HwmpProtocol class, where the routing and path discovery functions of HWMP are implemented. This class looks up the next-hop address, needed to forward the packet to its destination, and stores this information in a HwmpTag. A packet tag is a block of information which is appended to a packet without changing the content and size of the simulated packet. Hence it does not influence the simulated network itself or the simulation results. After adding the tag the packet is handed down the protocol stack and the IEEE 802.11s mesh header is added in HwmpProtocolMac with the next-hop address given in the HwmpTag.

The packet is then headed to the DcaTxop class and enqueued in WifiMacQueue. The DcfManager class handles channel access and manages different packet queues with respect to QoS classification. These are represented by multiple DcaTxop and their corresponding WifiMacQueue classes. This is depicted more detailed in figure 7.2. Note here that DcfManager and DcaTxop classes correspond to DCF channel access procedure, thus all queues use the same backoff timings. Priorisation is concerned only if two queues are granted channel access at the same time internally. After the packet is enqueued, DcfManager will monitor channel conditions, NAV and the backoff timers. If the backoff timers are expired and neither physical nor virtual carrier sensing indicate a busy channel condition, the packet is dequeued and handed to MacLow class. It is noteworthy here, that ns-3 does not employ a polling scheme for checking the backoff timers. Instead for reduced computational complexity, the remaining duration is calculated and an event is scheduled.

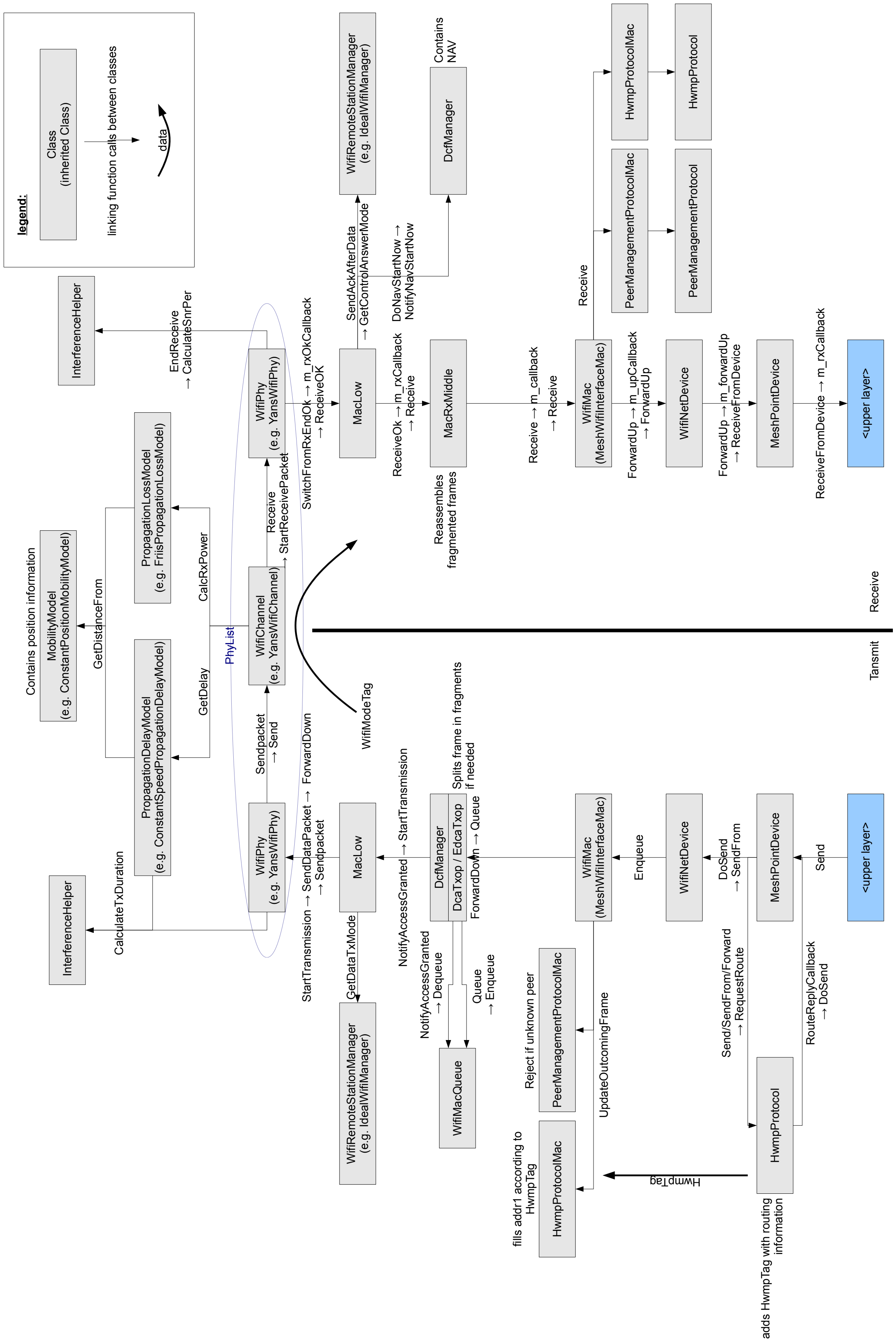


Figure 7.1: Unmodified ns-3 Transmit/Receive Path

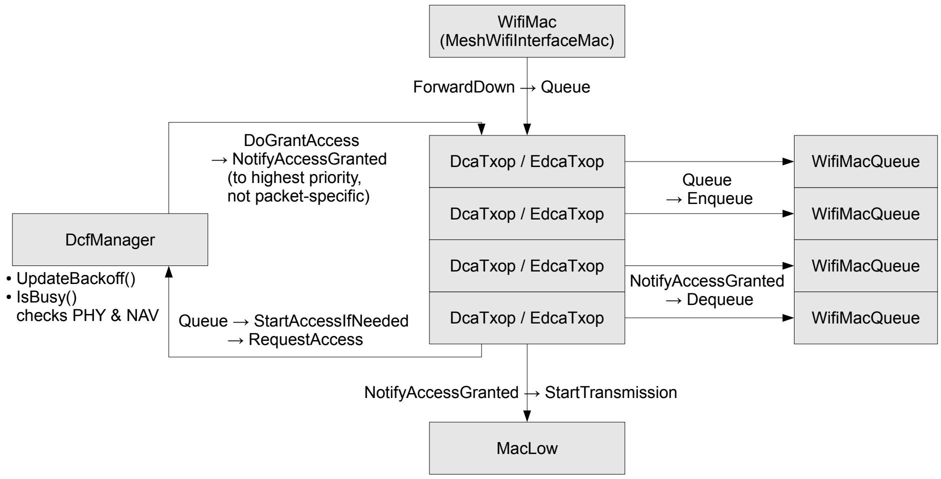


Figure 7.2: ns-3 Channel Access in Detail

The MacLow class will perform an RTS/CTS exchange prior to the actual packet transmission, if this is requested by the WifiRemoteStationManager or its derived classes. These classes employ the rate control algorithms. In ns-3 there are multiple rate control implementations, all derived from the base class WifiRemoteStationManager. Examples are an algorithm for constant rate or an ideal rate control algorithm. 'Ideal' in the sense that it employs knowledge about the SNR as received by the communication partner. After choosing an appropriate transmission rate, this information will be stored in a WifiModeTag which is appended to the packet, before the packet will be handed to the YansWifiPhy class. MacLow also handles all timers for ACK and CTS transmissions as well as the timeouts for unsuccessful tranmissions. Notifications of successful and errorneous transmissions are handed to the corresponding classes.

The class where all simulated nodes are linked is YansWifiChannel. A transmitted packet is forwarded to all YansWifiPhy classes of all simulated nodes with respect to propagation delay and power loss according to [78].

As ns-3 is a time-discrete simulator, the receive process in YansWifiChannel consists of two steps. At the receive process start it is checked, whether the PHY is currently in a state, able to receive a packet and the incoming energy is higher than a threshold. If these conditions are positively met, the receive process begins. Until the receipt end any other incoming transmissions are rejected and noted as interference according to their power and duration. The transmission duration is calculated in the InterferenceHelper class with respect to the frame length and data rate. After this time the receive process is finished. Now the InterferenceHelper class is called to piecewise calculate the frame SNR and finally the error rate of the complete frame. This value is compared to a random value, deciding whether this frame will be reported as successful or errorneous. This implementation provides a statistical packet loss with respect to received interference, frame duration, modulation and rate. As mentioned earlier, the YansWifiPhy, YansWifiChannel, PropagationDelay, PropagationLossModel and InterferenceHelper classes are implementations of the YANS wifi model as described in [78].

In case the packet was received successfully, it is handed up from YansWifiPhy to MacLow, where an ACK (or CTS in case of a received RTS and idle channel) is scheduled and the NAV is set according to the duration value specified in the received packet. MacRxMiddle handles packet fragmentation before forwarding it to MeshWifiInterfaceMac. This class serves as interface for multiple mesh or ad hoc protocols. In the case of IEEE 802.11s mesh, it handles the received frame to the PMP and HWMP classes, which only react, if the received packet is a corresponding management frame. Otherwise the packet will be handed up towards the receivers applications.

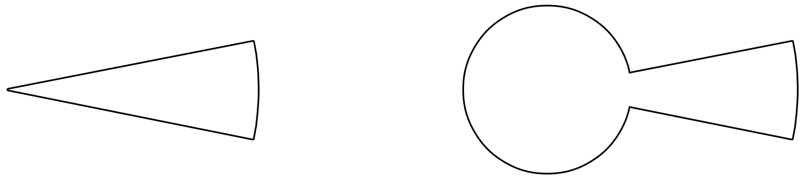
7.2 Simulator Amendments

This section covers the amendments to ns-3, which have been incorporated into the ns-3 source code to simulate the MHWMP protocol. A graphic overview about the source code changes is given in figure 7.3 in contrast to the standard implementation previously illustrated in figure 7.1.

To simulate MHWMP in ns-3, the first general problem was the distribution of antenna mode information to the different stack classes. This problem is solved by using the tagging system of ns-3. As mentioned earlier, packet tags are blocks of information appended to a packet, which are only used internally and do not influence the simulated network. Therefore a new tag 'SmartAntennaTag' is created to carry transmission mode information, including antenna mode, transmission direction, antenna opening angle and receiver-side SNR. This tag is appended to each packet and used to trigger a specific transmission mode and directivity in a per-packet fashion. Upon receipt the tag is updated with receiver SNR and incoming direction. It is stored in the HWMP path table for each next-hop entry.

7.2.1 PHY Model

The antenna model of this thesis is used to model the properties of a UCA as described in section 4.2. Therefore the the idealized- or 'stencil beam' antenna model is used for BF transmissions and receptions, which is illustrated in figure 7.4a. Although this model looks very simplistic, it models the properties of the adaptive BF antenna quiet well with low complexity. On contrary to the commonly used keyhole antenna model opposed in figure 7.4b, this model also covers the ability to avoid interference completely by pointing nulls at interfering signals. Further it is assumed, that the degrees of freedom are higher than the number of concurrent interferers. Since nulls cannot be formed in close proximity to the main beam, a beam width of 15° is predefined. While nulls are assumed to be pointed at neighbours upon transmitting, sidelobes are assumed to be negligible small and thus not further modeled.



(a) Stencil Beam Antenna Model

(b) Keyhole Antenna Model

Figure 7.4: Comparison of Directional Antenna Models

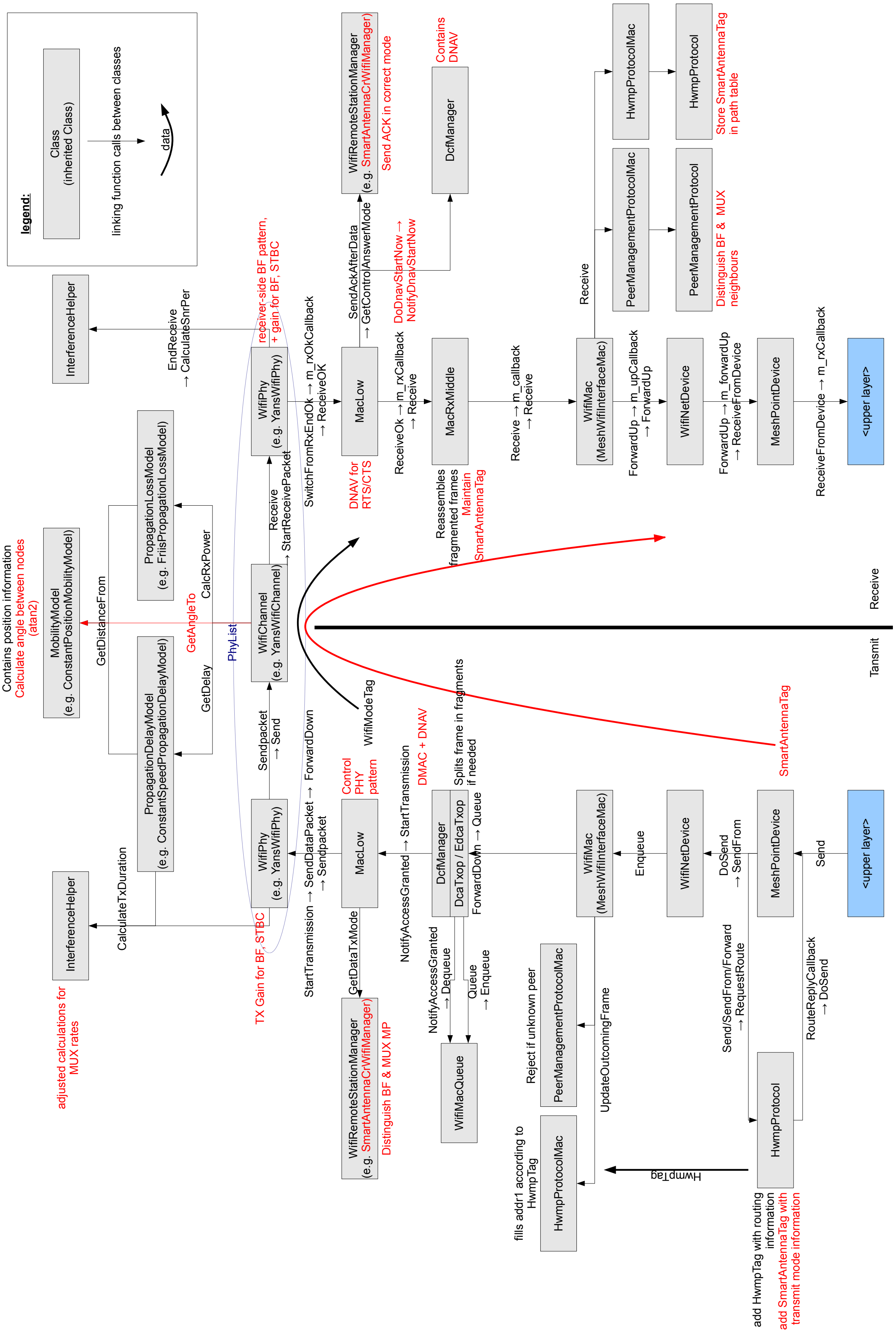


Figure 7.3: Modified ns-3 Transmit/Receive Path

As mentioned in the previous section, in the standard ns-3 implementation all nodes associated to the YansWifiChannel class are notified after tranmission of a packet. For MHWMP this behaviour is modified to reflect the stencil beam antenna model. Thus the nodes position and their current antenna settings are examined, to decide whether it is able to receive an incoming transmission or not. For examining the position, the MobilityModel class is used and extended to calculate the resulting angle to each other.

The aspects of BF antenna gain as well as diversity gain were modeled with an increase of transmission and receiption gain for transmissions tagged as BF or STC. Upon transmission the antenna gain of both modes is increased by 4dB in YansWifiPhy. According to $G_{res} = (\sqrt{G_{TX}} + \sqrt{G_{RX}})^2$ [11], if the receiver PHY points its antenna in the direction of the incoming signal, the signal power is increased by 16dB overall. To maintain the same range for BF and STC, the same gain as for BF is applied to STC transmit and receipt, while maintaining its omnidirectional characteristics.

The MAC-steerable receiver-side BF capability is implemented with functions called by YansWifiPhy and MacLow, while the latter is priorized and may lock the antenna in a specific state. These states are BF in a specific direction or omnidirectional listening. These antenna states are locked by MacLow at the beginning of a frame exchange and unlocked after a success condition or after a timeout indicating a communication failure. If the antenna setting is not locked by MacLow the PHY may point the antenna at incoming signals freely.

The aspects of a MUX transmission were modeled with an increase of data rate over a link. Therefore if a transmission is tagged as MUX, the duration calculated for this transmission in InterferenceHelper class is reduced by factor 4, as 4x4 MIMO using VBLAST scheme is assumed (see section 4.6.1). This influences multiple aspects of the protocol stack, like the resulting transmission data rate and metric calculation.

In real life systems, antenna weights are calculated to transmit and receive signals according to the current transmission scheme. Since these aspects are not covered in the apllied PHY model, the weight calculation is skipped.

7.2.2 MAC Model

Initial tests of the changed simulator showed, that BF communication is critically prone to collisions, if no directional channel access procedure is applied. Therefore the shared medium channel access procedure described in section 6.2.2 is implemented. The DNAV implementation replaces the standard NAV, which only consisted of timestamps of channel usage start and duration. The DNAV is implemented as a list, where information about neighbours channel access is gathered. The informations from RTS/CTS and data frames are noted here with MAC address, start and duration timings, DoA and an ID. The ID is used to delete a RTS entry, which was not acknowledged with a CTS or a transmission did not start according to the IEEE 802.11 standard ([3] 9.2.5.4). The ID is also used to link corresponding RTS and CTS, to determine when a node is placed right in between of a neighbours transmission. Expired timers are removed from the vector while new ones are appended.

Two sources of information are used to check whether a queued packet transmission conflicts with current DNAV entries. First before sending a packet it is examined for the requested transmission mode and directivity. Therefore functions are implemented to examine the top packet of a queue. It should be noted here, that this feature may be implemented imperfectly, as it is difficult to determine the transmission mode of a future packet, when the current channel access queue is empty. Second the modified PMP provides information about the number of neighbours in a specified direction and whether a DNAV entry represents a MUX or BF neighbour (see section 6.3). Based on these informations DcfManager class decides whether a packet may be currently sent or not according to the rules defined in section 6.2.2. Based on this decision the packet is handed to MacLow for transmission or an internal collision is performed, delaying the current queue and its packets.

The rate control algorithms are modified to enable separate handling of the different transmission modes. SmartAntennaTag information is used to decide whether a RTS/CTS exchange should be performed. To model the DMAC notification scheme described in 6.2.2, this is configured to schedule RTS/CTS before every BF transmission.

Different transmission statistics and rates to a specific neighbour are stored for the different transmission modes, so for example a high frame error rate in MUX mode do not influence the rate and metric chosen for the same neighbour with BF. Two specific rate control classes are modified accordingly: a constant rate control algorithm, which uses fixed rates for each transmission mode, and an ideal rate control algorithm, which chooses ideal rates for each transmission mode and neighbour independently. For all simulations in chapter 8 the ideal rate control algorithm is used.

An important task of the MAC layer is to send ACK for successfully received unicast frames. Therefore MacLow is extended, to send the ACK using the same transmission mode and direction as the received packet. MacLow also sets the broadcast transmission mode of the RTS/CTS according to the following data frame.

Also the procedures after receipt of an ACK or a missing ACK, which correspond to a successful or unsuccessful transmissions, are extended to support multiple transmission modes. In case of a missing ACK for MUX transmissions only the variables counting the frame error rate of MUX transmissions to the respective neighbour should be increased. This is vital, since a loss of MUX frames often does not represent the quality of BF transmissions to the same neighbour. In ns-3 the state of communication partners is monitored in the rate control algorithm as well as the PMP, which are both modified accordingly.

7.2.3 Peer Management Protocol

Beaconing is extended to alternate between sending beacons with STC transmission mode and beacons sent using SEL. Since the receipt of these beacons triggers the handshake functions, it causes the PMP to fill two separate neighbour tables: a beacon received with SEL triggers the process for setting up a MUX neighbour, while a beacon received with STC adds a BF neighbour. The peering frames are sent using the corresponding transmission modes, with one exception: STC instead of BF is used for unicast PMP frames. This workaround had to be used, since in the simulations all the nodes start beaconing almost at the same time, which causes many deafness and collision problems in highly populated networks. This is only a workaround for the simulation, since in real life networks nodes do not wake up and start beaconing at the same time.

Also functions are added to the PMP for extracting information about neighbours in a specific direction and for distinguishing, whether a neighbour is a MUX neighbour or a BF neighbour. These functions are employed for DMAC channel access and metric calculation.

7.2.4 Routing Model: MHWMP

For implementing of the core routing aspects, first the path table is extended to contain multiple routes to a single destination for the different path types. This approach is equivalent to two different path tables for BF and MUX, except for an additional transmission mode field for each path table entry. In standard ns-3 the STL container 'map' is used for the path table. This type is exchanged by 'multimap', since map has a unique association between a destination MAC address and a path. Multimap is able to store multiple routes associated to a single destination MAC address. The results given by the first lookup by MAC address then have to be re-checked for the correct transmission mode.

In the HwmpProtocol class an optional path maintenance interval may be specified. This triggers a path discovery for a specific path and transmission mode, if a path is older than a given threshold.

For path discovery a different behaviour upon receipt of PREQ and PREP as well as BFPREQ and BFPREP IE with multiple metrics is implemented. The path discovery is performed as described in section 6.4.2. Therefore different functions are implemented for PREQ and BFPREQ as well as PREP and BFPREP respectively. Also each node may be configured to be a mesh root node. But since this feature is not used for simulations, no specific settings for the transmission mode of the proactive path discovery procedures are implemented.

For the new IE BFPREQ and BFPREP two new wifi IE classes are created with new unique identifiers. The new information elements are structured equal to standard PREQ and PREP, besides they contain two metric fields. According to the identifiers, these information elements are handled in differerent functions. For path errors, which only influence one path type, a special PPERR information element is created. This PPERR has the same structure as a standard PERR with an additional flag. This IE triggers the removal of paths to unreachable destinations, indicated by the contained list of MAC addresses. The additional flag decides, whether to delete the BF path or the MUX path. A standard PERR triggers the removal of both path types. As mentioned in section 6.4.3, management frames containing PERR or PPERR IE are broadcasted with STC.

For unicast data packets a path table lookup is performed in both path tables as explained in section 6.4.4. The resolved path then decides the next hop as well as the to-be used transmission mode. Both informations are added to the packet in the form of the respective packet tags: HwmpTag and SmartAntennaTag. These tags are read in the following classes to set the mesh header addresses and define the to-be used transmission mode and directivity.

7.2.5 Collecting Simulation Data

For collecting simulation results own classes are created for gathering data through the use of ns-3 standard and new trace sources. This data includes for example:

- visualisation of multi-hop packet traces through the mesh
- packet success/loss statistics
- throughput
- end-to-end delay

- path table contents
- data rate chosen by the rate control algorithm

These classes, called DataCollectors, are defined in the simulation scenario file and instantiated together with the simulation model instances they are connected to. This means for example that an application pair is defined for two nodes with the respective ns-3 classes and a corresponding DataCollector is instantiated, which monitors this data stream. During the simulation runtime these classes receive callbacks from the simulator classes and annotate various state variables and properties in own lists. After the simulator run has finished these lists are analyzed and output is written to measurement files containing plot data in *.csv format (comma-separated-value). Also corresponding gnuplot scripts are generated to immediately create plots. Through the use of these DataCollectors, creating new simulation scenarios and extracting information is made easy. This also beneficial for scripting to schedule multiple simulator runs with different parameters given with commandline arguments.

8 Results and Discussion

In this chapter the performance of MHWMP will be compared and evaluated. To show the benefits and drawbacks of MHWMP, different topologies and traffic characteristics are applied in the following simulations. In the first section 8.1 simplistic scenarios are used to show selected benefits of MHWMP. The following section 8.2 covers random network scenarios to show the performance of MHWMP in more realistic network topologies.

To show the benefits, the obvious idea would be to compare the results of MHWMP against a standard IEEE 802.11s implementation without smart antenna features. This would be a very uneven contest, as both increased range and data rate of MHWMP would allow higher throughput compared to its counterpart in all situations. To get a more even comparision, different contestants have been chosen: O-MUX and O-BEAM.

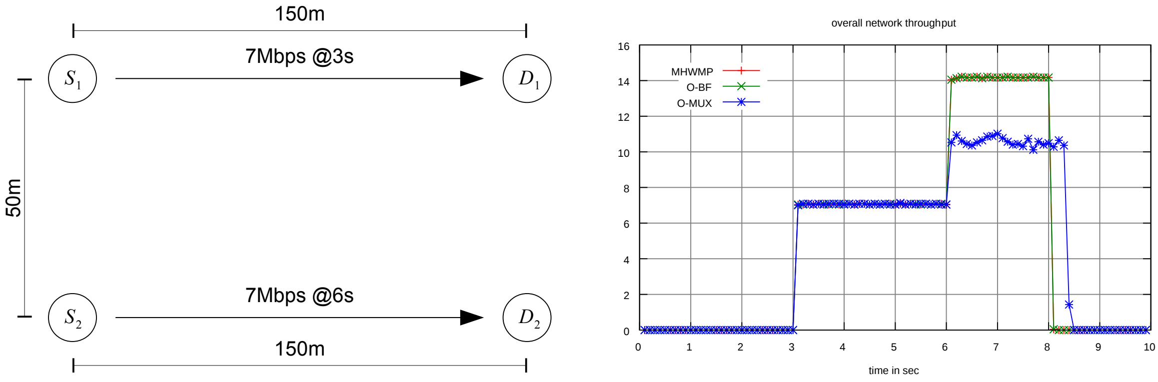
O-MUX is a standard IEEE 802.11s implementation, which uses the smart antenna feature of MUX transmission mode for all its transmissions. Thus O-MUX is able to provide higher throughput with unchanged range. Also this ns-3 implementation has been slightly modified, fixing known bugs and adding trace sources for obtaining the same simulation data as from MHWMP.

The second protocol variant O-BEAM is a modified version of MHWMP, which is restricted to use BF transmissions only. Therefore all features of MHWMP are implemented, without the dual mode aspects of path table, neighbour table and rate control. Also the standard airtime metric is used for all routing aspects instead of the DAM.

These contestants are used to compare the performance of MHWMP with mesh protocols that only use one aspect of smart antennas. Thereby it is examined whether MHWMP satisfies the core aspect of this thesis; to combine multiple smart antenna features in a single protocol.

8.1 Simple Scenarios

8.1.1 Parallel BF Transmission Scenario



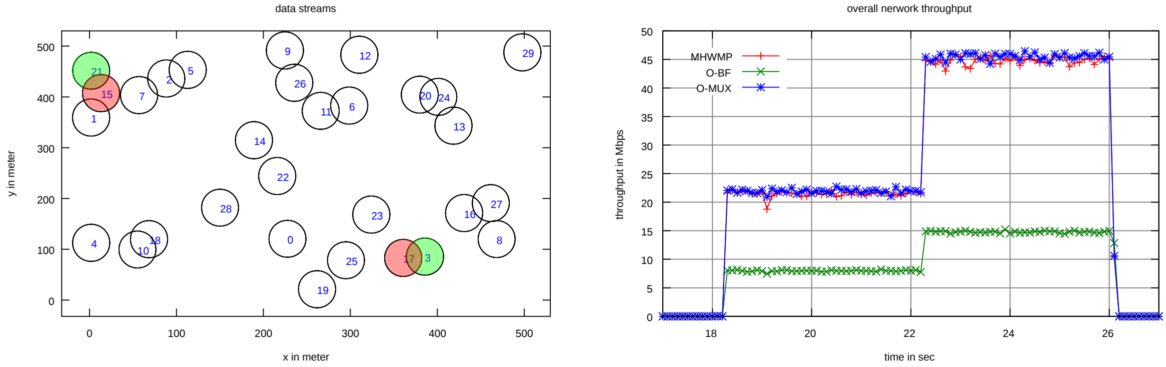
(a) Topology (b) Throughput

Figure 8.1: Parallel BF Transmission Scenario

The scenario shown in figure 8.1 shows the benefits of interference-free parallel communications in MHWMP and O-BF compared to the omnidirectional transmissions of O-MUX. The first data stream starts generating UDP data at 3s. At 6s a second data stream starts in parallel to the first in a distance of 50m.

All protocol variants are able to handle the transmission of 7Mbps over the distance of 150m for the first stream. The start of the second stream at 6s adds a source of interference for omnidirectional transmissions. Thus for O-MUX the interference from the other stream together with the low PYH layer data rate for 150m transmission saturate the channel capacity. Thus the overall throughput is less than 2x7Mbps and the data stream needs longer time to transport all queued packets. MHWMP and O-BF use BF transmission mode, thus the individual streams do not interfere with each other. Also due to the increased SNR, a higher PHY data rate may be used, which allows the transport of 2x7Mbps in parallel.

8.1.2 Parallel MUX Transmission Scenario



(a) Topology

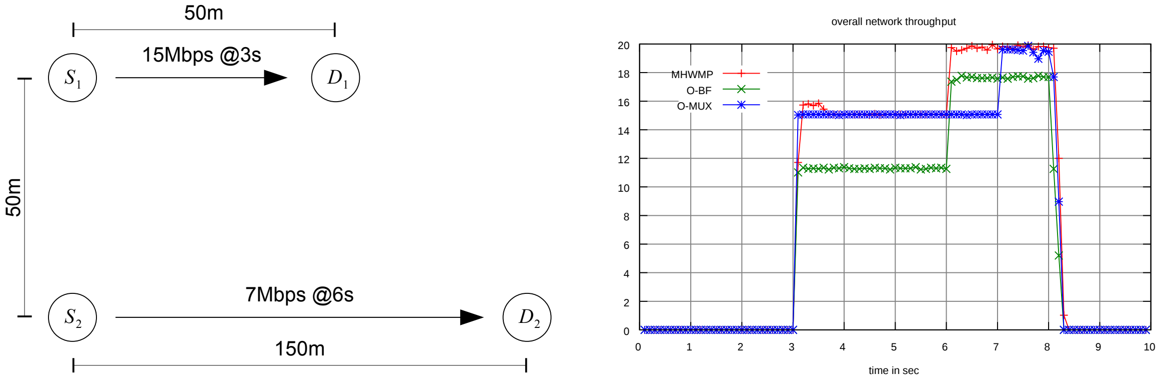
(b) Throughput

Figure 8.2: Parallel MUX Transmission Scenario

Scenario 8.2 shows the benefits of MUX transmission mode, when used for closeby destinations. It uses a different type of traffic generator than the previous scenario. Instead of generating a constant bit rate UDP traffic, this traffic generator uses TCP as transport layer and uses all availible bandwidth for its own data stream. This resembles for example a transfer of a large file in peer-to-peer filesharing. The traffic generator uses information about the TCP transmit buffer fill level: the simulated application fills this buffer as soon as new buffer space is availible after a successful transmission. Two such data streams are placed in the topology. The stream from node 21 to 15 starts at 18s, the other at 22s.

In contrast to O-BEAM the throughput for MHWMP and O-MUX is more than doubled in plot 8.2b. The throughput is not multiplied by four, as the fourfold PHY data rate would make believe, since the MAC layer functions still use the same backoff times, inter-frame intervals and overhead frames. The overall throughput of both streams is almost the sum of both separate streams, since they do not interfere with each other. For omnidirectional MUX transmission mode this is only possible when both streams use individual collision domains, due to the distance between them.

8.1.3 Parallel BF and MUX Transmission Scenario



(a) Topology (b) Throughput

Figure 8.3: Parallel BF and MUX Transmission Scenario

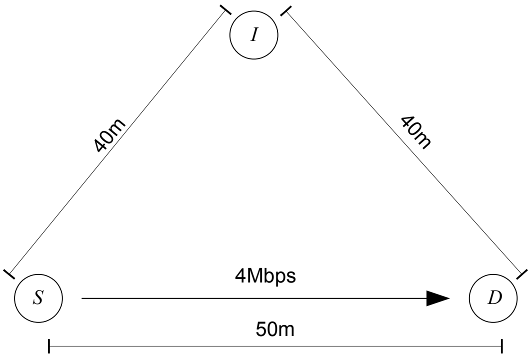
The scenario seen in figure 8.3 shows the benefits of MHWMP compared to O-BF and O-MUX in scenarios with BF and MUX used in parallel. The first data stream from S_1 to D_1 starts at 3s. It generates UDP packets at a data rate of 15Mbps, which have to pass a distance of 50m to the destination. The second data stream from S_2 to D_2 with 7Mbps starts at 6s and traverses 150m.

As visible in plot 8.3b, O-BF is not able to provide a throughput of 15Mbps to a single stream: only 11Mbps are achieved over 50m distance. O-MUX and MHWMP do not suffer from this issue due to their use of high-rate MUX transmission mode.

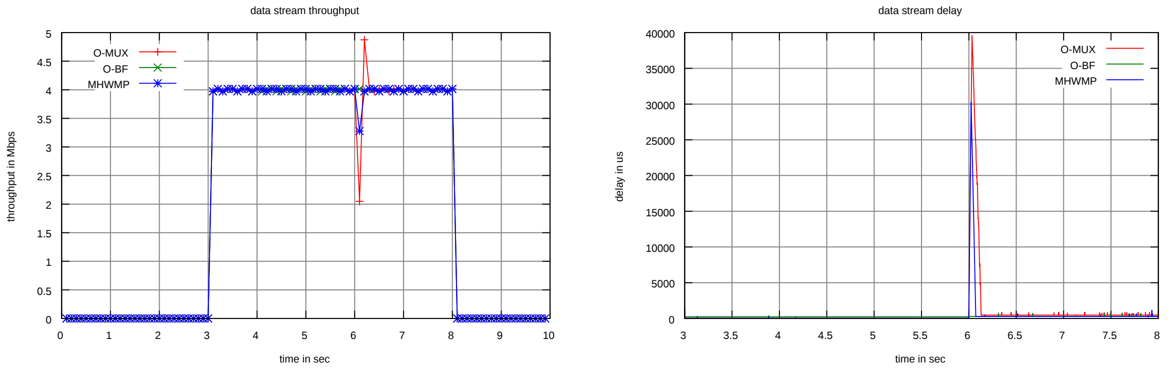
But also for MHWMP and O-MUX the overall throughput is not 22Mbps as expected. For O-MUX the overall data rate exceeds the channel capacity for omnidirectional transmissions, as experienced in the previous scenario. MHWMP is expected to avoid these issues, since the second stream uses BF transmission mode. But due to DMAC issues this possibility of parallel communication is unused. When nodes S_1 and D_1 access the channel with omnidirectional MUX transmission mode, channel reuse through parallel BF transmissions is impaired. This exposed node problem in mixed directional and omnidirectional environments was explained in section 6.2.2. Without these issues, MHWMP is expected to perform better than both O-MUX and O-BEAM.

An interesting effect is visible for O-MUX: the second data stream is delayed and starts only at 7s. This is due to an occasional collision which affected a management frame containing the PREQ. Since broadcast frames are unacknowledged and HWMP limits the rate of PREQ generation ([4] 11C.10.5.5) this delay occurs. This collision only happens by chance for O-MUX, since the other stream generates lots of interfering packets. In MHWMP and O-BF the probability for such a collision is reduced since the nodes employ receiver-side BF, which blocks interference from other directions. Also since two independent path discoveries are performed in MHWMP, the probability of both path discoveries failing due to lost frames is lower.

8.1.4 Fast Recovery Scenario



(a) Topology



(b) Throughput (c) Delay

Figure 8.4: Fast Recovery Scenario

The scenario illustrated in figure 8.4 is used to demonstrate the fast recovery mechanisms of MHWMP through the use of its second path type. As explained in section 6.1, the second path table entry to a single destination serves as a backup path, in case the other paths fails. In this scenario, a sudden worsening of channel quality is scheduled in the simulation. This deterioration is implemented as reduction of SNR with a specific amount at a specific timepoint. At 6s the gain drop is scheduled, which reduces the gain for all nodes by -16dB. This sudden decrease of channel quality is expected to break the link between S and D, which makes it neccessary to find a different path over the intermediate node I.

As visible in figure 8.4b, the throughput of both MHWMP and O-MUX drops measurably. The reason for this behaviour is the detection of link breaks in IEEE 802.11s. A link break is detected, if the number of consecutive transmission failures exceedes a predefined threshold of two. A single transmission failure includes multiple MAC layer retransmissions. This means, that until a link break is detected multiple milliseconds may pass only for transmitting and retransmitting the frames needed to detect the link break. Thus the throughput drops and the frames needed to detect the link break are lost. Throughput and end-to-end delay influenced by the link break are plotted in figures 8.4b and 8.4c. It is visible, that delay as well as the throughput drop are reduced in MHWMP, as the packet stream continues without a forced path discovery procedure. It is also noteworthy, that without the intermediate node I, the data stream of O-MUX would be interrupted completely, as no new path may be established over this link due to the worsened channel condition.

8.2 Random Network Scenarios

In the following WMN scenarios 30 MP are distributed randomly in a square area. A random topology is used instead of a more reproducable grid topology, because these topologies are more practical and natural than strict grids. Also in grid topologies multiple MP are placed in line, which is exactly a condition that the DAM is focused to avoid to reduce interference. In these scenarios the paths formed using the DAM would seem irrational and uneffective.

In the following sections three types of network scenarios will be examined: many low data rate applications in section 8.2.1, multiple mid-range data rate applications in 8.2.2 and few high data rate applications in 8.2.3. While the parameter of the first section is the number of source/destination pairs, the parameter of the following two sections is the network footprint size. Due to the random topologies the results of a single specific scenario do not neccessarily reflect the general behaviour of the compared protocols. Therefore multiple simulation scenarios are evaluated and a conclusion of the experienced behaviour of MHWMP is given at the end of each section.

In all following simulations, after the starting time of the last data stream one second is given to stabilise the network. Then the average network throughput and standard deviation is calculated over at least three seconds before the simulation ends. The average throughput of O-BEAM, O-MUX and MHWMP with changing parameters is then compared in a common plot. The standard deviation is given for evaluation reasons. For additional plots and measurement data the interested reader is referred to the attached DVD.

For visualisation, figures of the topology and packet traces are given. Both are depicted in the same aspect ratio as the plots for layout reasons. The network footprint is actually square in all following topologies. A color indicates the data packets path through the mesh. The originator is depicted in green and the packet stream destination in red. In the packet traces additionally intermediates are revealed in yellow. The percentage of the packets that successfully arrived at a node is given in a pie chart fashion and the main packet routes of a stream are marked with a grey line.

8.2.1 Low Rate Applications

In the following section the scale of the network is kept constant, while the number of source-destination pairs is variable. The pairs are chosen pseudo randomly[1], with the constraint that no node is used twice as either source or destination. The pairs of the following scenarios are listed in order in table 8.1. Each data stream generates UDP traffic at the constant bit rate of 2Mbps.

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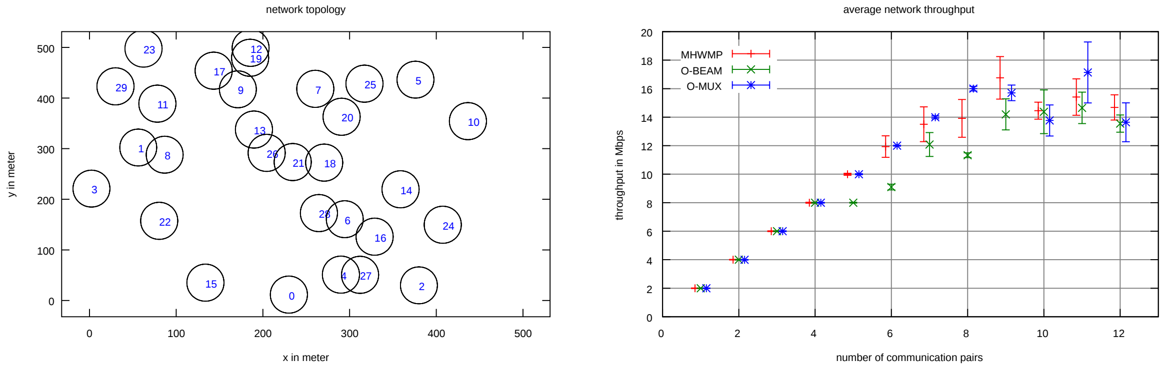
[1] For convenience reasons the random number generator of ns-3 creates the same random numbers for each simulation. This may be avoided by generating random numbers from a given random seed.

This setting is expected to show benefits of MHWMP and its paths formed with the DAM against their O-BEAM counterparts formed with airtime metric. Due to the reduced interference to the other data streams, MHWMP should provide higher overall throughput with high number of forwarding nodes. Also benefits against O-MUX are expected due to MUX saturating the omnidirectional channel capacity.

Stream #	Source	Destination	Starting time
1	9	29	15s
2	16	7	16s
3	4	2	17s
4	22	1	18s
5	13	10	19s
6	23	8	20s
7	14	21	21s
8	27	24	22s
9	20	17	23s
10	11	26	24s
11	19	12	25s
12	25	3	26s

Table 8.1: Data Streams of the Variable Number of Stream Scenarios

8.2.1.1 Low Degree of Clustering Scenario



(a) Topology (b) Throughput 500m

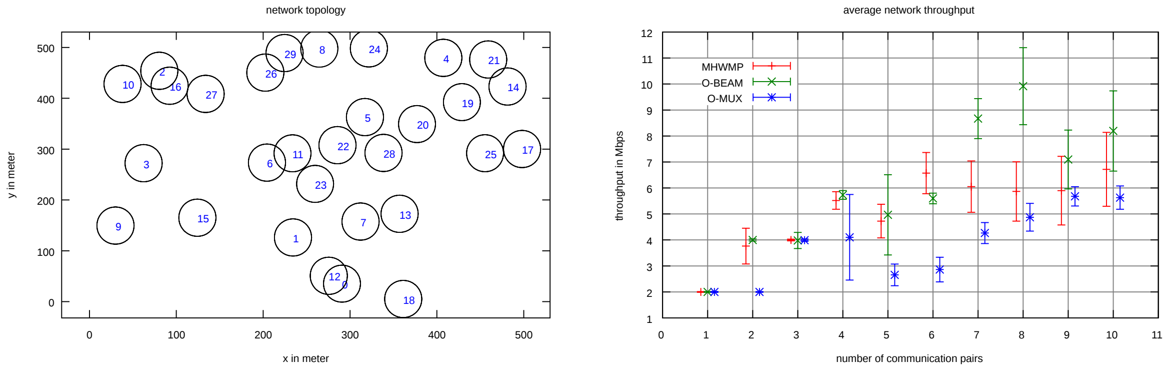
Figure 8.5: Low Degree of Clustering Scenario

The topology of figure 8.5 provides slight network clustering while connectivity of all clusters remains intact and no isolated nodes should occur.

In this topology O-MUX does not suffer from connectivity losses and thus shows the best overall results. Nonetheless the throughput of O-MUX saturates at 18Mbps for 9 data streams. This is due to the omnidirectional interference pattern of O-MUX. Channel reuse might not be possible, if a node in the network center occupies it in this medium sized network footprint.

O-BEAM suffers from drawbacks as the number of transmitting nodes increases, as it does not account for interference avoidance. The interfered area of BF transmissions is genearally smaller, yet if the beams are placed in an unlucky direction, multiple other nodes may be interfered. Because MHWMP actively avoids these situations, the performance is increased compared to O-BEAM. The performace is worse than O-MUX because MHWMP suffers from its DMAC issues in mixed directional and omnidirectional environments, especially under high channel saturation. This problem was explained in section 6.2.2 and previously experienced in scenario 8.1.3: if physical carrier sensing indicates a busy channel, no parallel BF transmission may be established with the current DMAC implementation.

8.2.1.2 Moderate Degree of Clustering Scenario



(a) Topology

(b) Throughput 500m

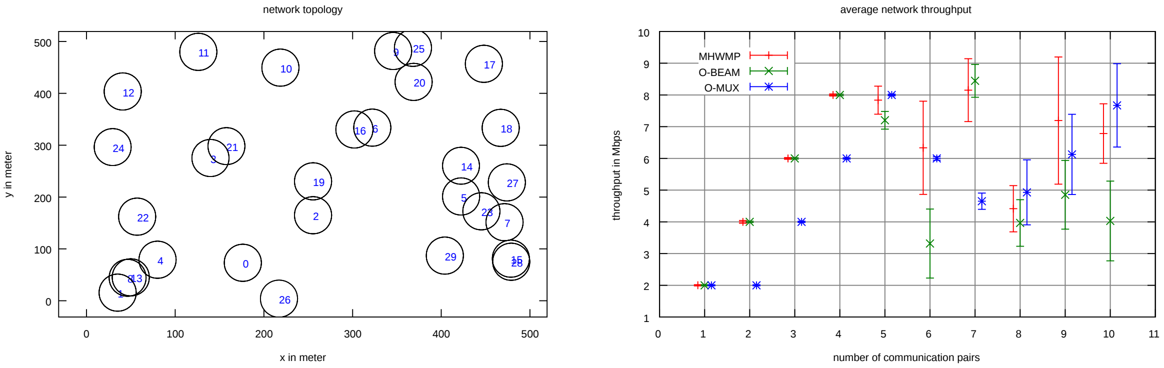
Figure 8.6: Moderate Degree of Clustering Scenario

The topology seen in figure 8.6 shows a clearer partitioning than the previous network. Thus some clusters should be isolated using MUX transmission mode because of its lower transmission range. Also the randomly placed communication partners are further away from each other. The resulting additional number of hops should increase the inter-stream interference.

As expected MUX shows clear drawbacks, since some communication pairs may not establish connectivity. For example the stream from node 16 to 7, which was ought to start as pair number two in plot 8.6b. Since most streams rely on multiple hops and retransmissions that further occupy the channel, the throughput of O-MUX saturates at 6Mbps.

O-BEAM and MHWMP suffer less from increasing distances and show increased throughput compared to O-MUX. The lower throughput of MHWMP compared to O-BEAM is again an issue of mixed mode channel access, since closeby communication pairs often choose MUX transmission. This is clearly visible for stream number seven from 14 to 21: while O-BEAM adds this additional stream to its overall throughput, in MHWMP this stream uses MUX transmission mode, which reduces the availible channel capacity for the surrounding streams. Also the next stream from 27 to 24 uses MUX transmission mode and thus again reduces the overall throughput. Under these conditions the throughput of MHWMP saturates around 7Mbps, which is only slightly higher than the saturation throughput of O-MUX.

8.2.1.3 High Degree of Clustering Scenario



(a) Topology

(b) Throughput 500m

Figure 8.7: High Degree of Clustering Scenario

Topology 8.7 shows a clustered placement and multiple isolated nodes.

As expected O-MUX suffers drawbacks compared to MHWMP and O-BEAM, due to its limited range. For example stream number two from 16 to 7 is not able to connect at all.

For all protocol variants the throughput drops with the start of the stream number six from 23 to 8, as it traverses areas which are in use by at least four other streams. Here MHWMP shows its benefits compared to O-BEAM through its interference-reduced paths. Also with further increasing number of transmitters, MHWMP shows better throughput compared to O-BEAM. The start of stream eight from 27 to 24 has a similar effect as stream six. As it starts in the lower right area, where already multiple previous streams occupy the channel, this stream now oversaturates the medium in this area and reduces the throughput of all affected streams.

8.2.1.4 Conclusion

MHWMP performed well against its contestants in the previous scenarios. It provided good results in scenario 8.2.1.1 and 8.2.1.3. In scenario 8.2.1.2 MHWMP suffered from DMAC issues due to concurrent use of MUX and BF.

MHWMP is beneficial in topologies, where a node sparseness or clustering prohibits connectivity or throughput for O-MUX. Also MHWMP shows benefits with multiple data streams over longer distances, where O-MUX relies on multiple hops. In such a scenario each hop adds to the channel occupation in O-MUX until the channel is saturated and throughput is cut off. MHWMP and O-BEAM need less hops and channel occupation is reduced, since the transmissions occupy different collision domains.

MHWMP was expected to perform better than O-BEAM in networks with many active data streams, as it actively tries to avoid interference to as many nodes as possible. This benefit was experienced in the first scenario 8.2.1.1 and the third scenario 8.2.1.3. But as this ability is not focused on avoiding nodes that are actually busy, this feature gives only a statistical benefit. For example in a situation where the DAM chooses to avoid interference to multiple idle nodes at the cost of interfering one busy node, this feature may become a drawback.

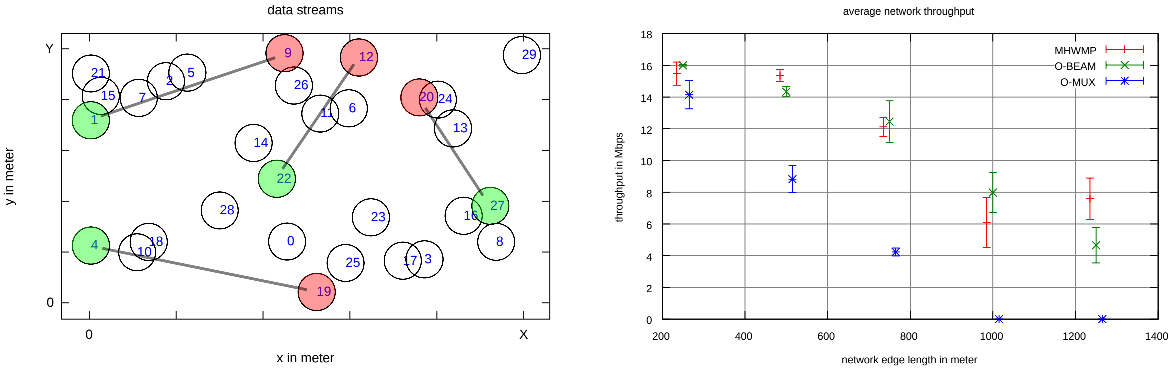
The simulations also showed, that the concurrent use of MUX and BF is problematic in MHWMP: if nodes decide to use MUX, they occupy the channel for the area they cover with their transmissions. This distracts and blocks nodes which could use concurrent BF transmissions and thus removes one of the major benefits of MHWMP. As described in section 6.2.2, the DMAC and DNAV schemes are currently not able to solve this problem. The extent of these effects may also be a result of an imperfect DMAC implementation as described in section 7.2.2.

8.2.2 Moderate Rate Applications

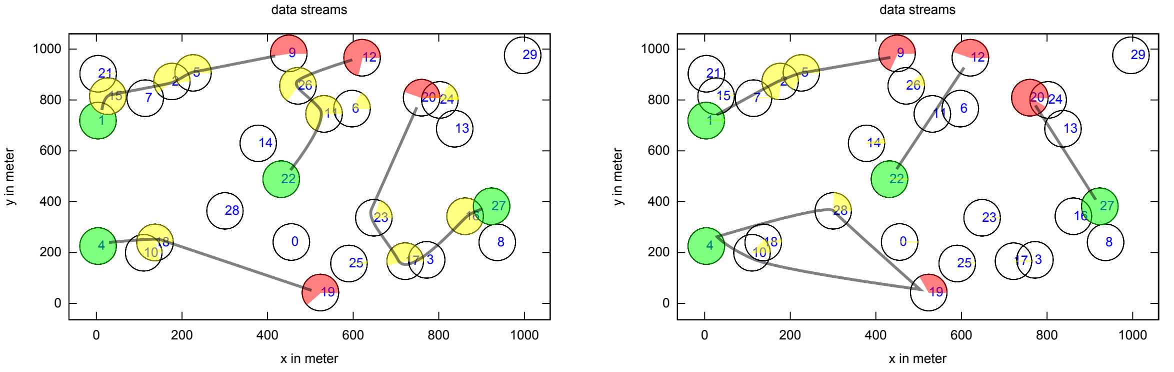
In the following four scenarios four communication pairs are chosen in the random network topology. Each transmits UDP data at 4Mbps to test the protocol variants under multi-hop conditions with moderate data rate. The scale of the network is variable, as the edge length of both x- and y-axis are scaled between 125m and 1250m depending on the scenario. The node placement is constant except for the scaling. The increasing network sparseness is expected to show the benefits of the BF transmission technique in MHWMP and O-BEAM, while O-MUX is expected to suffer from longer paths or node isolation.

While in the first scenario the transmitter-receiver pairs are placed in a fashion, that minimizes inter-flow interference, the following scenarios raise the amount of interference between the data streams. The enhanced paths of MHWMP are expected to provide increased throughput compared to O-BEAM under these conditions. Thus the following scenarios illustrate path choices more detailed, to show characteristics of the paths chosen by the DAM.

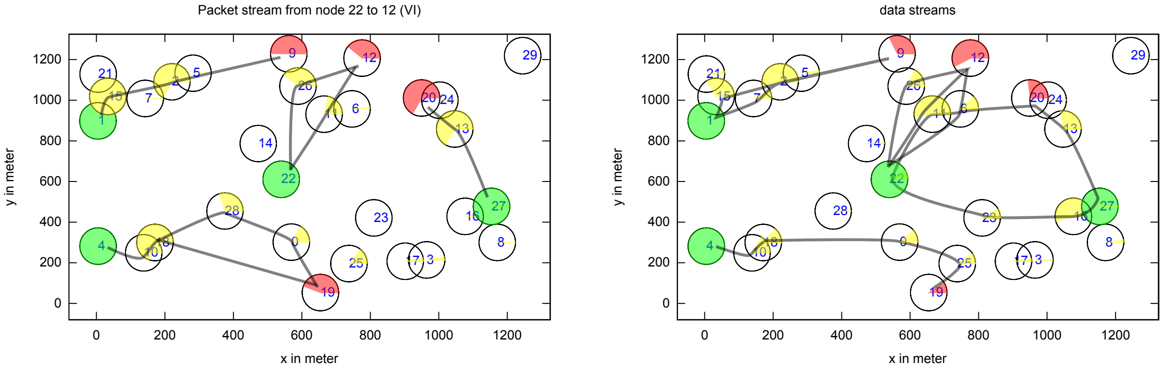
8.2.2.1 Low Inter-Stream Interference Scenario



(a) Topology (b) Throughput



(c) 1000m MHWMP Packet Trace (d) 1000m O-BEAM Packet Trace



(e) 1250m MHWMP Packet Trace (f) 1250m O-BEAM Packet Trace

Figure 8.8: Low Inter-Stream Interference Scenario

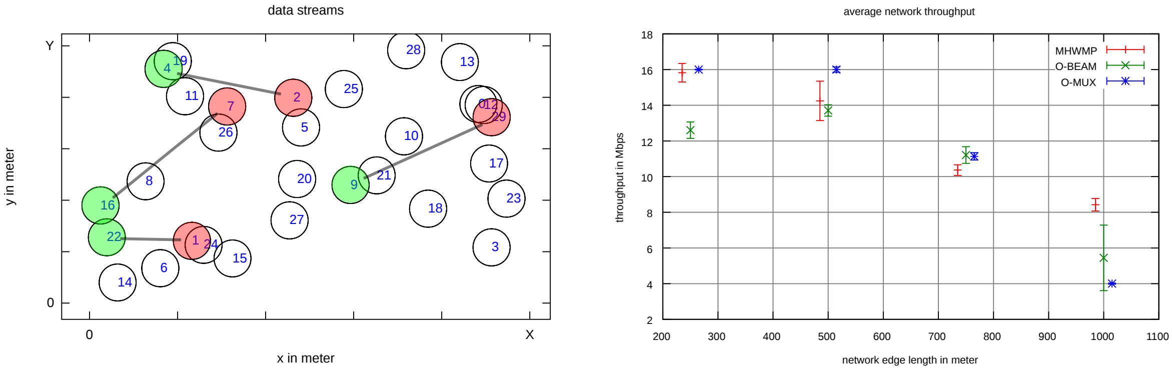
In the scenario depicted in figure 8.8a the transmitters are placed in a fashion, that enables multi-hop paths that should not cause high grades of interference to each other.

As visible in plot 8.8b the three protocol variants perform almost similar in the 250m scale, while the throughput of O-MUX is slightly reduced. O-MUX suffers from channel saturation due to the dense network, which places many transmitters in a single collision domain. With increasing network sparseness the performance of O-MUX drops significantly due to the limited range. Above 1000m network footprint no connectivity of the transmitter receiver pairs is possible anymore.

MHWMP and O-BEAM perform almost equally well with less throughput reduction than O-MUX. In the 1000m scenario MHWMP suffers from its longer, interference-reduced paths compared to the more direct paths of O-BEAM. The comparison of both paths is visible in figure 8.8c and 8.8d. A good example is the packet stream from node 27 to 20. It is visible that MHWMP and its DAM avoid interference to the clusters around transmitter and receiver. But this interference avoidance is achieved at the cost of unoptimal paths with respect to hop count and throughput. Also since the closeby nodes are idle, the effort is in vain.

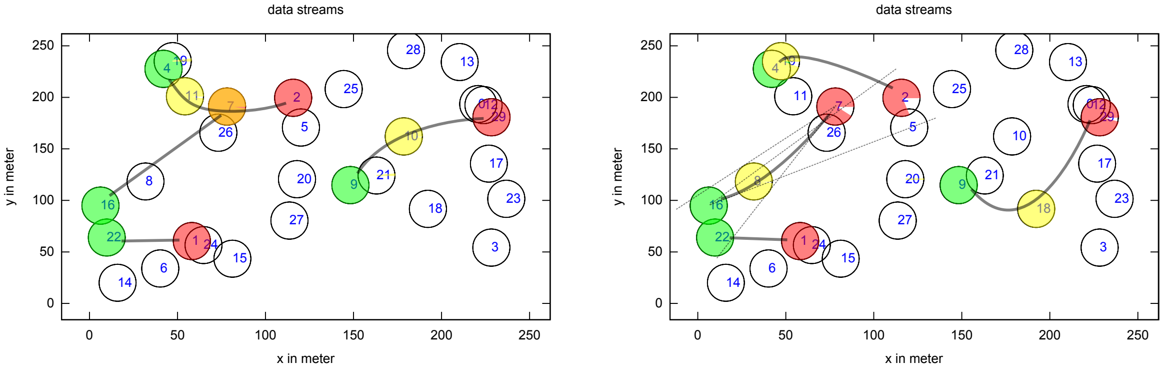
In contrast to the previous scale, in 1250m MHWMP performs better than O-BEAM. This is due to unlucky path choices of O-BEAM. For MHWMP the additional neighbour-factor of the DAM gives more weight on forming short paths with fewer interfered nodes. The airtime metric of O-BEAM prefers multiple high-rate hops to few low-rate ones. This is visible for the stream from node 27 to 20: while MHWMP takes the loss of lower rate over the long hop, O-BEAM chooses an unlucky longer path, which interferes with the stream from 22 to 12.

8.2.2.2 Moderate Inter-Stream Interference Scenario



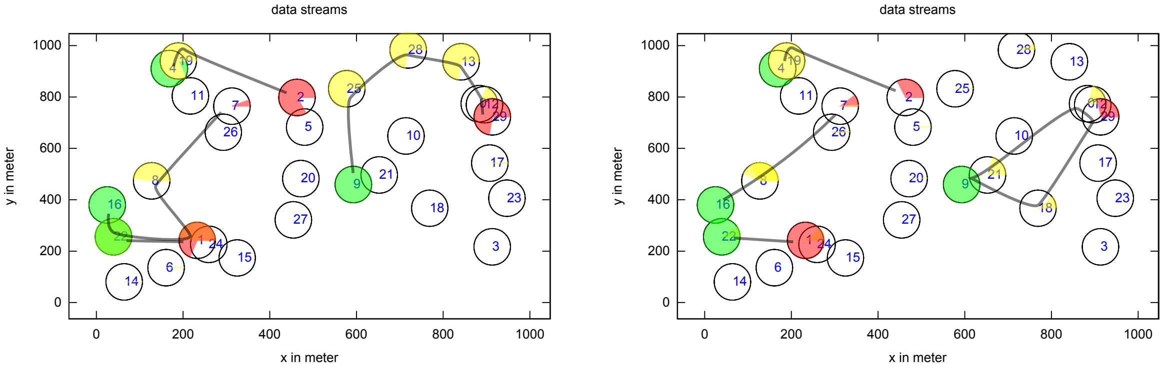
(a) Topology

(b) Throughput



(c) 250m MHWMP Packet Trace

(d) 250m O-BEAM Packet Trace



(e) 1000m MHWMP Packet Trace

(f) 1000m O-BEAM Packet Trace

Figure 8.9: Moderate Inter-Stream Interference Scenario

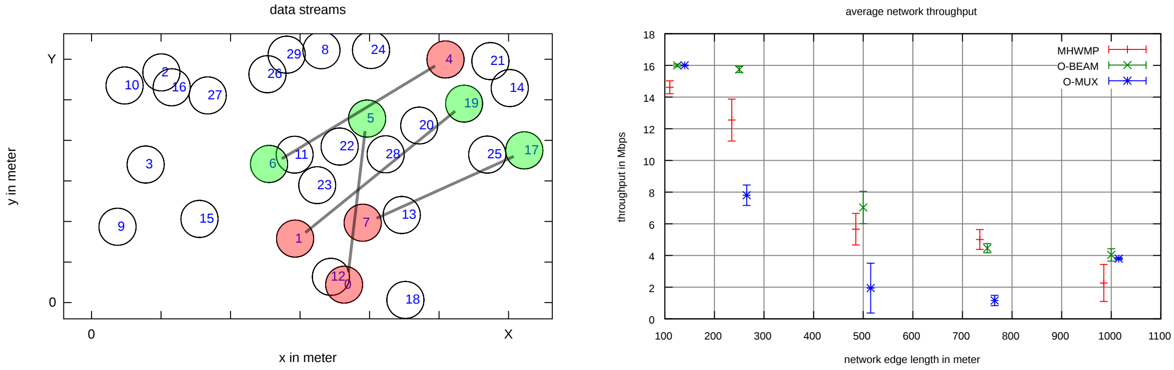
In scenario 8.9f the topology provides distinct routes, which MUX may use to maintain throughput in increased scales. The four transmitter-receiver pairs are positioned to cause increased interference to each other.

In the 250m scale MHWMP uses MUX transmission mode for all paths except 16 to 7 and thus achieves full throughput together with O-MUX. The throughput of O-BEAM is reduced, because of inter-stream interference. The comparision of MHWMP and O-BEAM is depicted in figures 8.9c and 8.9d. It is visible, that the path choice of O-BEAM result in multiple exposed nodes, which causes packet collisions and deafness effects. An exposed node situation is for example, when node 2 is exposed to the transmissions of 16 to 8. In this case it either cannot receive a RTS from node 19, or it cannot answer back with a CTS, since it senses the channel busy.

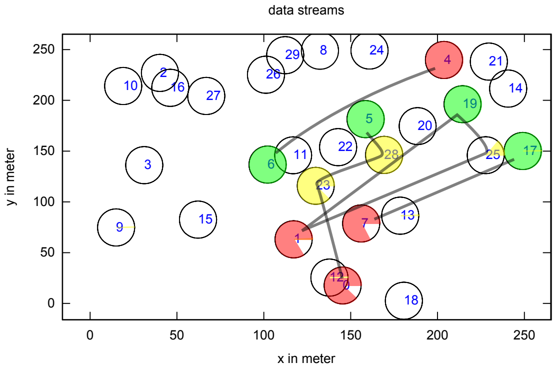
MHWMP uses MUX together with BF in the 500m scale. Again this is problematic, as the BF transmitters are not able to transmit in parallel due to DMAC issues.

In the 1000m scale MHWMP benefits from interference-reduced path choices, as depicted in figures 8.9e and 8.9f. Also scheduling issues of the DMAC implementation may be a reason for the bad performance of O-BEAM.

8.2.2.3 High Inter-Stream Interference Scenario



(a) Topology (b) Throughput



(c) 250m MHWMP Packet Trace

Figure 8.10: High Inter-Stream Interference Scenario

The scenario visible in figure 8.10a is used to demonstrate the performance of MHWMP in a scenario, where communication pairs are close to each other and the paths overlap to a high degree. O-MUX is expected to suffer from the close proximity of the possible retransmitters and the resulting channel saturation.

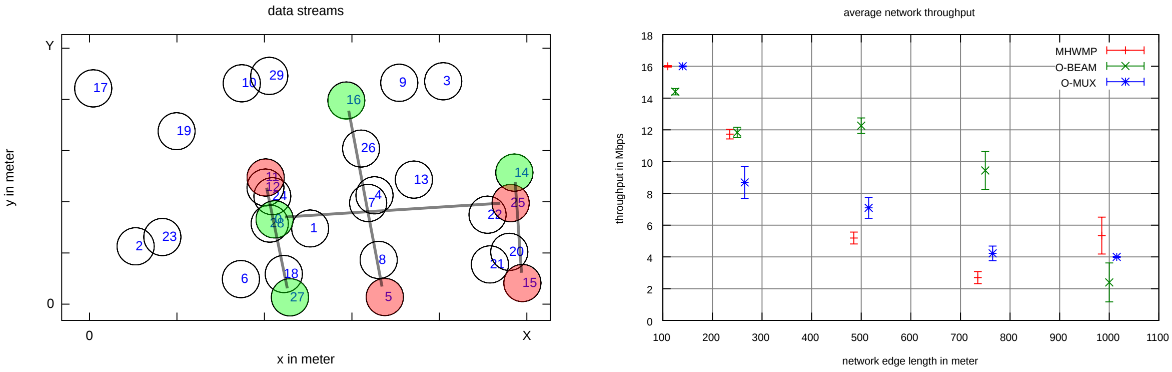
O-MUX performs best in the dense 125m scaling, where few retransmissions are needed for each stream. As expected O-MUX suffers critically due to the the overlapping streams, because multiple retransmitters are placed in a single collision domain. The 1000m scale has separated the nodes so far, that individual collision domains are formed, which increase the throughput once again, before connectivity would drop with further increasing scale.

The bad results of MHWMP in the 125m scale are a result of the use of BF transmission mode together with MUX. The path table entries reveal, that all packet sources exept node 19 use BF. Hence DMAC issues cause throughput reduction. This leads to a further issue of MHWMP: the MUX paths are given too few weight. For the short hop distances of the 125m scale MUX is expected to provide better results than BF, which should be reflected in the metrics.

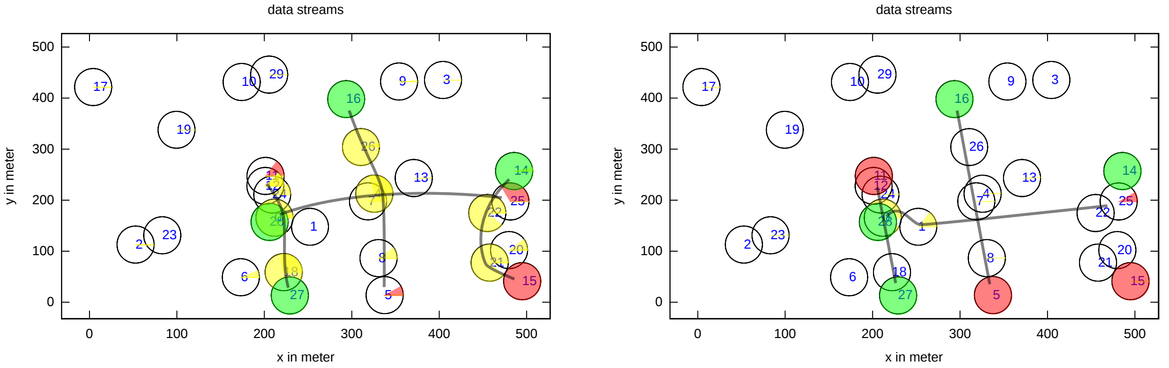
MHWMP in the 250m scale suffers from the same impairment, as all nodes exept 5 use BF transmission mode. As visible in figure 8.10c this stream uses two intermediate hops, placed in a highly busy area. These omnidirectional retransmissions permit channel reuse and reduce the throughput of all streams in the network. Thus this scenario again shows problems of DMAC with mixed directional and omnidirectional transmission modes: if some nodes use omnidirectional transmission, all neighbouring nodes lose their benefit of parallel transmissions when using BF (see section 6.2.2).

In the 1000m scale MHWMP suffers from frequent collisions and path changes due to unlucky path choices.

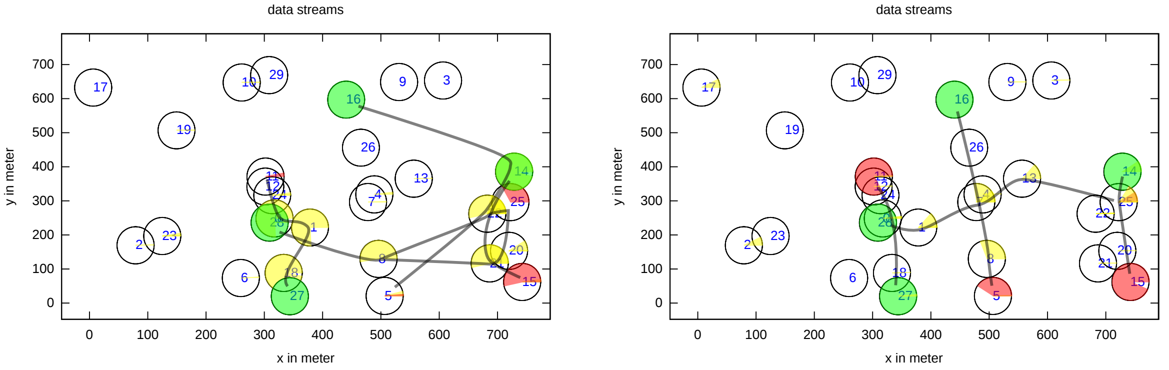
8.2.2.4 Linear Topology with High Inter-Stream Interference Scenario



(a) Topology (b) Throughput



(c) 500m MHWMP Packet Trace (d) 500m O-BEAM Packet Trace



(e) 750m MHWMP Packet Trace (f) 750m O-BEAM Packet Trace

Figure 8.11: Linear Topology with High Inter-Stream Interference Scenario

The scenario depicted in figure 8.11a shows destinct linear node formations between the transmitter-receiver pairs. This is used to demonstrate problems of MHWMP in scenarios with linear node placements.

MHWMP and O-MUX show best results in the 125m scale, as each destination is in range of a single hop transmission. The performance of O-BEAM is reduced, since it unfortunately chooses one of the busy nodes as intermediate for another stream. In the 250m scale O-MUX suffers from increased channel saturation due to multi-hop paths, while O-BEAM and MHWMP are able to transmit in parallel along fewer hops.

The bad performance of MHWMP in the 500m scale is analyzed in detail in figure 8.11c. MHWMP employs MUX for the streams from 16 to 5 and 27 to 11 although BF would obviously be a better choice. This is a special issue due to the linear node placement formed between the transmitter receiver pairs of this topology. Long detours are taken into account by the DAM metric for the BF paths to avoid interference to the linearly placed nodes. Thus when both path types are availible the airtime metric indicates the multi-hop MUX paths as more favourable. This leads to the previously explained problems of channel over-saturation and DMAC issues. The only benefit MHWMP shows here is the path from 14 to 15, as it reduces the interference to node 25. This results in a higher delivery ratio for stream 20 to 25 compared to O-BEAM visible in figure 8.11d.

In the 750m scale MHWMP again suffers from unoptimal paths depicted in figure 8.11e due to the linear node placement. The stream from 27 to 11 uses MUX transmission mode, which increases channel access problems. Compared to O-BEAM in figure 8.11f, MHWMP takes into account long detours to avoid interference to the linear node placements.

8.2.2.5 Conclusion

In the previous scenarios it is visible, that MHWMP is able to perform as good as O-MUX in dense scenarios and as good as O-BEAM in sparse scenarios. Best results were achieved together with O-BEAM in scenario 8.2.2.1. In scenario 8.2.2.2 MHWMP performed optimal, as it provided the maximum throughput in dense as well as in sparse network footprints. In scenarios 8.2.2.3 and 8.2.2.4 MHWMP performed worse due to DMAC issues and problems with linear node topologies.

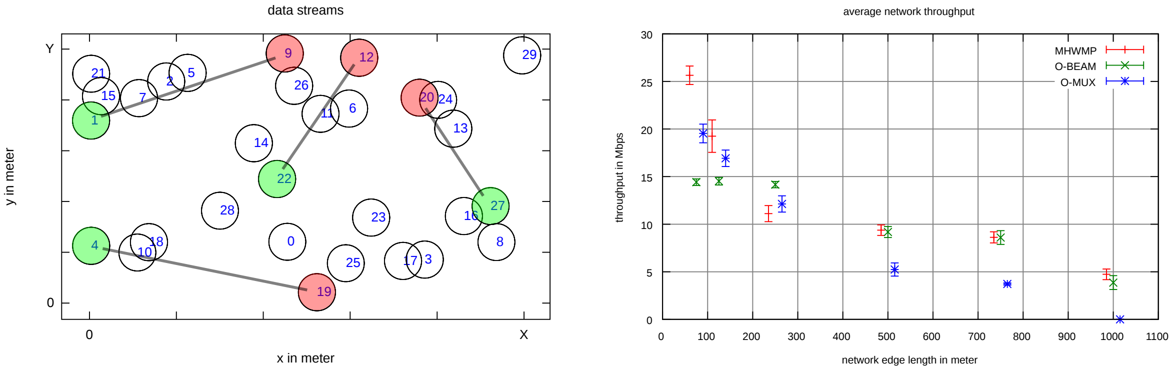
Under good circumstances in mid-range scenarios MHWMP performs better than O-BEAM, as it uses low interference paths. But on the other handside in these scenarios MHWMP often suffers from DMAC issues due to the concurrent use of BF and MUX. Also the performance of MHWMP highly depends on the current topology and the position of busy nodes. This is due to the DAM, which does not take into account time-critical load balancing aspects. Also scenario 8.2.2.3 showed that the airtime metric is given too few weight with respect to the possible throughput. In relatively dense scenarios often the BF path is chosen, although the MUX path would provide increased throughput.

A characteristic problem of MHWMP visible in scenario 8.2.2.4 is linear node placement. In these topologies MHWMP is forced to use longer MUX paths or unfavourable long BF paths to avoid interference.

8.2.3 High Rate Applications

In the following scenarios the performance of the protocol variants is again compared with increasing network footprint. In difference to the previous section, the traffic generator previously used in scenario 8.1.2 is employed, which resembles the file transfer in peer-to-peer filesharing. This different traffic pattern allows to show benefits and drawbacks of MHWMP for high-rate data streams.

8.2.3.1 Channel Over-Saturation Scenario



(a) Topology

(b) Throughput

Figure 8.12: Channel Over-Saturation Scenario

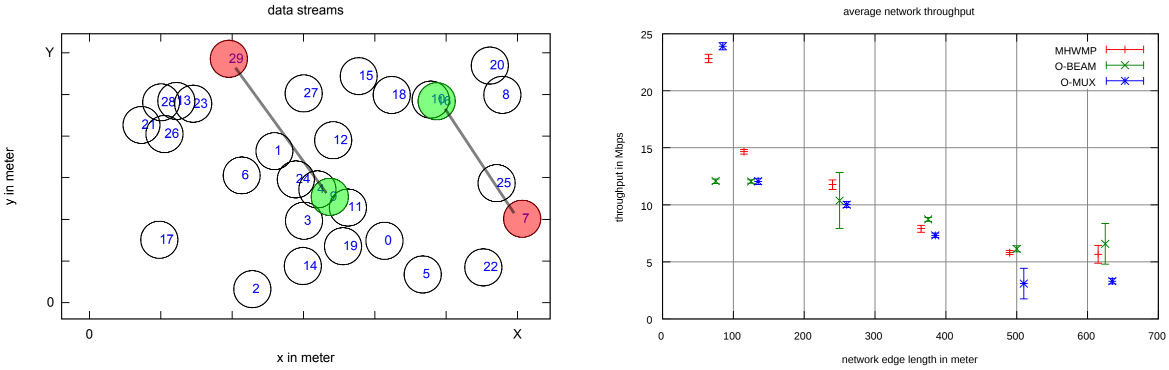
In scenario 8.12 the same topology and source-destination pairs as in scenario 8.2.2.1 are used together with the peer-to-peer traffic generator. This setting is used to show characteristics of the protocol variants under oversaturated channel conditions.

The results visible in figure 8.12b show that MHWMP and O-MUX achieve much higher throughput in scales below 250m. In these dense scales the use of MUX is beneficial, as it uses highly increased PHY data rates.

The 75m and 125m scales show an odd bahaviour, as O-MUX performs worse than MHWMP although they use very similar paths. The only explaination for this behaviour is the DMAC scheme employed in MHWMP, while O-MUX employs the standard ns-3 channel access procedure. Overriding of DNAV entries (see 6.2.2) is not the reason for this difference, since all nodes are direct MUX neighbours in the 75m scale. Thus the modified channel access scheme seems to avoid a limiting factor of the standard channel access procedure or possibly a bug of ns-3.

The results of the scales up from 250m resemble those of the moderate rate scenario 8.2.2.1 with one major difference: the overall throughput is generally lower. This is the case since through the use of the high rate packet generation, the channel is generally oversaturated making packet collisions more common. This is also the reason for the worse results of MHWMP in the 250m scale: the stream from node 4 to 19 uses MUX and the increased channel busy ratio increases DMAC problems with mixed directional and omnidirectional transmissions (see section 6.2.2).

8.2.3.2 Low Inter-Stream Interference Scenario



(a) Topology

(b) Throughput

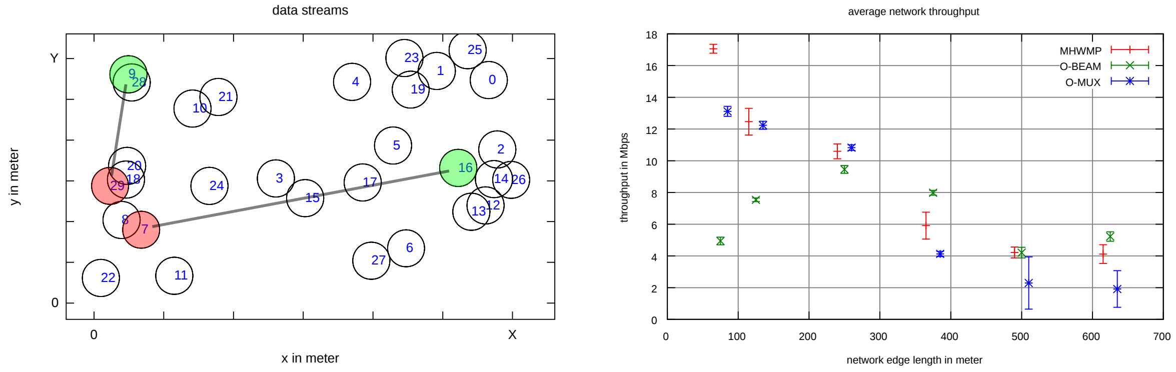
Figure 8.13: Low Inter-Stream Interference Scenario

The scenario in figure 8.13a shows a random network containing two data streams. The networks is slightly clustered and the two data streams each need to pass a gap between clusters.

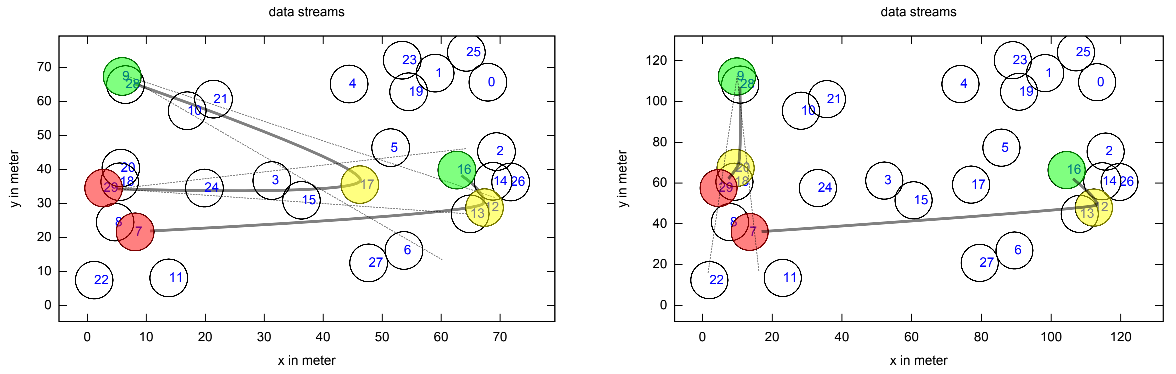
In the 75m scale MHWMP and O-MUX show their benefits of MUX transmission mode compared to O-BEAM: the throughput is highly increased. In the 125m scale the DAM prefers direct links instead of using intermediate hops, to minimize the overall interference. O-BEAM and O-MUX rely on intermediate hops, thus MHWMP shows the best throughput.

The high standard deviation of O-BEAM in the 250m scale is due to a link break. The throughput of O-MUX is reduced in scales above 375m, because it suffers from the growing gaps of the topology.

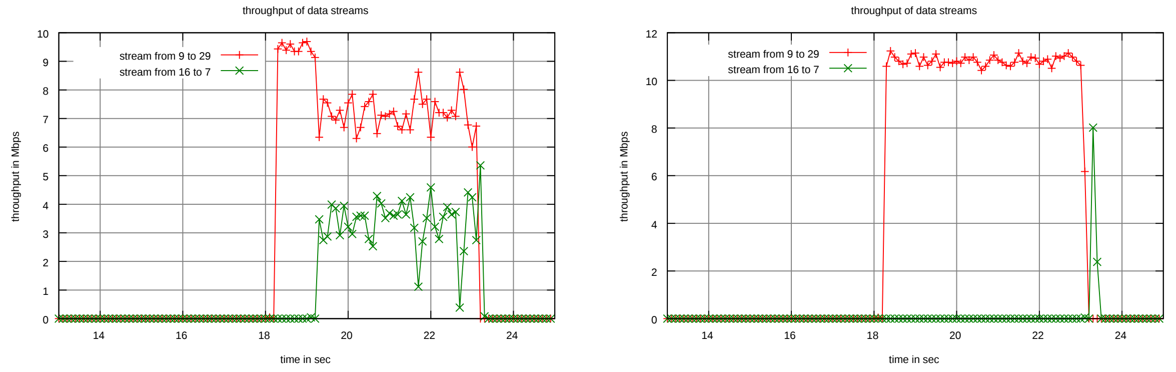
8.2.3.3 Moderate Inter-Stream Interference Scenario



(a) Topology (b) Throughput



(c) 75m O-BEAM Packet Trace (d) 125m O-BEAM Packet Trace



(e) 250m MHWMP Throughput (f) 250m O-MUX Throughput

Figure 8.14: Moderate Inter-Stream Interference Scenario

The scenario of figure 8.14 again contains two data streams, one passing a long distance over a possible chain of intermediate nodes, the other passing a wider gap. The stream destination nodes are very close to each other, which may cause inter-stream interference for BF transmissions.

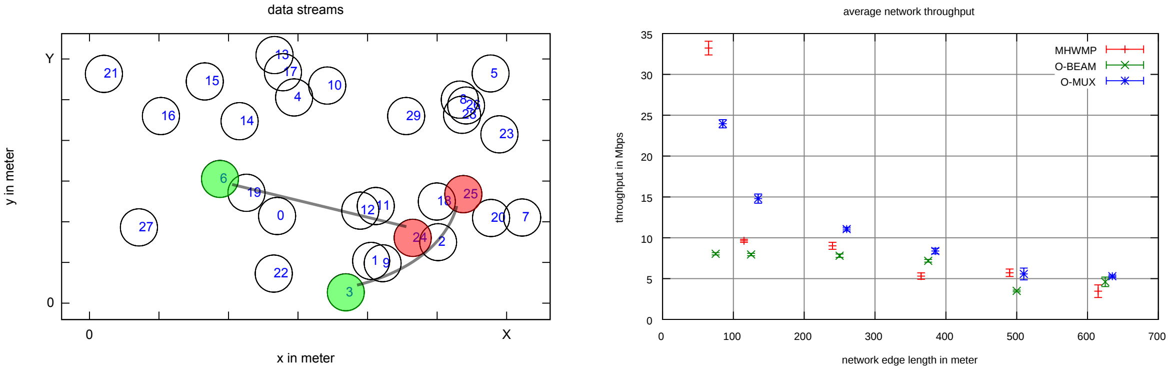
Since the traffic source generates much higher bit rates, MUX transmission mode is in favour, when short paths are possible such as in the scales up to 250m. Thus MHWMP and O-MUX show highly increased performance compared to O-BEAM. Again the increased throughput of MHWMP compared to O-MUX seems to be a bug of the ns-3 channel access implementation. The bad peformance of O-BEAM in this scale is due to an exceptionally bad path choice depicted in figure 8.14c, which causes interference to the other stream twice. Also in the 125m scale O-BEAM uses an unlucky path visible in figure 8.14d and experiences reduced throughput.

An interesting behaviour of O-MUX is visible in figure 8.14f: O-MUX serves only the stream from 9 to 29, while the other stream starves completely. This is because no path is established due to the high interference from the other stream. MHWMP is less prone to lost path discovery frames as it performs two independent path discoveries. Thus MHWMP is able to serve throughput to both connections as seen in 8.14e. Note that MHWMP uses BF transmission mode for the path from node 16 to 7, while 9 to 29 uses MUX. Due to the DMAC problems for mixed channel access the interference between the two streams is clearly visible in 8.14e.

The result of MHWMP in the 375m scale is a result of the concurrent use of MUX and BF, where interestingly the longer path from node 16 to 17 uses MUX. Similar to scenario 8.2.2.4 the DAM forms unoptimal BF paths in the relatively linear node placement. O-MUX is not able to bridge the gap between 9 and 29 and thus transports only one stream.

The unsteady behaviour of O-MUX in the 500m and 625m scale is a typical result of unfavourable links due to the long distance hops. These paths have a high packet error rate and cause frequent retransmissions and link breaks.

8.2.3.4 High Inter-Stream Interference Scenario



(a) Topology (b) Throughput

Figure 8.15: High Inter-Stream Interference Scenario

The topology visible in figure 8.15a places two streams in a fashion, that one stream destination is prone to interference from the other. Thus O-BEAM is expected to suffer from increased interference, while MHWMP should avoid these paths.

In dense network scales O-MUX and MHWMP benefit from higher throughput. Similar to the previous scenario the increased throughput of MHWP compared to O-MUX seems to be an unintended effect of the directional channel access implementation. In the 125m scale a further problem of MHWMP is experienced. Although the two metrics of both path types are very similar to each other, it is visible that O-MUX achieves much higher throughput. This points out that the MUX path would be a far better choice for MHWMP and that these paths are currently given too few weight. Also the metric calculation in ns-3 often computes equal metric values[2]. This is due to the metric being stored as integer in ns-3.

In the 375m scale MHWMP suffers from multiple link breaks due to poor path choices and the temporary use of MUX transmission mode. In the 625m scale the path choices of MHWMP are very poor, as it uses a direct link between 6 and 24, while also using 24 as intermediate for the other stream. Accordingly the throughput of MHWMP is the lowest in this scale.

8.2.3.5 Conclusion

MHWMP clearly performed best in the previous scenarios 8.2.3.1, 8.2.3.2 and 8.2.3.3. As expected it provided the higher throughput of MUX in very dense scenarios and the more stable throughput of BF for sparse network footprints. Bad results were experienced in scenario 8.2.3.4 due to bad path choices of MHWMP.

Under conditions with close source-destination pairs and high application data rate, MHWMP is able to outperform O-BEAM. Unfortunately MUX transmission mode is given too few weight through the metrics, thus BF is often used in scenarios where MUX would allow higher throughput. As in the previous scenarios, with increasing distance MHWMP performs better than O-MUX because it maintains connectivity over higher hop distances. Also the two independent path discoveries of MHWMP prove to be useful under high interference, when O-BEAM and O-MUX are prone to lost path request and reply frames.

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[2] In case of equal metric values of both paths, currently the BF path is preferred to reduce network interference.

9 Conclusion and Future Work

The task of this thesis was to enhance the performance of the IEEE 802.11s protocol with smart antenna features. Thus MAC and routing protocols should be adapted for full exploitation of the multiple smart antenna gains.

Concerning the MAC layer, the use of directional transmissions increases the hidden node problem. To overcome this issue, multiple techniques proposed in the literature have been incorporated and combined with new concepts. A notification scheme based on RTS/CTS is employed prior to directional tranmissions. To broadcast control frames for BF transmissions, diversity techniques have been used which maintain the desired omnidirectional transmission pattern while providing a range similar to BF. The virtual carrier sensing scheme of the IEEE 802.11 MAC has been extended to allow channel reuse for the different transmission schemes.

For multi-hop packet forwarding the smart antenna transmission schemes BF and MUX are employed. BF provides a longer communication range with a directional transmission pattern. MUX allows connectivity over short distances with highly increased data rate. To adapt to the dissimilar neighbours experienced, multiple aspects of the mesh protocol stack have been implemented separately for these different transmission schemes. In the proposed approach two separate neighbour and path tables are maintained for MUX and BF. The routing protocol MHWMP switches between the paths formed with MUX and BF according to the current channel conditions. The proposed protocol has been evaluated with the open-source network simultion tool ns-3. The existing ns-3 802.11s models have been extended with a directional channel model, antenna model and the proposed MAC and routing models. Furthermore simulation scenarios have been designed and functions for collecting and visualizing simulation data have been implemented.

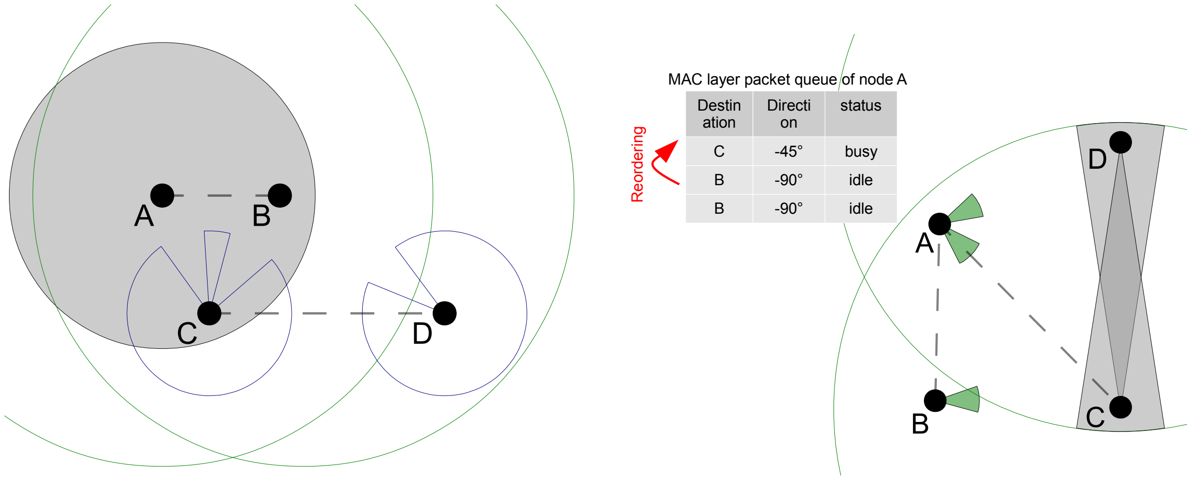
Simulation results show that MHWMP improves the average throughput of the network under various network conditions. It successfully adapts PHY transmission techniques according to the channel conditions and shows robust behaviour against link failure. MHWMP achieves high throughput in dense topologies through the use of high-rate MUX transmission mode. In sparse networks it provides steadily high throughput by using BF for increased range and robustness. The density-aware metric of the BF paths provides better overall network throughput in presence of many active nodes.

Significant gains in throughput were expected from the aspect of using MUX and BF in parallel. Unfortunately due to the exposed node problem in mixed directional and omnidirectional environments this benefit is currently not achieved. Suitable MAC layer amendments are expected to improve the efficiency of MHWMP. A possible solution to avoid the exposed node problem might be the use of 'MAC-steerable nullforming'. This concept is illustrated in figure 9.1a: if nodes A and B whish to communicate using MUX, they announce their communication beforehand by transmitting RTS/CTS with STC. Nodes C and D receive these frames and point nulls into the directions of A and B. Thus while the omnidirectional frame exchange between A and B is active, these nodes may still communicate with each other or in other directions using BF. However the implementation and evaluation of this approach is left for future work.

An interesting future research topic, that might increase throughput of multiple active data streams, is queue reordering according to the packets destination. This means that when a specific direction is blocked by directional virtual carrier sensing, packets destined to other idle directions should be granted channel access first. For example in figure 9.1b a packet destined to the currently busy node C would not block packets to the idle node B when queue reordering is performed.

To ensure QoS in MHWMP, suitable amendments at the MAC layer together with QoS-aware metrics is also an intersting future research topic.

Furthermore different metrics could be evaluated, which enhance the interference-awareness and tune the weights given to BF and MUX paths.



MAC layer packet queue of node A

Destination	Direction	status
C	-45°	busy
B	-90°	idle
B	-90°	idle

(a) Possible Solution for current DMAC Problems

(b) Queue Reordering

Figure 9.1: Future Work Illustrations

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