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State of the Art Analysis of Wireless Mesh Technologies 2006

T. Huovila*, P. Lassila†, J. Manner*, and A. Penttinen†
*University of Helsinki
†Helsinki University of Technology

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Abstract

Wireless mesh networks are a recent architecture for multihop wireless networks. Also, standards for realizing mesh networks are being actively developed, especially in the IEEE working groups. In contrast with mobile ad hoc networks, mesh networks consist of static nodes communicating with each other over wireless links. The static nodes are essentially wireless routers. Such networks can be used, for example to provide a cost effective alternative to a wireline Internet access network. As opposed to the nodes in mobile ad hoc networks, the nodes in mesh networks are not energy constrained and node mobility is not a concern in protocol scalability. Instead, the main technical problems relate to achieving high user data rates over multihop wireless paths by using advanced MAC/routing layer solutions.

This report presents a state-of-the-art analysis of wireless mesh networks, both from the point of view of standardization and academic research activities. In the standardization, we focus on the recent developments on defining new physical layer and MAC layer standards for mesh network in the IEEE 802.11 and 802.16 working groups. At the IP layer, in addition to routing, mobility management is a key issue, and these are reviewed from the point of view of recent IETF activities in the field. In academic research, the emphasis has been on identifying feasible mechanisms that can be used to mitigate the impact of interference on the capacity of multihop wireless networks, for example by increasing spatial multiplexing through the use of several orthogonal channels and multiple radio interfaces. The solutions typically involve cross-layer approaches, and a specific survey on these is also provided. Finally, a review is given on some of the current commercial products available on the market, as well as operational academic test beds.

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1 Introduction

With the emergence of WiMAX (802.16) and other IEEE 802 broadband technologies (802.20, 802.11n) and the forthcoming 3G/4G/next generation cellular networks and Unlicensed Mobile Access (UMA), broadband connectivity is rapidly growing beyond wired networks. Wireless connectivity offers users flexibility and makes broadband more ubiquitous. Wireless broadband network equipment offers a high speed to price ratio. Due to the relatively simple radio technologies used and wide adoption in homes and offices, the unit cost for off the shelf equipment is low. If, in addition, installation and maintenance costs of wireless networks can be kept low, they offer a cost effective alternative to wired networks.

Existing wireless local area network (LAN) equipment is usually deployed in so called hotspots. In a hotspot deployment a wireless base station routes client connections within the range of the base station or to a wired network (e.g. the Internet). This limits the mobility of clients, that wish to maintain connections, to the coverage area of a single base station. The wired connection increases deployment costs for the hotspot.

Flexible and ubiquitous future mobile computing and communication needs to better take into consideration the needs and mobility of users. Such future mobile computing calls for, among other things, reconfigurable systems and efficient wireless communications [123]. Devices need to automatically adapt to different kinds of network connectivity. Heterogeneous wireless networks need to cooperate to support the movement of users. Mobility and performance issues in communication protocols need to be solved, to provide the user seamless mobility and required quality of of service.

1.1 Mesh access networks and scenarios

In *wireless mesh networks* (WMNs) wireless mesh routers form densely interconnected multi-hop topologies. The routers automatically configure a wireless broadband backbone for local communication and routing to a wired access network. Three kinds of wireless mesh networks can be identified [5]. In *infrastructure WMNs* mesh routers form a network offering connectivity to clients. The network is meant to be self-configuring, self-healing and to offer gateway functionality for connections to wired networks, such as the Internet. *Client WMNs* are are ad-hoc networks formed by clients among them selves. No dedicated routers or infrastructure exists, so the clients have to be self-configuring and act as routers for the traffic in the client WMN. *Hybrid WMNs* combine the advantages of the two other WMNs. Both clients and wireless mesh routers participate in the routing of traffic, thus increasing coverage and connectivity of the network. The infrastructure provided by wireless mesh routers forms a backbone for the network and offers gateways to wired networks. An example of a hybrid WMN is shown in Figure 1.

Emerging and existing commercial applications of infrastructure WMNs include the following. So called intelligent transportation systems can be realized efficiently using mesh technology to provide real time travel information related to public transportation. Public transportation vehicles can be equipped with radios to communicate with wireless routers, which communicate with each other to distribute the real time information, as depicted in Figure 2 (left). Also, private networks used for public safety services can benefit from mesh technology. The most popular commercial application of mesh technology is to use WMNs as a wireless access network to the public Internet. The idea is to equip for example houses in a sparsely populated areas with mesh routers that communicate with each other over long distances using wireless multihop communications, thus offering an alternative to wireline DSL technologies for providing broadband Internet access to rural areas, see Figure 2 (right). Another important application relates to providing an alternative for realizing the distribution network that connects WLAN base stations together. Currently, WLAN base stations need to be connected together by using fixed links, and WMNs provide an alternative to this. Also, WMN-based architectures could be used for implementing the radio access network in future cellular networks.

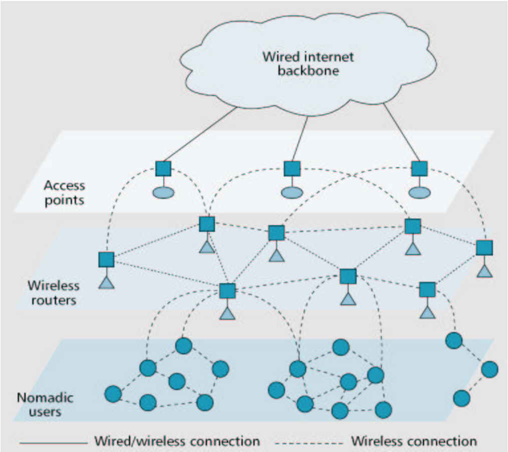

Figure 1: Illustration of a hybrid WMN [14].

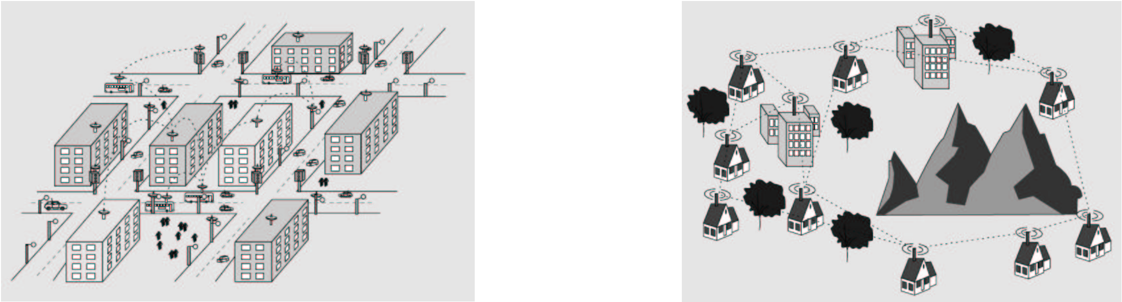

Figure 2: Applications of mesh networks; intelligent transportation systems (left) and neighborhood networks (right) [14].

1.2 Mesh Network Architectures

A mesh network can be built with a number of options regarding the technology. From the user device point of view, what matters is the protocol layer that mostly handles the mobility, and the connectivity in general. A mesh network could be handled purely on the link layer, the IP layer (Fig. 3), or something in between.

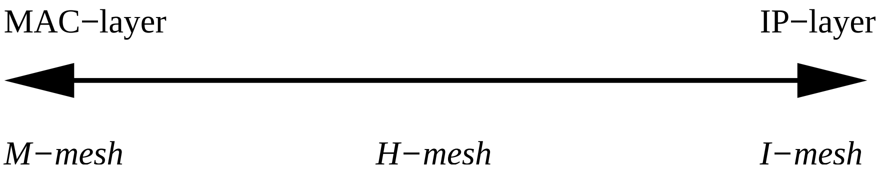

Figure 3: Design choise for mesh networks.

An infrastructure WMN could be built as a single domain connecting the wireless client to the Internet. A pure link layer infrastructure mesh network, we call a *MAC-mesh, or M-mesh*, would appear to the wireless client as a single link. The client has a default gateway configured, and handovers only change the link layer attachment point to the network, while keeping the IP configuration information intact. On the opposite end, a pure IP layer mesh network, an *IP-mesh, or I-mesh*, would be the opposite; a client has a default gateway configured on the same node it has link layer connectivity to, and after a handover the default gateway, and possibly the client's own IP address, must be reconfigured.

Yet, another option could be to have a mesh network that includes both pure MAC-layer mesh routers, and IP-capable mesh routers; something in between the extremes in Fig. 3, a *hybrid mesh, or H-mesh*. The *H-mesh* could further have a hierarchy, a mesh of infrastructure WMNs (Fig. 4). Here WMNs would be connected to other WMNs, and some of these WMNs would have the connection to the Internet. Clients in leaf WMNs would have their traffic routed through more than one WMN before reaching the Internet. In this scenario, an individual WMN could be built on the link layer, an *M-mesh*, and traffic between WMNs would be routed using IP routing protocols. Handovers within a single WMN would be transparent to a client, only handovers between WMNs could be noticed at the client. Notice in Fig. 4 that the IP connection between mobile clients and mesh routers, or between two mesh routers, is not necessarily the same as the link layer connectivity - there can be more than one wireless link between two neighboring nodes at the IP layer.

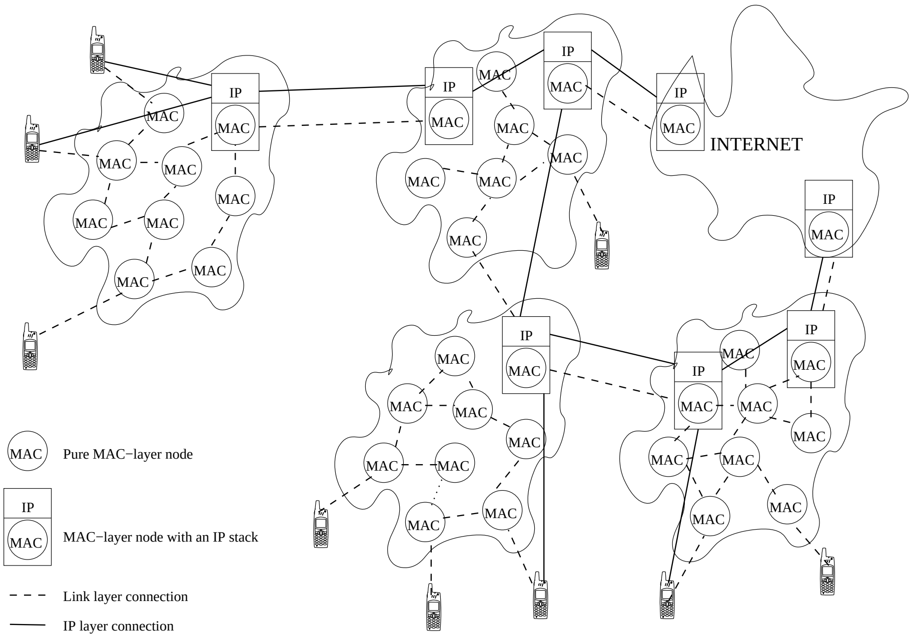

Figure 4: A hierarchical *H-mesh*.

1.3 Link Layer issues

A wireless mesh network has several appealing characteristics [5]. Using a multi-hop topology can be more robust, allow transmissions with less power over shorter distances and thus lessen power consumption in client nodes, cause less interference and allow efficient frequency use. The aim of a wireless mesh network is to organize and configure its functions autonomously. Self-healing WMNs recover automatically from disturbances caused by addition or removal of nodes.

A mesh topology also presents several challenges [5]. Available bandwidth is affected by radio technology, the networks multi-hop topology and used routing mechanisms. Delays such as round trip times (RTT) and handovers between access points can also be varying.

Spectrum is a tightly regulated resource [142]. Freely available radio spectrum for broadband connections has therefore been limited. Regulatory changes and introduction of new technologies like digital television, make redistribution of previously reserved frequencies possible. It is still important to efficiently share the available frequencies. Directional antennas and software radios, that adapt to the surrounding transmissions, can be used to cut down on interference. In multi-hop, mesh topologies small cells can be used to bring down the power required for transmissions. This cuts down on (the range of) interference and allows reuse of the same frequencies within a smaller area (spatial reuse).

A multi-hop topology scales bandwidth. When using a single radio, it is not possible to receive and transmit data at the same time (half-duplex). Therefore a node can not relay information while receiving it. As in many networks, Medium access control (MAC) protocols are needed to control transmissions. These factors scale down the available bandwidth from the theoretical maximum, even if transmissions from close by nodes do not cause interference for the transmission. The bandwidth available for an end-to-end connection decreases over hops as, $\Theta(c/\sqrt{n})$ bits/sec, where c is the available bandwidth and n is the number of nodes [57]. To conserve the bandwidth, there is a need to limit the amount and scope of traffic overhead from routing and management protocols.

To increase the capacity of wireless multihop networks several technological approaches can be applied. For example, greater spatial reuse can be achieved by using multiple orthogonal channels and multiple radio interfaces. Alternatively, directional antennas may be used. The use of these technologies is also considered in the standardization of new mesh networking standards. In this report we review the current activities in the standardization, as well, in the performance modeling and analysis of wireless mesh networks.

1.4 Outline

The outline of the report is the following. Chapters 2 and 3 review available solutions on the link- and ip-level respectively. Chapter 4 describes the modeling and performance evaluation of mesh networks. In chapter 5 some commercial and community developed mesh products and implementations are introduced and experimental results from testbeds are stated. Chapter 6 offers some final conclusions.

2 Link-layer solutions

2.1 Introduction

The core of the WMN technology is the radio technology. While the physical layer of the emerging mesh network standards remain more or less in tact, the MAC layer needs to be enhanced to enable more efficient multi-hop communications. Also, routing at the link layer needs to be supported in some cases.

In this chapter we review the fundamental physical layer issues relevant to mesh networks, especially the properties of the 802.11 and IEEE 802.16 technologies. Then the proposed mesh solutions for both radio technologies are described including the MAC layer mechanisms and the link layer routing mechanisms.

Note that the IEEE 802.15 working group, which proposes standards for wireless PANs (Personal Area Network), is also considering amendments to include mesh functionality. However, in this report the interest is on technologies providing larger area coverage rather than the technologies used in PANs with very limited coverage.

2.2 Enabling technologies for wireless mesh networks

2.2.1 Review of IEEE 802.11 (non-mesh mode)

IEEE 802.11 based technology is the most widely used wireless LAN technology at the moment. The IEEE 802.11a/b standard [63] was completed in 1999. Somewhat counterintuitively the legacy IEEE 802.11 standard from 1997 has been labelled as IEEE 802.11b, and IEEE 802.11a is indeed an enhanced version of 802.11b. The original standard has been subsequently extended in various ways, for example new physical layers to support higher data rates have been defined in IEEE 802.11g and IEEE 802.11n (still in preparation), and QoS support is defined in IEEE 802.11e.

The most successful usage of 802.11 in practise is where nodes equipped with 802.11 devices communicate with a so called access point to access the public Internet. Several access points may be connected together to form a network of access points. However, the interconnection of the access points is done via wired links. The 802.11 can also be used for multi-hop communications to form ad hoc networks requiring no pre-existing infrastructure. However, despite the tremendous research effort in developing ad hoc networks, the practical use of multi-hop ad hoc networks has not been that great.

Physical Layer: The physical layer of 802.11b operates at the 2.4 GHz frequency range. It is based on direct sequence spread spectrum (DSSS) and uses two modulation schemes to produce physical data rates of 1 or 2 Mbps. To achieve the higher 5.5 Mbps and 11 Mbps rates, a modulation technique known as CCK (complementary code keying) is used. The idea in these direct sequence spread spectrum techniques is to modulate the user's bit stream with a much higher data rate modulation signal, the so called chipping code, thus spreading the user's signal across the entire physical spectrum of the system. The chipping codes of the users are chosen to be orthogonal to each other. Note that the 802.11b physical layer does not include any forward error correction (FEC) mechanisms to improve the quality of the transmission. The 802.11b standard divides the spectrum into 14 overlapping channels whose center frequencies are 5 MHz apart. To obtain minimally interfering independent channels that can potentially be used in close proximity of each other, it is commonly stated that, e.g., channels 1, 6 and 11 can be used (or any other grouping of channels with similar separation in frequencies). Thus, usually it is claimed that with 802.11b there are three independent channels available for transmissions.

The physical layer of 802.11a uses the 5 GHz frequency band and employs OFDM (orthogonal frequency division multiplexing) for modulation. The idea in OFDM is roughly to send the high data rate bit stream using concurrently multiple low data rate channels. The benefit is that it is possible to eliminate the impact

	802.11b	802.11a	802.11g	802.11n
Physical layer	DSSS	OFDM	DSSS/OFDM	OFDM/MIMO
Maximum rate	11 Mbps	54 Mbps	54 Mbps	540 Mbps
Frequency band	2.4 GHz	5 GHz	2.4 GHz	2.4 GHz
Number of channels	3	4/8	3	?

Table 1: Physical layer properties of 802.11a/b/g/n.

of so called intersymbol interference caused by multipath propagation, compared with just transmitting at a higher rate. Furthermore the channels (subcarriers) in OFDM are orthogonal with respect to each other. The basic operation of transmitting a frame passed from the MAC layer to the physical layer consists of first using convolutional encoding and interleaving to enhance the bit error performance, i.e., FEC is used in 802.11a as opposed to 802.11b. The resulting frame is then divided into groups consisting of 1, 2, 4, or 6 bits depending on the chosen modulation scheme, and converted into complex numbers representing the so called constellation points of the modulation method. These complex numbers (corresponding to groups of bits) are then allocated sequentially to the 48 data subcarriers, i.e., group of bits 1 to channel 1, group of bits 2 to channel 2, etc. The complex numbers (i.e., the bits) that are allocated to the 48 subcarriers in one round are called an OFDM symbol, and obviously to get the entire original frame transmitted several OFDM symbols are constructed. The complex numbers in an OFDM symbol are used as input to the inverse Fourier transform operation which yields a time domain signal of the OFDM symbol that is finally transmitted on the antenna. The different OFDM symbols are transmitted in a sequential manner. The receiver performs the above steps in a reverse order to reconstruct the original frame. In the above process the coding rate and the modulation are indeed the same on all subcarriers. However, the coding rate and the modulation can be changed depending on the channel quality to yield a certain set of available data rates. The IEEE 802.11a standard defines the following rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. Furthermore, the standard has defined 8 non-overlapping channels for indoor usage and 4 for outdoor usage.

Signals in the 5 GHz frequency range suffer more from signal strength attenuation than in 2.4 GHz frequency range. Thus, the legacy 802.11b technology provides better coverage than 802.11a. There was a need to achieve higher speeds at the 2.4 GHz range, and the 802.11g standard was specified for this purpose. The 802.11g operates in 2.4 GHz range, provides the same data rates as 802.11a and is compatible also with 802.11b, i.e., the physical layer uses the DSSS technology of 802.11b if connected to an 802.11b access point, and the more advanced OFDM coding/modulation schemes if the the access point supports it. In response to en ever growing need for higher speeds, the emerging IEEE 802.n will operate in the 2.4 GHz range and utilizes MIMO (multiple-input-multiple-output) technology, i.e., multiple transmitter and receiver antennas. Some of the relevant physical layer characteristics of the 802.11a/b/g/n standards are summarized in Table 1.

MAC layer: The 802.11 MAC layer consists of two alternative MAC schemes, DCF (Distributed Coordination Function) and PCF (Point Coordination Function). DCF is a mandatory mechanism that any 802.11 compliant device must support while PCF is an optional scheme. Shortly, PCF corresponds to a simple polling scheme where a designated access point node controls all the communication (similarly as a base station in cellular networks) and allocates bandwidth to the nodes by periodically polling them. In practise, PCF is very rarely supported.

DCF is the typical operation mode for 802.11 devices. It implements a distributed and asynchronous MAC scheme known as CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). In CSMA/CA, nodes constantly monitor the channel to detect whether the channel is used or not. Only after sensing the channel idle, a station may try to reserve the channel and start transmitting the frame. To implement the carrier sensing and collision avoidance the default operation of DCF uses physical carrier sensing, where nodes determine whether the channel is idle or not by monitoring the energy level of the channel. However, this leaves the nodes vulnerable to so called hidden nodes (nodes A and B that are not aware of each other may interfere with a node C lying in the intersection of sensing areas of A and B), which increases the risk of collisions. To solve this problem, a mechanism known as virtual carrier sensing can be optionally used.

In virtual carrier sensing, short control messages, i.e., RTS (Request To Send) and CTS (Clear To Send) frames, are exchanged between the nodes prior to any actual data transmission to determine whether or not data transmission may take place or not, and to make sure that hidden nodes remain silent during the transmission. The general problem with DCF is that it is fundamentally a random access scheme and their performance under higher loads is poor.

QoS enhancements to 802.11 MAC have been provided in the amendment 802.11e. The approach there is to enhance the basic DCF functionality with shorter guard intervals (these were not discussed in detail above) for higher priority traffic. This enables higher priority traffic to seize the channel with a higher likelihood than traffic with a lower priority.

2.2.2 Review of IEEE 802.16 (non-mesh mode)

IEEE 802.16 defines a new air interface for realizing wireless networks with considerably larger coverage areas, i.e., so called Wireless MANs (Metropolitan Area Network) and higher bandwidth than achievable with 802.11. The standardization of the technology has been performed by IEEE but the development of commercial products is promoted by the WiMAX Forum consortium.

The IEEE standardization began in 1999 and the first standard IEEE 802.16 was finalized in 2001. The standard was subsequently followed by several amendments, 802.16a 802.16b and 802.16c to address issues related, e.g., to new physical layers and QoS issues. However, the IEEE 802.16-2004 standard [64] replaces the original standard and the a,b and c amendments. The most recent amendments include 802.16e, which considers issues related mobility management of users.

The original usage scenario of 802.16 devices corresponds to the traditional access point configuration, where there is a base station and the stations around it communicate directly only with the base station. In the standard this is referred to as the Point-to-Multipoint mode (PMP). The nodes are assumed to be stationary (or at most portable, mobility management has been added in the 802.16e amendment). Initially line-of-sight communications was considered, but it was quickly realized that also non-line-of-sight scenarios need to be supported, which also required new physical layer definitions (this was considered in the amendment 802.16a). The MAC protocol is very different from the random access based 802.11. In 802.16, the MAC layer is connection oriented, supports various QoS classes and operates on a TDMA basis.

In the following we review shortly the physical layers and the MAC protocol of 802.16 as defined in [64] and the 802.16e amendment. However, it is a very broad standard and hence here we focus on the part of the standards which constitute the so called Mobile WiMAX air interface, as described in [111].

Physical layer: Mobile WiMAX uses the 2-11 GHz frequency range and it is designed for outdoor (non-line-of-sight) environment. It supports channel bandwidths ranging from 1.25 MHz to 20 MHz. The physical layer of Mobile WiMAX is based on OFDMA (OFDM with multiple access). Depending on the channel bandwidth, the number of OFDM subcarriers ranges from 128 to 2048, i.e., there are much more subcarriers than in 802.11. As discussed already in connection with 802.11, in an OFDM system, the input data stream is divided into several parallel sub-streams of reduced data rate (cancelling inter-symbol interference) and each sub-stream is modulated and transmitted on a separate orthogonal sub-carrier. To support multiple access, the data subcarriers are divided into groups that make up subchannels (48 data subcarriers in a subchannel). The subcarriers that constitute a subchannel are distributed across all of the available carriers. Particular users are allocated a number of different subchannels to send and receive data. The subchannelization and desubchannelization modules map and demap the raw constellation data to particular subcarriers within subchannels. A permutation formula maps the subchannels to physical subcarriers in the OFDMA symbol. The formula varies for the uplink and downlink and the strategy used for packing sub-carriers into subchannels.

The WiMAX OFDMA physical layer supports sub-channelization in both downlink and uplink. Users are allocated slots for data transfer and these slots represent the smallest possible data unit. A slot is defined by a time and subchannel dimension. In the specification, a slot consists always of a single subchannel, but the time dimension varies depending on the operation mode; it may be either 1 symbol duration or 3 symbol durations. The user data to be transmitted in the slots are packed into fixed length frames. Multiple frame durations are supported, for example 5 ms frame duration has been adopted by WiMAX Forum for initial products. Each frame consists of 48 OFDM symbols.

As mentioned above, time is slotted in the uplink and downlink directions. The uplink and downlink transmissions can be multiplexed either in a time sharing manner (part of the frame duration is allocated for uplink and downlink, respectively) or there may be separate channels for both directions (frequency division multiplexing). However, the time sharing approach is the recommended mechanism due to the possibility of, e.g., adaptively changing the allocated bandwidth in the uplink and downlink directions.

In a mobile environment the channel conditions may vary rapidly. To this end the system also supports efficient channel measurement methods as well as adaptive modulation and coding techniques. Support for QPSK, 16QAM and 64QAM are mandatory in the DL with Mobile WiMAX. In the uplink, 64QAM is optional. Both Convolutional Code (CC) and Convolutional Turbo Code (CTC) with variable code rate and repetition coding are supported. Block Turbo Code and Low Density Parity Check Code (LDPC) are supported as optional features. The combinations of various modulations and code rates provide a fine resolution of data rates. For example, on the 10 MHz channel in the downlink direction, 11 different data rates can be achieved with the aggregate data rates in the range from 1 Mbps to 30 Mbps. The base station scheduler determines the appropriate data rate (or burst profile including the slot allocation and modulation/coding parameters) for each burst allocation within the frame based on the buffer size, channel propagation conditions at the receiver, etc. Profile can be changed on a per frame basis, i.e., at a time granularity of a few milliseconds. The system also supports an advanced hybrid ARQ scheme to control the retransmission of corrupted frames.

The above functionality is reflected in the frame structure of 802.16, see Figure 5. Each frame is divided into downlink and uplink sub-frames separated by guard intervals. In a frame, the Frame Control Header (FCH) together with the Downlink Media Access Protocol (DL-MAP) and Uplink MAP (UL-MAP) contain information about the allocation of mini slots to user data (bursts in the figure) and the channel coding parameters of the mini slot allocations. The uplink ranging subchannel (Ranging) is allocated for mobile stations to perform closed-loop time, frequency, and power adjustment as well as bandwidth requests. The uplink CQICH channel is allocated for the mobile station to feedback channel state information. The uplink ACK channel is allocated for the mobile station to feedback downlink HARQ acknowledge.

In contrast with the above described Mobile WiMAX physical layer (or 802.16e), the original standard from 2001 defined a physical layer for the line-of-sight environment in the 10-66 GHz frequency range. Under this setting the physical layer operated used a simple single carrier modulation scheme. The non-line-of-sight case was also already addressed in the 802.16a amendment, which is sometimes also referred to as Fixed WiMAX. In Fixed WiMAX, the operating frequency is 2-11 GHz and the physical layer was based on a normal OFDM scheme with 256 subcarriers. Thus, it did not support sub-channelization, but all the carriers were allocated to one user during a slot.

MAC layer: The Mobile WiMAX MAC scheduling service is designed to efficiently deliver broadband data services including voice, data, and video over a time varying wireless channel. Fundamentally, the MAC layer is based on time sharing and users are allocated slots for transmission/reception of data as controlled by the base station. The main idea is that the allocation of slots, the used modulation/coding of the data in the slots, as well as the allocation of bandwidth between uplink/downlink can be all adaptively changed on per-frame basis. In more detail, the MAC scheduling service has the following properties:

- Data scheduler: The MAC scheduler allocates available resources in response to bursty data traffic and time-varying channel conditions and it is located at each base station. The data packets are associated to service flows with specified QoS parameters in the MAC layer so that the scheduler can determine the packet transmission ordering over the air interface. Realtime channel measurement

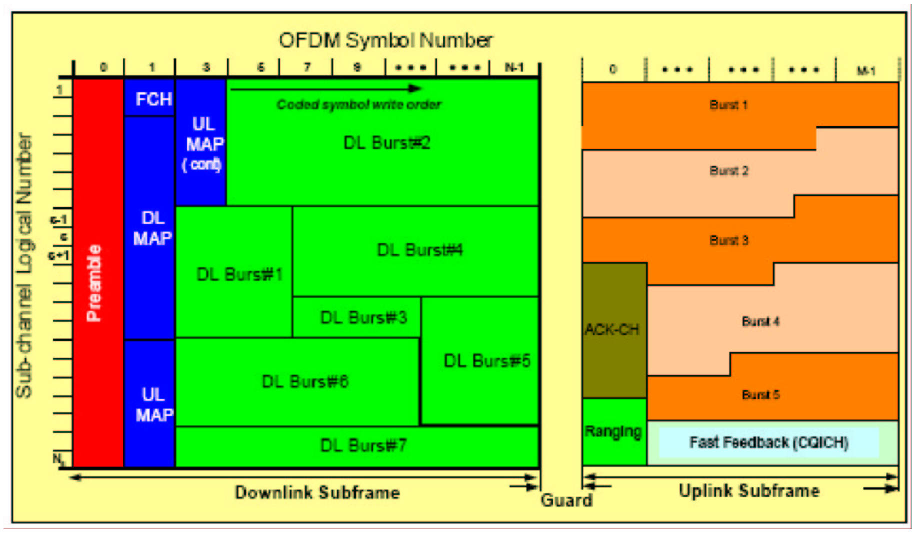

Figure 5: Frame structure in 802.16 [111]

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methods provide fast channel information feedback to enable the scheduler to choose the appropriate coding and modulation for each allocation. The scheduling service is provided for both downlink and uplink traffic. In the downlink, the base station primarily controls the allocation of burst profiles for the receivers based on signal quality measurements (receivers may also request for changes in the profiles). In the uplink, the receivers are competing for the uplink capacity by issuing requests for bandwidth and the base station decides the appropriate allocations.

- Dynamic Resource Allocation: The MAC supports frequency-time resource allocation in both downlink and uplink on a per-frame basis. The resource allocation is delivered in control messages at the beginning of each frame. Therefore, the resource allocation can be changed on frame-by-frame in response to traffic and channel conditions. Additionally, the amount of resource in each allocation can range from one slot to the entire frame.

- QoS Oriented: The MAC scheduler handles data transport on a connection-by-connection basis. Each connection is associated with a single data service with a set of QoS parameters. The standard supports four QoS classes: UGS (Unsolicited Grant Servcice) is for realtime connections which require a fixed amount of bandwidth, rtPS (Realtime Polling Service) is for periodic variable packet size realtime communications, e.g., MPEG video, nrt-PS (Non-realtime Polling Service) is for delay tolerant data traffic for which there is a minimum rate requirement, and BE (Best Effort) is for data without any specific service requirements.

- Frequency Selective Scheduling: The scheduler can use different types of strategies for selecting the carriers that belong to a specific subchannel. For frequency-diverse sub-channels, where sub-carriers in the sub-channels are pseudo-randomly distributed across the bandwidth, sub-channels are of similar quality. With deterministic contiguous subcarrier selection strategies, the sub-channels may experience different attenuation. The frequency-selective scheduling can allocate mobile users to their corresponding strongest sub-channels, and enhance system capacity.

2.3 Mesh standards for IEEE 802.11 and IEEE 802.16

WMN aims to increase the capacity of a given wireless network technology by utilizing various methods to limit the impact of interference. This is possible since a WMN consists of stationary nodes, and hence the devices can be more complex than is generally assumed for traditional, say, 802.11 based networks. In general, the following techniques can be used to mitigate the effect of interference:

- As discussed in [143, 96] directional antennas can be used to significantly increase the performance of the wireless network. Specifically the benefits of directional antenna technology include [96]: improved network capacity through reduced interference, improved signal quality at the receiver, improved routing performance (directional antennas allow longer hops), higher connectivity due to increased transmission range and reduced power consumption. The design choices in utilizing directional antennas involve deciding whether to use them both at the transmitter and the receiver or only at either of these, as well as the level of sophistication in the ability of the directional antenna to change its beam form adaptively. The specific problem that directional antennas exhibit at the MAC layer control (compared to omni-directional antennas) is called deafness, that is a node using a directional antenna may not be able to “hear" a transmission request originating from outside its own beam form. Deafness is a problem particularly with mobile devices. However, with stationary wireless routers deafness is not a problem.
- FSO links (free space optical links) are also a viable technology for wireless mesh networks [53]. The benefits of the technology include the extremely high directional properties of optical signals (low interference), and FSO links are basically an alternative to using directional antenna technology. Thus, they would be ideal for providing connectivity between stationary wireless routers. However, due to the higher frequencies used for the signals, the interference effect are more challenging, e.g., atmospheric conditions (rain or snow) impair significantly the signal reception conditions.
- The 802.11 and 802.16 standards support the use of multiple (orthogonal) wireless channels. These can be used, e.g., to allow neighboring nodes to transmit simultaneously on different channels, even if simultaneous transmission would be impossible due to interference if only a single channel was available. Reducing hardware costs have made it possible to equip nodes with multiple interfaces, and it is typically possible to control the used channel from the device driver’s software. However, it may not always be possible to equip every node with as many interfaces as there are channels, which calls for new MAC layer solutions to handle the associated co-ordination function [88]. In addition to multiple physical interfaces, the use of so called cognitive radio may be beneficial [91], where the idea is that the radio is capable of dynamically utilizing the available spectrum across multiple technologies. In practise this means that, for example the radio device can support both 802.11a/g interface and the 3G air interface, and can switch between these dynamically depending, e.g., on the availability of the service.

To utilize any of the above techniques requires in practise modifications to the MAC layer. Additionally, the mesh topology may affect the routing. In the following, the standardization activities related to mesh networks based on 802.11 and 802.16 technologies are reviewed.

2.3.1 IEEE 802.11s proposal

The standardization of mesh networks using 802.11 based technology is being presently pursued within the Task Group s, TGs. The 802.11s standard will specify the functionality as the extended service set (ESS). The aim is to apply multihop mesh techniques to specify the functionality of a wireless distribution system for interconnection 802.11 access points together that can be used to build a wireless infrastructure for small-to-large-scale WLANs. Its implementation shall be based on the existing PHY layer of IEEE 802.11a/b/g/n operating in the unlicensed spectrum of 2.4- and 5-GHz frequency bands. The main functional features of the standard will include a new MAC layer that supports multiradio/multichannel operation, a MAC routing layer routing protocol, a MAC layer broadcast/multicast mechanism and support for extensive auto-configurability.

The standardization process was initiated in 2004. By now the work has progressed such that the selection of proposals to be used as a basis for the standardization process is completed. This was accomplished in the March 2006 meeting, where the merged proposal of the earlier SEE Mesh and Wi-Mesh proposals was accepted. The standard is targeted to be approved by 2008.

In the following, the current proposal for the MAC layer and the routing scheme are discussed based on the descriptions in [49, 95, 1].

MAC layer: The MAC layer functionality tries to reuse as much of the original 802.11 MAC as possible. Thus, the MAC layer will remain a fundamentally random access based scheme. To implement QoS support, the idea is to utilize the already existing schemes in 802.11e, i.e., there will be different guard intervals in the access scheme for different traffic classes, which allows prioritizing the traffic. The MAC layer will also support the use of multiple channels. This is referred to as the Common Channel Framework (CCF) in the proposal. Roughly, the idea is that all stations use a single common control channel. The stations are then able to dynamically select the data channel by announcing their selections on the common control channel. In practise this is implemented by performing a similar handshaking operation with so called RTX/CTX frames as is done with the RTS/CTS frames in the virtual carrier sensing of the legacy 802.11 DCF. After a successful RTX/CTX exchange, the transmitter and receiver switch to the destination channel.

Routing: As mentioned earlier, the 802.11s proposal is based on using layer 2 routing, i.e., forwarding of packets is based on MAC layer addresses such that to the IP layer the network appears as a single layer 2 network. Thus, given a node having a destination IP address to which data is to be sent, the sender needs to obtain the destination MAC address via ARP and will then use the forwarding table to determine the next hop along the route. The route selection supports a hybrid scheme with both reactive and proactive features, as well as radio-aware link cost metrics. The proposed routing protocol is called Hybrid Wireless Mesh Protocol (HWMP) and its operation is briefly as follows. The operation differs depending on if there is a so called Root Portal (RP) node configured or not. The RP node corresponds to a gateway node for the mesh providing, e.g., access to the wired public Internet. Thus, in such a network most traffic will be towards the RP node or from the RP node towards the other stations. If an RP node is present, a distance vector routing tree is built and maintained by a proactive protocol similar to, for example OLSR. If there is a need inside the mesh for two nodes to communicate with each other, the protocol may then instruct the nodes to initiate a path discovery procedure by using a reactive routing protocol, the so called Radio Metric AODV (RM-AODV), which is a modification of the standard AODV protocol with better support, e.g., for various wireless link cost metrics. When an RP node is not configured, RM-AODV is used to discover routes to destinations in the mesh.

Other issues: The standardization is still in its early stages. Hence, the above merely represents the current status of the work. In addition to the features discussed above, [49]) discusses the role of Connection Admission Control (CAC) and TDMA based modifications to the MAC layer for maintaining QoS in the mesh network. For example, to control the separation of the users' access traffic at a single access point node and the relay traffic flowing towards an RP node from other access points.

2.3.2 IEEE 802.16 mesh mode

In addition to the base station configuration, the IEEE 802.16 standard includes a “mesh mode". An essential difference between the mesh network scenarios for 802.16 based networks and 802.11 based networks is that the 802.11 mesh network is clearly specified as a network that aims at connecting multiple small 802.11 operated cells together to form a single extended WLAN. However, an 802.16 mesh is basically a cellular network where nodes are assumed to always communicate towards a base station or that traffic originates from the base station towards other nodes, although in the mesh mode this communication may occur over several hops, see Figure 6. In the following the main principles of the MAC mesh mode operation are summarized, as discussed in [20] and [95].

MAC layer: The 802.16 standard has two mechanisms to schedule the data transmission in mesh mode - centralized and distributed scheduling. In centralized scheduling, the base station works like a cluster head and determines how the nodes should share the channel in different time slots. Because all the control and data packets need to go through the base station, the scheduling procedure is simple. In the distributed scheduling, the nodes form connections with their immediate neighbors and each node is assumed to know its two hop neighborhood. A node determines its next transmission time during its current transmission time. Because other nodes may also transmit in the selected time slot, the node uses an election algorithm to compute whether it can win or not. If it wins, the node broadcasts its schedule to the neighbors and repeats the procedures in the next transmission time. If it fails, the node selects the next time slot and continues the contention procedures until it wins. The election algorithm guarantees that a node will eventually win and will thus obtain a chance to transmit data.

Routing: The 802.16 standard [64] only specifies the MAC layer and routing is left for the higher layers. However, the network topology in the 802.16 mesh is considerably different than in 802.11 mesh networks. In 802.11 mesh networks the design is based on allowing the topology to be an arbitrary mesh network. Correspondingly, routing is more complex in 802.11 mesh networks. In contrast with this, an 802.16 mesh network consists of a single base station and the mesh is a tree network, see Figure 6. Thus, the routing problem is considerably simpler in 802.16 networks and it essentially concerns only the scheduling of the links in the network to achieve fairness for the end-to-end flows. However, this represents only the current viewpoint, and the standards may evolve so that in the future more general topologies would be supported.

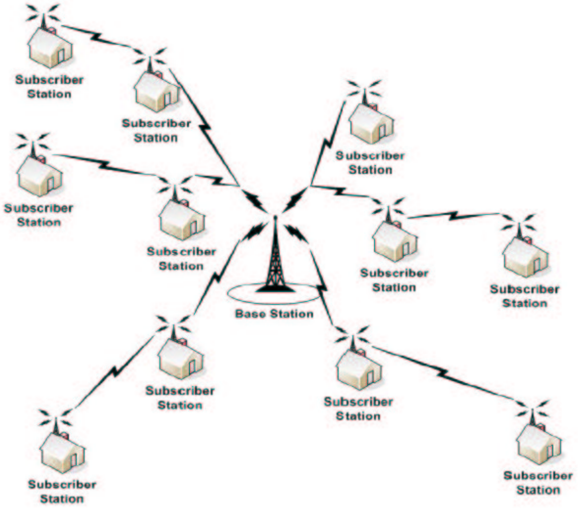

Figure 6: An example of a 802.16 mesh network [82]

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2.3.3 IEEE 802.16 mobility management and multihop relaying

Procedures for mobility management with support for handovers has been standardized in the amendment 802.16e. The work was completed in early 2006 and these efforts even further establish 802.16 based networks as an alternative technology for traditional cellular networks.

The mesh mode in 802.16 does not have a very clear use case behind it to advance the deployment of 802.16 based mesh networks. This is in contrast to 802.11, where 802.11s has been defined to implement a wireless distribution service connecting 802.11 access points. However, within the 802.16 working group there has been a strong interest in developing an amendment supporting mobility and a limited form of multi-hop communications known as multi-hop relaying which would be compatible with the PMP operation mode. To this end, another study group called the “Mobile Multihop Relay (MMR)" was established in July 2005 under 802.16 working group. The main purpose of this study group is to study the possibility for extending the PMP mode for a node outside the coverage of a base station and to support mobile nodes by using so called relay stations, which simply relay information between a node towards a base station and vice versa. Hence, unlike the mesh mode, dedicated relay stations form a treelike topology for forwarding the traffic to the base station. The standardization work on this is presently pursued in the 802.16 task group j.

3 IP-layer solutions

As many kinds of networks (cellular, wlan and manets) need to be integrated in future heterogeneous wireless networks [21] it is important to consider IP-level functionalities. The network layer can provide a common level of operation and unify the different network types, from the point of view of upper layers. Inter-network client mobility, between networks using different link-level designs, could possibly be accomplished with IP-level solutions.

In this chapter, we discuss mesh networking and routing at the IP-layer. Several current best practice and new state of the art conventions are presented and their suitability for wireless mesh networking is estimated. In sections 3.1 and 3.2 we review some options for implementing routing in a mesh network. Key issues to consider when choosing a routing solution are, for example, the suitability of the protocols to the MAC layer, requirements on the mesh routers and on the end user terminals, and support for mobility, load balancing, and various security measures. Section 3.3 describes approaches to local mobility management. Then, in section 3.4 we examine different autoconfiguration methods. In section 3.5 we describe how detection of network attachment and link notifications can enhance network level performance.

3.1 Routing in wireless mesh access networks

Wireless networks used for more than simple access point and last-hop technology usually contain paths with multiple hops using a wireless connection. As mentioned in chapter 1, this affects the performance of the network. Depending on the routing protocol, multiple paths between local nodes and towards the Internet may be available. Multi-hop wireless mesh networks require a new evaluation of routing protocols.

Link-layer functionality is very important in wireless mesh networks. Section 2 presented several protocols that have a very central role in the operation of WMNs. Many proposals move some routing functionality from the network layer protocols to the MAC-protocol. It is however yet unclear how well these proposals work in practice. Cross-layer design and other dependencies between layers requires caution [79]. Heterogeneous networks can include several access technologies which necessarily cant share a single MAC protocol [21]. Network layer functionality is needed to integrate different technologies into an unified network. Even with an advanced MAC protocol some network layer functionality is bound to be needed. Protocols suitable for wireless mesh networking need to be developed or discovered from existing ones.

For wired networks a hierarchal topology is commonplace. Cross cables add to the cost of the network. In wireless networks mesh connectivity is a natural consequence of radio technology. Even with directional antennas the effort of adding new links between nodes is much smaller than that of laying cable in the ground. A mesh topology increases the robustness of the network, since single-points-of-failure, commonplace in hierarchies, are absent. Multiple routes between nodes and several gateways to the wired access network are available.

3.2 Ad-hoc routing

Routing protocols developed for ad-hoc networks offer novel approaches to routing in wireless mesh networks. Even though WMN routers are relatively immobile and the backbone routes thus quite stable, are clients in WMNs often mobile. Ad-hoc routing protocols could be used to create networks where clients actively participate in routing. Clients with a suitable protocol stack or software package could for example gain wider access to bandwidth in exchange for participating in routing of other clients traffic. In addition to adapting to node or router mobility, ad-hoc routing protocols are often designed to conserve bandwidth and to otherwise adapt to wireless network environments

In this section we introduce the basic principles of some popular ad-hoc routing protocols. There are two main approaches to ad-hoc routing, namely proactive and reactive protocols.

3.2.1 Proactive routing

Proactive routing protocols resemble many routing protocols for traditional wired networks in that they try to gather and maintain routing information about the whole network they are being used in. Routing information is exchanged and processed proactively, i.e. before any need to route data arises.

Optimized Link State Routing (OLSR) protocol [47] is a proactive routing protocol for ad-hoc networks [35]. The development and standardization of the protocol is currently producing a second version [35]. As the name conveys, OLRS is similar to a link state routing algorithm, but with some enhancements. The main feature of OLSR are multipoint relays (MPRs). Multipoint relays are selected in a distributed fashion among routing nodes of the network. The MPRs are then used to constrain the amount of traffic needed to maintain routing information proactively. When information needs to be spread through out the network, i.e. ’flooded’, it is done via MPR nodes, so that redundancy of transmitted information is cut down considerably. Every MPR also spreads link state information for those nodes, that have selected it as their MPR. This way not all link states need to be propagated, just links between MPRs and the links between MPRs and nodes that have selected them.

Each node selects one or more nodes among its one hop neighbors to be among it’s MPR. By constantly monitoring local connectivity to neighbors two or less hops away, the selection of MPRs can be done so that a node can reach all its two hop neighbors via it’s MPRs. This requirement ensures that communication is done on paths with minimal number of hops, even though all link states are not known.

From a WMN point of view the concept of multipoint relays has many favorable characteristics. The amount of traffic is cut down by grouping nodes around their MPRs, which then relay much of the traffic. Nodes with many links to other nodes and thus maybe also otherwise better connectivity, are more likely to be selected as MPRs. In a WMN this could for example make good use of mesh routers. The distributed selection of MPRs makes it adaptive and fault tolerant.

3.2.2 Reactive routing

Reactive routing protocols are the second kind of approach to ad-hoc routing. Reactive routing aims to reduce the amount of resources taken up by routing. The idea is to only create routes when they are needed and to only maintain routes that are in use. Bandwidth can be saved, when route updates for unused routes do not need to be propagated across the network. Storage and computing resources and thus ultimately also electricity, are saved when all nodes do not store and process big routing tables.

Ad hoc On-Demand Distance Vector (AODV) Routing [121] is a reactive routing protocol. Using messaging from node to node, the protocol creates routes, when nodes need to talk to each other. Timers and sequence numbers are used to avoid stale or flawed routes.

In addition to normal routing information, like destination address and network interface, a routing entry in AODV contains a destination sequence number, a list of precursors and a lifetime counter. Sequence numbers are used as a simple form of distributed time. The numbers are created and incremented by the host that is the destination of a route. Another host may only modify a destination sequence number it has stored, if the route times out or breaks. A host always uses the routing information that has the most recent sequence number. This way routing can be kept loop free. The list of precursors contains nodes that possibly use the route through this node. Such nodes need to be informed, if the connection to the next hop is broken. Routes in AODV are soft state, ie they time out when not used. The lifetime is used for keeping track of how long a route is in active use and after that a period before deletion of the information. A route expires by default after three seconds of inactivity and is deleted about 15 seconds later.

There are three main message types used in AODV. A *Route Request* (RREQ) is sent to acquire new routes. Requests are broadcasted with a low TTL, that is gradually incremented if no route is found. Nodes that receive a request forward it only once, by keeping track of sequence numbers, and store a route back towards the source of the request. A *Route Reply* is a response to a RREQ, completing the creation of a route. It travels back through the reverse path created by the request. A node other than the destination can also send a RREP, if the requester does not mark it forbidden on the request. In case a node along the way replies, it needs to send a 'gratuitous RREP', a carbon copy ,of the reply to the destination, so that the destinations routes towards the requester are kept up to date as well. A *Route Error* (RERR) is used to inform other nodes about errors.

In addition to arriving protocol packets, several methods can be used to gain information about neighboring nodes. RREP packets with a TTL of one can be used as hello messages, but only when a node is part of an active route. Triggers from the link layer, if they are available, can be used as well.

Dynamic MANET On-demand (DYMO) Routing [22] is a newer development in the area of proactive routing. It is not fully standardized yet, but the initial design is very similar to that of AODV. The same three protocol messages are used as well as sequence numbers. DYMO uses a generalized packet and message structure, which might make it more compatible with other future ad-hoc protocols. Another improvement compared to AODV is simple Internet attachment and gatewaying, which enables a node to function as a gateway to outside network for nodes that configure addresses from the nodes address prefix.

3.3 Local mobility protocols

Mobility is important in wireless networks. It is central for good user experience, that a a mobile user gets continuous uninterrupted service, while on the move. Mobility is often categorized into local and global mobility. Local mobility refers to clients changing their point of attachment within the same administrative domain. Mobility on a wider scale, global mobility, enables clients to move between different local mobility domains. For global mobility, insomuch as it is deployed, Mobile IP [74], defined by the IETF, is the dominant approach.

When a mobile host attaches to a network it needs an IP address. Many times it is the responsibility of the local mobility management protocol to make address resources available to the host. A host also needs a default gateway address and preferably other network parameters like a domain name system address. A central function of the local mobility management is to configure routing in a manner that enables both inbound and outbound communications for the mobile host. When a host performs a handover and reattaches to the network at another location, it is essential, that the host can maintain existing connections, ie. the previously assigned address is kept reachable and the host is allowed to keep or reconfigure it. The host also needs to be informed of network parameters, such as the default gateway, that might have changed.

Location of the default gateway and thus the frequency it changes at during mobility depends on whether the network is an I-mesh, M-mesh or H-mesh, as described in section 1.2. In a M-mesh a single IP router might be seen as the default gateway for the whole mobility domain and in a I-mesh every handover could change all network parameters, including gateway.

Mobility patterns of the network can also greatly vary. Traditionally movement is most often along the edge of the access network. In this type of 'edge mobility' a mobile host mostly moves in a linear and orderly fashion from one access point to the next, at the edge of a structured and hierarchical network. More recently ad-hoc networks have introduced a wildly different kind of movement. In an ad-hoc scenario mobile nodes form a multihop networks where any node might move in unpredictable directions and connectivity can be unreliable and rapidly changing. A WMN is something in between these two extremes. The topology is not completely stable, as routers can be added and removed at any time. Deployed protocols must be able to handle route and node failures. Still, the network might have some hierarchical structure, with a wireless backbone providing more ample and reliable bandwidth and routes. Even though routers might move, it is mostly mobile hosts that change their points of attachment from one access router to another.

There are some additional aspects to consider, when it comes to performance and scalability of local mobility protocols [119]. Essential for latencies is, that as few and as short as possible round trip times are used for signaling. Preferably central protocol functions should be performed with one message.

Routing should be kept as optimized as possible. The indirection added by local mobility management usually creates some deviation from regular routing, but it should be kept to a minimum. A local mobility protocol should not assume mobility functionality from all devices in the access network and it should function in parallel with other routing mechanisms and not assume the presence of only some specific routing protocol. Autoconfiguration is important in dynamic networks. Mobility entities should be able to adopt to changes in the network and addition of new mobility entities as independently as possible.

If the use of a global mobility management protocol is assumed, the performance of a local mobility management solution also depends on the number of intra-domain handovers compared to inter-domain one. Also the number of peers the mobile host communicates with outside the local mobility domain . A node that moves infrequently and has little communication with outside nodes does not benefit from a distinct mobility management for the local domain. It can use global mobility protocols for all movement. For fast movement, strict speed requirements or voluminous communication however, local mobility management might be indispensable.

Numerous solutions exist for managing handovers between points of attachment, changing routes and forwarding traffic, within a single administrative area. In this section we present four protocols that well describe different main approaches in designing for local mobility management.

3.3.1 Hierarchical Mobile IP

Plain Mobile IP (MIP) has shortcomings that are remedied by various additions. The *Hierarchical Mobile IPv6 Mobility Management* [138] (HMIP) extension to Mobile IP was designed to address scalability and efficiency issues with local movement. Without HMIP extensions MIP signaling suffers from potentially long RTTs, when communicating with the Home Agent (HA). A longer route also increases the probability of packet loss, though not always significantly. When using wireless connections, a longer route and more hops can cause delays due to retransmissions on the link level. Sending Binding Updates, especially to very remote hosts, frequently is a scalability issue for mobile hosts and their Correspondent Nodes (CNs) and at the least wasteful on resources from the visited networks point of view.

With HMIP a new level of indirection is introduced. A new mobility entity, a *Mobility Anchor Point* (MAP) is placed in the local mobility domain. It is used by the mobile node as a local HA. When the mobile host arrives in the local mobility domain it receives one or more Router Advertisements containing HMIP specific options that allow it to statelessly configure an address and to become aware of the MAP. The acquired address is registered with the MAP as a *Regional Care of Address* (RCoA). A binding is established between the MAP and the HA of the mobile host. The mobile host also acquires, either via stateless or stateful configuration, a regular address and gateway, so that it has hierarchically routed IP connectivity within the APs subnet of the mobility domain. The address is referred to as a *Local Care of Address* (LCoA). When the mobile moves into another subnet or addressing area within the HMIP mobility domain, it acquires a new LCoA as usual. Then it sends a *Local Binding Update* (LBU) to the MAP, so that a binding between the RCoA and the new address is established. As long as the mobile host moves between points of attachment within the HMIP access network, it does not need to signal outside CNs or its HA about changes. Only one LBU to the relatively close by MAP is needed. The difference in signaling between local and global mobility is illustrated in Figure 7.

While visiting HMIP operated domain the the mobile host can exchange data with outside nodes using its RCoA as the source address. Such packets are tunneled between the mobile host and its MAP using the current LCoA of the host.

There can be several MAPs within an access network. The presence of multiple MAPs can give redundancy against a MAP failure and MAPs at different positions, fex different levels in a hierarchical network, can be used by clients with different mobility patterns. In a large access network, possibly with multiple gateways, the path from the MAP to the mobile hosts current access router can become suboptimal. A host may use multiple RCoAs at the same time. To make a switch between MAPs smoother a host can register, with a LBU, the LCoA from the new MAPs area with the old MAP. This way packets using the old RCoA, that arrive after the handover, are forwarded to the new location. It is however explicitly forbidden to establish a binding to a MAP using a RCoA acquired from an other MAP, thus ’concatenating’ RCoAs into several layers of forwarding.

To help a mobile host choose between multiple advertised MAPs, a preference value is included in the HMIP RA option. The algorithm suggested by the specification for selecting a MAP is not very flexible. It simply always selects the MAP that is furthest away from the mobile host. In some hierarchical scenarios this might be reasonable, but in a WMN it seems very unsuitable, unless the topology is very stable and centrally planned.

Even the one extra level of forwarding and tunneling adds a delay and might make routes suboptimal. Several MAPs are allowed, but an RCoA is always bound to a certain MAP, so there is a single point of failure for globally routable traffic with any given RCoA used as source or destination IP address.

Handover signaling is quicker with HMIP, but it does not make handovers smooth. Some packet loss might still occur, while setting new bindings. To alleviate this it is possible to use Fast Handovers for MIP [46] with HMIP. With Fast Handovers the access routers involved in the handover preconfigure new LCoA before the handover and forward traffic arriving at the old access router, to the new AR. Forwarding is even possible in a handover, where the LCoA does not change. Anticipating the correct time for traffic redirections is still difficult and requires link layer notifications[1].

3.3.2 Cellular IP

The designers of Cellular IP envision a wireless Internet with many hundreds of millions of wireless subscribers [18, 155]. Like the name suggests, many of these are pictured to be cellular phone -like wireless IP communicators. These devices would be switched on constantly, ready to send and receive data. It is anticipated, however, that a majority of the mobile hosts would at any given time be in a passive state. By supporting paging of idle hosts it is more feasible, that the design will scale to support the envisioned very large number of hosts and at the same time devices can save energy by limiting signaling over the wireless link.

A Cellular IP access network consists of *base stations*, that function as wireless access points for the mobile hosts and route traffic to and from *gateways*, that connect the network to the Internet. Cellular IP is compatible with Mobile IP (MIP). While in the Cellular IP access network tunnel between the MIP Home Agent and the Care-of-Address (CoA) of the mobile host is terminated at the gateway and the data routed by Cellular IP. The gateway periodically broadcasts a packet that is flooded through the access network. Base stations record the ingress interface of this packet and use it to route traffic towards the gateway. The base stations are assumed to be interconnected by wired links.

Cellular IP is, like the name also suggests, an IP level protocol. It completely replaces regular IP routing in the access network and on the mobile hosts. Other IP stack functionality is unaffected. Mobile hosts are identified by their MIP CoA or any other unique IP address they have preconfigured. To route active connections, most base stations, but not necessarily all, run *routing caches* (RCs). The RCs maintain soft-state host specific routes for mobile hosts whose traffic is routed through them. The timeout for a route in a routing cache is in the magnitude of of a few seconds.*Paging caches* (PCs) also maintain routing information, but with a longer timeout. When a host is idle and its route times out from RCs, the PCs can

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[1] more about link layer notifications in section 3.5

be used to determine its location. PCs are not required to run on as many base stations as RCs, but demand more computing resources, since they , due to the longer timeout, collect more routing information. The timer for PC entries depends on the frequency of host mobility and whether the hosts update their location information after a handover, even when idle.

Entries in both types of caches are refreshed by regular data packets sent by the mobile host. In addition hosts that want to maintain active connections, but currently don't have any data to send, can use special ICMP packets, *routing updates*, to refresh the RC entries on the route from their point of attachment to the gateway. Idle hosts should similarly send *paging updates* to maintain a presence in PCs.

Cellular IP supports two types of handovers. Both types are initiated by the mobile host. In the hard, 'break before make', handover the mobile host just breaks its link level connection to its current base station and connects to another one. The other type of handover allows the mobile host to make a semisoft handover by briefly switching over to the new base station and sending a *semisoft packet*, which creates a new route from the new base station to the gateway, but does not affect the old route. Thus the traffic is duplicated until the mobile host has changed to the new base station and the old route has timed out. The new and old traffic streams are however not synchronized or necessarily even buffered in any way, so some packet loss may occur. If a mobile host is able to have two wireless connections simultaneously, it is possible for it to maintain and refresh routes originating from two base stations, making handovers smoother.

Cellular IP does require modifications to both routers and mobile hosts in the AN. Though using per host routes potentially removes the need for address configuration functionality and speeds up handovers, it makes hierarchical routing impossible and requires that mobile host addresses are somehow preconfigured.

Evaluated from a WMN point of view Cellular IP is not a perfect fit. The assumption that base stations, ie the network nodes forming the access network, are wired together does not hold true in a WMN context.

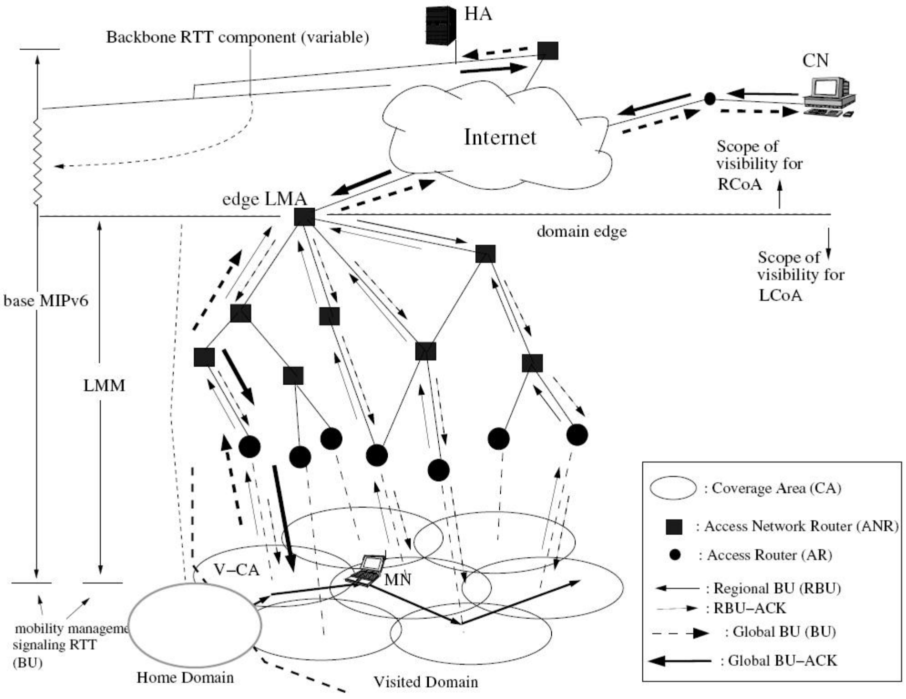

Figure 7: Domain differentiation in mobility binding signaling for signaling reductions in local mobility management [119]

Periodically flooding the address of the gateway is not a good choice when it uses up wireless bandwidth. The hop-by-hop building of routes towards the gateway is able to recover from broken links and to take advantage of cross-connections typical of meshes. However, the the forwarding Cellular IP uses for routing packets seems to implicitly assume nodes in the forwarding topology to have at least two separate interfaces, so that it always makes sense to forward a packet arriving on the interface 'downstream' from the gateway on to the 'upstream' interface. It is unclear how well this would work in a mesh and it seems likely that, at least with a single radio frequency, it would waste bandwidth. The lightweight protocol, autonomous and distributed design and computation efficient use of network level signaling are still worth keeping in mind.

3.3.3 Brain candidate mobility management protocol

Brain candidate mobility management protocol (BCMP) [13] has common features with both HMIP and CIP, but as a whole it represents an original approach to local mobility management.

In addition to the mobile host, two other network entities participate in BCMP, an *anchor point* (ANP) and all access routers at the edge of the network, ie those ARs that the mobile host directly communicates with. All three types of nodes are required to have BCMP specific functionality.

All functions in BCMP are initiated by the mobile host. However the mobile host does not need to address any specialized entity or anchor within the access network. Commands by the hosts are issued to its current access router, which forwards them to target entities withing the network. So when a host enters the local mobility domain it issues a login command. The access router it uses forwards the message to a suitable ANP. The ANP's reply, that is in turn forwarded from the access router to the mobile host, provides the host with an IP address. The address is allocated from the ANP's subnet or prefix. A tunnel is created between the ANP and AR. All inbound packets to the mobile host are intercepted by the ANP and tunneled to the AR it is attached to. Outbound packets from the mobile host are sent using the access networks regular routing mechanism and the mobile hosts default gateway is always its current AR.

A handover can be either prepared or unprepared. When the mobile hosts knows in advance which access router it will attach to next and that the handover will happen soon, it can send a handover preparation message. The preparation command checks whether the mobile host is allowed connect to the potential AR and if so, creates a temporary tunnel between the current and new AR. All packets addressed to the mobile host are duplicated to the future location. When the handover, prepared or unprepared, takes place, the mobile host sends another command, this time via the new AR. The new AR forwards the command to the old AR, which replies with information about the mobile host. In case the handover was unprepared the tunnel between the old and the new AR is created at this point. Finally the new AR signals the handover to the ANP and the tunnel from the ANP to the old AR is then modified to terminate at the new AR. After all this the mobile host receives a single reply announcing a successful handover.

Its also possible to switch between ANPs. From the mobile host's point of view it is performed in the same way as the initial login. The address of the mobile host changes to one that is located with the new ANP. Similarly to the handover between ARs, a tunnel is created, but in this case between the old and new ANP. Packets arriving for the old address are tunneled to the new ANP and from there to the mobile host.

Compared to the extensive MIP/HMIP specifications BCMP is quite simplistic. This means that some features might not be present, but on the other hand it makes the protocol significantly lighter to implement. As a working implementation already exists it can be claimed that the most central functions of a local mobility management protocol are fulfilled.

Unlike HMIP, BCMP does not depend on any specific global mobility protocol. Like CIP, it could be used together with any suitable global mobility protocol, also MIP.

Allowing the mobile host to issue its commands through its access router and making the AR its default gateway abstracts the intricacy of choosing a target ANP for commands and isolates the mobile host from network level topology changes in the access network. On the other hand this feature removes some freedom of choice, compared to HMIP. It might not be possible to put algorithms for choosing between ANPs in the mobile hosts. Then again, it might be easier to put failover mechanisms in the access routers and thus add features without further complicating the mobile host's interface.

From a WMN standpoint BCMP's type of signaling, that only requires the client to send a single message and receive a single reply, is desirable. It saves the bandwidth between client and AR, which might be the most scarce in the whole access network and conserves the potentially low power resources of the client. There are results indicating, that BCMP signaling benefits from cross connections typical of WMNs [81]. Handover preparations are signaled directly between the access routers at the edge of the network and handovers involve only minimal signaling to the ANP and mobile host. This way the signal path is shorter, as it does not need to be routed through an anchor point or gateway. The handover is similar to that of HMIP with Fast Handovers (described in section 3.3.1), but without the requirement to implement three extensive specifications.

3.3.4 Network-based Localized Mobility Management

The three previous protocols all, to some extent, involve the mobile host in their workings. Network-based Localized Mobility Management (NetLMM) is the IETF's recent endeavor to create a method for local mobility, where all new functionality is located in other nodes of the network, than the mobile host. Mobile hosts can move around the NetLMM domain without being aware of any changes in their network layer point of attachment, ie continuously using the same IP configuration and maintaining seamless connectivity.

Design of the protocol is in the early stages. The goals that NetLMM strives to meet are quite extensive [44]. A fundamental one is providing local mobility management for unmodified mobile hosts. This means that a mobile host moving through a NetLMM domain would not need any NetLMM specific software. The design does, however, assume the presence of some other features in the network stack of the mobile host [92]. Several of the features are established and widely deployed standard practices, but others are not yet very widespread or fully standardized. Currently the assumed features of the host include:

- Neighbor Discovery for IP version 6
- IPv6 Stateless Address Autoconfiguration
- Dynamic Host Configuration Protocol for IPv6 (DHCPv6)
- Privacy Extensions for Stateless Address Autoconfiguration in IPv6
- Detecting Network Attachment in IPv6 - Best Current Practices for Hosts
- Detecting Network Attachment in IPv6 Networks
- SEcure Neighbor Discovery
- Cryptographically Generated Addresses

In addition the NetLMM protocol aims to provide handovers that are as seamless as possible, but using a low signaling volume, especially on the wireless link between mobile host and access router [44]. The requirements seems to implicitly assume a wired access network, but it is too early to say. Furthermore the requirements state, that the 'data plane' component of the access network should be configurable. This means, that it is possible to change the method used for carrying data between mobility entities, like the ANP and AR of BCMP and caches of Cellular IP. A configuration option like this might enhance usability in a WMN environment. Multipath routing or extra compression might fex be used to adapt to a meshed topology.

No extra security associations or bindings are required between the mobile host and the network. Since the host is unaware of the presence of mobility management, it can not be required to provide mobility specific authentication credentials. The access network can demand AAA procedures in some other context and that is assumed to be enough.

The protocol is meant to be independent from other design choices of the network. Though the initial design uses IPv6, the protocol is meant to work with IPv4 as well. Independence from link layer protocols is designed for and no specific global mobility protocol is assumed.

An initial draft of NetLMM protocol outlines the central principles of the protocol for an IPv6 based network [54]. The protocol uses two central entities placed in the access network. A *Mobile Access Gateway* (MAG) is attached to the link layer technology the mobile hosts use to access the network. The mobile hosts see it as a first hop router and the MAG is able to detect link layer attachment and possible detachment of mobile hosts. A *Local Mobility Anchor* (LMA) is a router that provides address space, that is allocated to mobile hosts and it maintains routing states for allocated addresses, so that they remain reachable. An access network can contain more than one instance of both MAGs and LMAs. A MAG can be aware of multiple LMAs and a LMA certainly needs to know several MAGs.

The NetLMM protocol has ten message and reply pairs, ie twenty different messages. These messages divide into two categories. Six of the twenty are used for configuring and maintaining associations between MAGs and LMAs. The remaining seven pairs are used for the core mobility functionality. All messages, except one optional pair of authentication messages, are exchanged between a MAG and a LMA.

When a mobile host first enters the access network the MAG whose link layer it attaches to requests address information from a LMA. The address space allocated by the LMA is then used, when the mobile hosts acquires an address using either stateless or stateful configuration, ie SAA or DHCPv6 (more about these in Section refsec:ip-layer:autoconfiguration). The MAG sends the LMA a message containing information about the configured mobile host. The LMA starts routing traffic for that address to the MAG and the MAG forwards it to the mobile host.

A handover happens, when the mobile host stops using one MAG and appears on the link of another MAG. The new MAG has no state information on the mobile host, so it queries a LMA identically to the scenario of mobile host initial network attachment. The LMA, if its the same LMA, on the other hand, has an entry for the host. It states this information in its reply. The MAG uses this, so the mobile host can optionally choose to configure the same address as previously. To the host it looks like it is on the same link as before the handover and network layer connectivity need no be disrupted.

NetLMM base design has very many messages and extensive signaling and might thus not be ideal for a WMN. Initial mobile host address assignment and handovers both require four messages to be exchanged between MAG and LMA, creating a delay of at a minimum two RTTs. Handovers between MAGs go through the LMA instead of using possible connections between. The design does acknowledge these deficiencies and future extensions or optimizations might be made to rectify them.

Some issues that other described designs take into account, like a host doing a quick ping-pong movement between two MAGs or failures of mobility entities, are not addressed in the early draft of NetLMM. LMA to LMA handovers are not discussed either.

3.4 Autoconfiguration

For clients to be able to roam between networks and for newly added mesh routers to become functional automatic configuration and negotiation of network parameters is required. The designs of most routing and even some, mobility protocols, especially local mobility ones, assume the availability of an IP address for the host.

Even when a node is supplied with an address by a local mobility management protocol, as in BCMP for instance, it might want to use an external method to configure another address for multihoming. This could be useful for communicating with nodes within the domain, if the mobility management does not provide a locally routable address.

Hardware addresses can not be relied upon to be globally unique [152]. When using IPv4 addresses and MAC hardware addresses it is also significant to note that a MAC address is 16 bits longer than an IPv4 address. Generating addresses of the former kind using the latter is thus not possible without collisions. Using hardware addresses either directly or even as a hash also has privacy issues, if the address always remains the same or even predictable [115]. A common address pool of any addresses is not possible without co-ordination or agreements of some kind.

A mesh may have a relatively stable topology or at least enough paths to keep most nodes connected and available at most times. In that case an established solution like *Dynamic Host Configuration Protocol* (DHCP) or in the case of IPv6 also *Stateless Address Auto-configuration* (SAA), might be the best choices. They are widely deployed and generally supported by network hosts.

When a network is more unstable and large segments of nodes at a time become isolated from the main network, other solutions might be more suitable, than DHCP or SAA.

The design issues of address auto-configuration can be divided into, among others, the following important events and properties [67].

- Initial address selection: the host configures an address
- Type of address pool: randomly selected, centrally assigned or addresses stored in some distributed manner can be used
- Address reuse: after a host leaves the network addresses can be put back into the available address pool
- Network partitioning and merging: large parts of address space disappearing, reappearing or new overlapping parts merging, require special consideration. Illustrated in Figure 8.

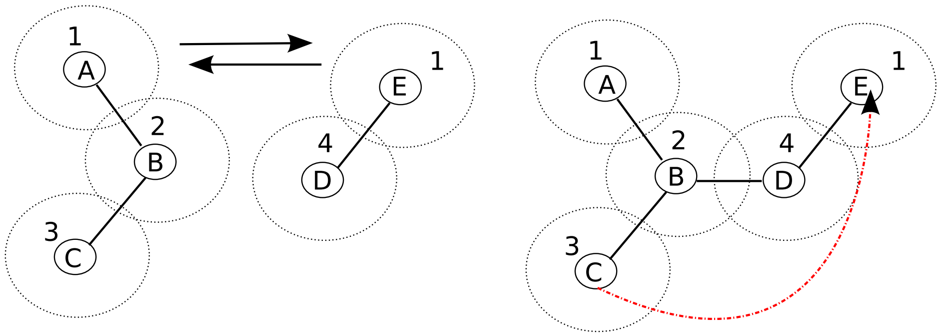

Figure 8: Network segments with conflicting addresses merge. Data from node C to A might be routed to E. (Adapted from [163])

3.4.1 Dynamic Host Configuration Protocol

Systems for allowing network hosts to automatically configure centrally coordinated addresses have been defined for both IPv4 and IPv6. These are called *Dynamic Host Configuration Protocol* (DHCP) [41] and *Dynamic Host Configuration Protocol for IPv6* (DHCPv6) [45] respectively.

Both specifications define a client server protocol using UDP transport. Before the client host has any address configured it can not receive unicast IP traffic. DHCP solves this by using broadcast for the initial request reply pair of messages. In DHCPv6 the client is expected to configure a link local IP address and send the request as multicast. In dynamic assignment addresses are leased for a specific period of time, but the leases can be renewed. DHCP and DHCPv6 both define ways to relay requests transparently, from the client point of view, between subnets (IPv4) or links (IPv6). The DHCP *client identifier* and DHCPv6 *DHCP Unique Identifier* are address independent identification labels. Their purpose is to uniquely identify clients, and in DHCPv6 also servers, across sessions. With these identifiers it might then be possible for a client to be identified after a handover, so that it can keep its IP level configuration. The identifiers are ’opaque keys’, meaning that their content does not need to be structured in any specific way, so they can be constructed with any method the client chooses. In practice they consist of a hardware address and possibly additional data like a timestamp, but that can only be used, if the host has a properly configured clock available before IP connectivity. So, because hardware addresses have their limitations, as stated in section 3.4, there is also a slight risk of identifiers colliding.

Of the properties listed in the previous section, DHCP offers address selection for hosts, storage of the address pool and reuse of freed addresses. Partitioning of the network presents a problem for DHCP. Hosts in the same network segment with the DHCP server still get configuration information after a network partitioning. The other segment however, is without address maintenance. Hosts might be able to continue to function, but arriving new hosts are not able to configure network parameters. Additionally a partitioning of the network can cause duplicate addresses to be assigned, so that merging segments cause address conflicts.

3.4.2 Stateless Address Auto-configuration

The IPv6 specification specifies a Stateless Address Auto-configuration (SAA) procedure for configuring an address in the absence of a stateful alternative (i.e. DHCPv6) [151]. It allows a node to automatically generate an IP address using local information and possibly advertisements obtained from the network. The procedure starts with the node forming a *tentative address* from its interface identifier (e.g. MAC address or equivalent) and a well-known link-local prefix. A *Duplicate Address Detection* (DAD) is performed. In SAA the IP level Neighbor Discovery protocol for IPv6 is used instead of ARP. If the tentative address is determined to be unique it is permanently assigned to the interface. With this address the node has link-scope IP connectivity. In SAA there are further steps to allow the node to configure a more widely usable IP address. If a router on the network supports it, the node can acquire a new prefix for its link-local address making it a site-local (routable within the access network) or even global. The two latter types of addresses are also unique, since they use the interface identifier dependent part of the link-local address. The specification does not address network merging, even though it is acknowledged to be a problem. (It is also worth noticing, that site-local addresses are most probably deprecated in coming versions of IPv6.)

3.4.3 Auto-configuration With Duplicate Address Detection

Ad-hoc IP Address Auto-configuration (AIAA) [68] is a relatively straight forward stateless protocol. The messages of the protocol somewhat resemble those of the Ad-hoc On -demand Distance Vector (ADOV) protocol used for ad-hoc routing. Development of the methods started in 2001 with a draft [122] by the often cited C. Perkins and others and it is currently continued in one of the drafts the autoconf wg is working on.

The protocol uses a two-phase DAD [68]. At first it executes a so called *strong DAD* to test if an address is unique. Then, continuously during the nodes operation, a so called *weak DAD* is performed. To remain simple to implement, the protocol only specifies one packet format, which is used for all three of its messages. Only the value of the type-field of the packet differs between messages. Because the packets headers are modified during transfer, the message contains the originators IP address. It also contains another IP address field, used for specifying a *requested address* or *duplicate address*. A 32-bit *identification* field is included to avoid loops in protocol level packet forwarding. The used messages are *Address Request* (AREQ) *Address Reply* (AREP) and *Address Error* (AERR). However the scheme also requires that the headers of the used MANET routing protocol are extended to contain an *interface key* for use in weak DAD.

Strong DAD starts by randomly selecting a *temporary address* from a range reserved exclusively for that use [68]. In IPv4 there are only 2047 alternatives, but in IPv6 many more. Then a *tentative address* is randomly selected from the available range, excluding the temporary addresses. The node forms an AREQ message containing the tentative address. The message is broadcasted to IPV[4/6]_BROADCAST_ADDRESS. If the node receives an AREP concerning the tentative address, it knows that the address is not available and restarts the strong DAD procedure. Otherwise, after a specified time and amount of retransmissions of the AREQ, the node can assume the tentative address is free and configure its interface. This is the end of the query-based strong DAD. After this the protocol only operates in weak DAD mode. When a protocol message arrives at the node, the packets identification field is inspected. Based on the identification the node decides if the packet is a duplicate of a previously processed packet. If that is the case, the packet is discarded. Otherwise the packet is processed according to what type of message it contains. If the packet is an AREQ for the address the node is already using, the node sends an AREP asserting its control of said address. An AREP matching the nodes IP address both in the destination address of the IP packet and duplicate field of the protocol message makes the node configure a new address. Arriving routing messages are compared against information from previously seen messages for conflicting address and interface key pairs. If a conflict is detected the node unicasts an AERR to the conflicting node with the smaller key value. Thus only one conflicting node needs to reconfigure its address. If the node itself is the valid (i.e. both destination address of IP packet and destination field match again) target of an AERR it starts the auto-configuration of a new, non-conflicting address.

This protocols is, compared to many, quite simple. Especially bandwidth overhead for management is low compared to stateful distributed approaches, that have to flood management information. Being limited to 2047 temporary and 65635 actual addresses in IPv4 is an obstacle for scalability [67]. Particularly since, as the birthday paradox states, address conflicts are more likely than common sense implies, when using a evenly distributed random scheme [68]. Required integration with the routing protocol is also an additional burden. A preliminary adaptation for AODV has been drawn up [69]. Two nodes performing strong DAD using the same temporary address or requesting the same tentative address are also problems [67]. In a worst case scenario both nodes have to repeat strong DAD. From a security point of view, it might be problematic that any malicious node can send packets that trigger address conflict procedures. The specification suggests that IP security with encapsulated security payload might be used to avoid this.

3.5 Network attachment and link notifications

Detecting initial network attachment and changes in the connectivity are functionalities that have a tremendeous effect on the performance of the IP connectivity. The previous section presented autoconfiguration issues, in this section we discuss network attachment and link notifications.

Detecting Network Attachment (DNA) [2] is an ongoing effort in the IETF to reduce the latencies in verifying the network connectivity. When a host connects to an IP network for the first time, some time is needed to request configuration information from a DHCP server, and optionally perform duplicate address detection. After the initial configuration is received and stored, a mobile host may encounter a series of handovers within the same administrative domain, or between administrative domains. A handover may move the mobile host to a subnetwork which would require new configuration information, but the handover may also happen so that no changes in the mobile host configuration are needed. There is a need for efficient methods for detecting a need to change configuration.

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[2] http://www.ietf.org/html.charters/dna-charter.html

DNA for IPv4 has been defined in RFC 4436 [3]. The key concept is for a node to keep a list of known peers and their IP addresses (routers, DHCP servers). After a link layer handover, a node sends a ARP request for one or more of these IP addresses. If a reply is received, the node may deduce that it is still connected to the same subnetwork.

DNA for IPv6 is somewhat more difficult, the problem statement is defined in RFC 4135 [30]. Some of the key technical and performance problems with IPv6 are the use of multiple routable prefixes per router, and Router Discovery and Router Advertisement.

Link layer triggers or notifications are key elements in detecting network connectivity and handovers [170]. The basic events are "link up" and "link down". A handover can be seen as a link down event followed by a link up event. The Internet Architecture Board has raised issues in the use of link events [2].

4 Modeling and performance evaluation of wireless mesh networks

A large number of scientific papers on various performance aspects of wireless mesh networks have appeared. In this section, we highlight the recent developments in the literature by focusing on three areas: proposals for experimental protocols (both MAC and routing), analytical performance modeling of wireless mesh networks and cross-layer optimization issues.

4.1 Research proposals for MAC/routing protocols in mesh networks

As the current status of the standards described in Section 2 indicates, the standardization is still not complete, especially for 802.11s. In the case of 802.11s, for example, the present status merely represents the desired design goals and requirements set on the system, which have been defined based on current state-of-the-art in research by selecting certain efficient solutions which are also deemed practical from an implementation point of view. However, there exists a large number of research proposals on more efficient MAC layers possibly supporting multiple channels/radios together with new routing schemes for multi-hop wireless communications. An additional problem not really addressed in the standards is the inherent unfairness at the flow level in the random access schemes based on 802.11. In the following, we give a brief overview of the most common approaches available in the literature.

4.1.1 MAC protocols for 802.11 mesh networks

Utilization of multiple channels: As mentioned earlier, the 802.11b standard defines 3 orthogonal channels that can be used for data transmissions, and the 802.11a standard defines up to 12 channels. In general the use of multiple channels can be used to substantially reduce the impact of interference by allowing two neighboring devices to communicate simultaneously over different channels, which would not be possible due to interference when using only a single shared channel. Another aspect in the problem is that it is technically and economically feasible to equip the nodes with multiple wireless interfaces. This combined with the use of multiple channels, enables the nodes to operate in a full duplex manner, i.e., a node may transmit and receive simultaneously. Depending on the assumptions made regarding the number of interfaces and the sophistication of the co-ordination among the nodes, different schemes have been proposed. The approaches available in the current literature can be categorized as follows [110]:

- *Common hopping*: In this approach, nodes have only one radio. Nodes not exchanging data cycle through all channels synchronously. A pair of nodes stop hopping as soon as they make an agreement for transmission and rejoin the common hopping pattern subsequently after transmission ends. These techniques require tightly synchronized transmissions and very fast channel switching times, which are not feasible yet in practise. Examples of these approaches include HRMA [149] and CHMA [154].
- *Split phase*: Also, in this approach, nodes use a single radio. Time is divided into an alternating sequence of control and data exchange phases. During a control phase, all nodes tune to the control channel and attempt to make agreements for channels to be used during the following data exchange phase. The advantage of this approach is that it requires only one radio per node. However, it requires time synchronization among all nodes, though the synchronization can be looser than above in “Common hopping" -approaches because nodes hop less frequently. Examples of this approach are MMAC [137] and MAP [24]. Their main difference is that the duration of the data phase is fixed in MMAC whereas it is variable in MAP and depends on the agreements made during the control phase.
- *Multiple radios*: One basic approach is to have exactly two radios. One radio is tuned to a channel dedicated to control messages; the other radio can tune to any other channel. The nodes listen to

a common control channel and announce their agreements. For the data exchange, the nodes then switch to the channel agreed upon in the control channel. This system's efficiency is limited only by the contention for the control channel and the number of available data channels. An example MAC protocol of this is DCA [165]. Also, the 802.11s MAC layer will be based on this approach. Genuine multi-radio protocols (with more than 2 radios) are considered, e.g., in [124] and [88]. In [124] a dedicated fixed channel is used as a default channel for the network. The idea in the protocol is to use a centralized server which periodically computes optimal channel allocation for the radios, which minimizes the amount of interference in the network, both due to the routers belonging to the considered mesh network and the co-located routers of other close by mesh networks. The information about interference levels is constantly monitored by the nodes and the information is sent to the server running the channel assignment algorithm. The default channel is used to forward traffic when the system is changing its channel state, otherwise traffic is sent on the channels specified by the channel assignment algorithm. Another approach for using multiple radios is HMCP [88]. In this approach the idea is also to determine for each node a set of fixed channels to be used by certain interfaces. The remaining interfaces are switchable interfaces that can be tuned to any of the channels. The fixed interfaces are selected so that interference is minimized, i.e., so that spatial reuse of orthogonal channels is maximal. This is done in a distributed manner and it utilizes information about the number of neighbors a given node has (which is obtained from exchange of “Hello" packets). All nodes in the mesh know the fixed interfaces of their neighbors, and the idea when, for example 2 interfaces are used is to use the fixed interfaces for receiving the data and tune the switchable interface to transmit at the receiver's fixed channel.

- *Multiple rendezvous*: In these protocols multiple device pairs can make agreements simultaneously on distinct channels. The main motivation is to overcome the single control channel bottleneck. However, since there are multiple rendezvous channels, special coordination is required so that two devices can rendezvous on the same channel. Examples of this approach include SSCH [7] and McMAC [110]. For example SSCH works roughly as follows. In SSCH there are as many pseudo-random hopping sequences that each device can follow as there are channels. Each device follows them in a time-multiplexed manner. When device A wants to talk to B, A waits until it is on the same channel as B. If A frequently wants to talk to B, A adopts one or more of B's sequences, thereby increasing the time they spend on the same channel. For this mechanism to work, the sender learns the receiver's current sequences via a seed broadcast mechanism (the seeds determine the pseudo-random hopping sequences). The point is that the time that the device stays on one channel is much longer than in “Common hopping" -approaches (several maximum length packet transmission times compared with fraction of this time). Thus, the synchronization requirement is considerably looser and the required synchronization for good performance can be easily achieved.

Directional antennas: The use of directional antennas increases capacity through increased spatial reuse. However, this comes at the cost of increased requirements for co-ordination between nodes. For 802.11 based networks, the use of directional antennas presents two specific problems: deafness and new types of hidden terminal problems. Deafness manifests itself when a node A, say, is communicating with B in a certain direction and another node tries to send an RTS to A, which node A is not able to detect due to the on-going transmission with B. New hidden terminal problems may arise for example due to unheard RTS/CTS handshakes occurring in the neighborhood of a node which is transmitting data to another node. Several protocols have been designed to cope with these problems, which modify the RTS/CTS handshaking procedure of the original 802.11 DCF (e.g., by using fully directional transmissions or combinations of directional and omni-directional transmissions) and include new state information per node on the status of the channel in different directions. Two recent approaches are discussed below:

- A recent general MAC protocol for multihop wireless networks based on 802.11 DCF is DMAC-I [33]. It uses directional RTS/CTS transmissions but for receiving the RTS frames the idle nodes are in omni-directional mode. The fact that reception of RTS frames is done in the omni-directional manner limits the possible transmission distance, compared with the situation when two nodes are both directed at each other. However, DMAC-I includes a mechanism, the so called Multihop RTS, that allows nodes to find out also what is the farthest node a node with directional transmission could reach if the receiver is also directed at the sender.

- Another approach is discussed in [127], which specifically addresses the problem of coordinating multiple directional antennas on a single device. The scenario considered in the paper corresponds to wireless mesh routers with fixed locations. The authors claim that the use of multiple directional antennas simultaneously on a single device for both transmitting and receiving (duplex operation) is not possible due to the interference caused by the side lobes of the directional antenna beam forms. However, synchronous transmission and reception is possible with appropriate power settings. The idea then is to use time sharing between the two modes corresponding to synchronous transmission and reception. This can be achieved by using the legacy 802.11 DCF as the MAC mechanism and adding a separate control layer on top of the DCF functionality.

Improved local coordination for 802.11: All previous approaches basically did not change much the fundamental nature of the 802.11 DCF random access mechanism. However, the used virtual carrier sensing mechanism to avoid collisions is not perfect and it is possible to do better. The objective is then to have a more efficient local coordination mechanism to reduce likelihood of collisions. Two recent approaches are summarized below.

- The approach in 802.11 DCF for handling contention is to use a temporal approach, where collisions are resolved adaptively by changing the length of the back off time of each node. An alternative approach, called spatial backoff [91], is to try to control the interference region of a node. In 802.11 DCF, this can be achieved by using several physical layer capabilities, such as transmission power control, rate control or adjusting physical carrier sensing threshold. A specific proposal exploiting the adjustment of the carrier sensing threshold is in [168].
- The traditional hidden/exposed node problems in 802.11 DCF still receive attention in the literature. A recent protocol, SELECT [25], utilizes the measured signal strength at the sender, and maintains a record of the channel success probability as a function of the signal strength. This relationship evolves over time and it is adaptively changed. This information can then be used to improve the success rate of channel access in the presence of hidden/exposed nodes.

Other MAC techniques/protocols: Below we briefly summarize other miscellaneous MAC layer approaches for increasing the capacity of the network.

- Striping is presented in [160] as a simple approach for taking advantage of multiple orthogonal channels. The idea is to add a separate control layer on top of the 802.11 DCF functionality that handles the transmission of IP packets independently across the multiple channels and also takes care of the possible re-ordering of the packets at the receiver's side.
- W-CHAMB [176] is a TDMA based proposal compatible with 802.11 physical layers. It bears some similarities with the 802.16 mesh mode MAC layer, for example the support for QoS and a distributed scheduler for fairness, along with the TDMA based MAC layer.

Fairness issues: Fairness of the 802.11 MAC layer at the flow-level is a problem in multihop communications. The unfairness at the flow-level basically stems from the fact that 802.11 DCF has been designed to provide fair access to the medium only locally within the coverage area of a single node. Thus, a flow traversing many hops needs to separately compete for bandwidth at each hop along the path since relay traffic is treated exactly in the same way as fresh offered traffic in 802.11 DCF. An extreme case of flow-level unfairness occurs in wireless backhaul networks, as studied in [52], where traffic is always directed from access nodes towards the Internet gateway node, essentially forming a routing tree towards the gateway. In such a setting, a branch in the tree can be represented by a parking lot topology, see Figure 9, from which it is obvious that indeed flows originating from closer to the gateway (e.g., from TAP4 in the figure) obtain a much larger fraction of the throughput than flows originating from further away from the gateway (e.g., TAP1 in the figure).

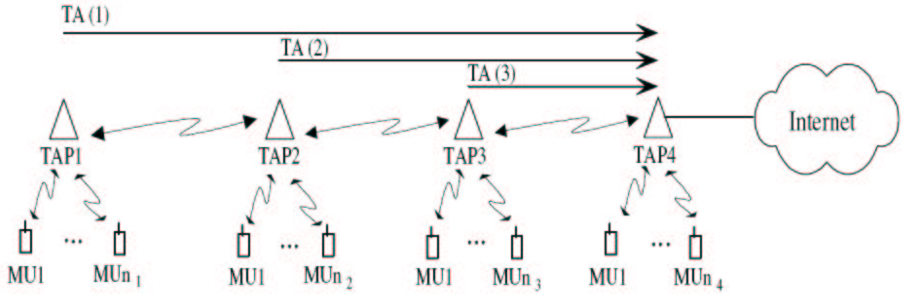

Figure 9: The unfairness problem of 802.11 DCF in the parking lot topology [52].

To solve the unfairness problem requires new/modified MAC protocols, which implement a more fair allocation of bandwidth at the flow-level. Distributed approaches to this involve the allocation of bandwidth to flows by collecting measured information about the offered traffic in different flows and then determining the fair flow shares using a distributed algorithm. In practise many of the proposals implement the enforcement of the fair rates by manipulating the length of the contention window of a node, see, e.g., [60, 106, 42]. Another approach, which implements the flow control as an additional layer on top of the MAC layer is in [52].

4.1.2 Routing protocols for 802.11 mesh networks

The 802.11s standard will use link layer routing. Hence, here we provide an overview of the literature on mesh routing protocols. The most distinctive characteristic of mesh networks compared with MANETs from the point of view of routing is that the routers are stationary. Thus, routing is not limited by the typical scalability problems of MANET routing protocols due to node mobility. A more acute problem for the routing is to design a suitable routing metric for selecting routes with good performance.

Routing metrics: Many ad hoc routing protocols simply use minimum hop count as the metric for identifying the best routes. However, in static ad hoc wireless mesh networks, minimal hop count paths can have poor performance because they tend to include wireless links between distant nodes. These long wireless links can be slow or lossy, leading to poor throughput. A routing algorithm can select better paths by explicitly taking into account the quality of wireless links. In [39], the performance three interference-aware metrics are compared against using only hop count in a single channel mesh wireless mesh network employing a DSR (Dynamic Source Routing) based routing protocol. The first metric, Expected Transmission Count (ETX), is based on measuring the average loss rate of broadcast packets between pairs of neighboring nodes. The second metric, Per-hop Round Trip Time (RTT), is based on measuring the average round trip delay seen by unicast probes between neighboring nodes. The third metric, Per-hop Packet Pair Delay (PktPair), is based on measuring the average delay between a pair of back-to-back probes to a neighboring node. Of these it appeared that the one-hop RTT and one-hop packet-pair metrics perform poorly, because their load-sensitivity easily leads to routing instability. The best performance was obtained by using the ETX metric. On the other hand, even under moderate mobility hop count performed better than any link quality related metric.

The choice of routing metrics is also addressed in [169]. Based on their analysis it is argued that routing in static mesh networks should be based on proactive protocols than reactive ones (since node topology is not expected to change rapidly). The routing metric should satisfy the following: the metric must enforce route stability and have good performance, and there must be efficient algorithms for determining the best routes and the algorithms must be loop free. For the latter two conditions, the requirement of isotonicity of the metric is identified as a critical property of the routing metric. Isotonicity roughly means that if cost from node A to C is higher than from node B to C, then cost from A to C to D must be greater than from A to B to D. Metrics in a single channel mesh are typically isotonic, but in multi-channel networks this property may not hold, if the metric attempts to capture the fact that routes with more varied channel allocations on the links should favored to reduce the interference, compared with routes where a single channel is used along all links on the route. Two multi-channel metrics are compared, WCETT [40] and MIC (from the authors), which are both non-isotonic, along with the use of hop count, ETX and a variant of ETX called Expected Transmission Time which simply multiplies ETX with the time to send a packet of fixed size at the link rate. However, whereas WCETT is non-isotonic, it is possible to devise a scheme with the MIC metric such that the isotonicity is preserved.

Multi-channel MAC routing: In [40] a routing framework in a multi-radio environment is discussed which is based on a proactive source routing approach. The radios are all tuned to certain fixed channels (i.e., the radios cannot be tuned on the fly to other frequencies). Hence the MAC layer is not aware of the use of multiple channels, i.e., no MAC layer modifications are required. The assignment of channels to the different radios is a difficult combinatorial problem but it is not considered in the paper. The protocol used for routing extends the LQSR (Link Quality Source Routing) protocol with a new path cost metric (WCETT). The LQSR protocol itself is based on DSR (Dynamic Source Routing), which is a reactive (on-demand) source routing protocol. The path cost metric attempts to capture the impact of link loss rates and link bandwidths on the route cost. Additionally, the metric is designed to also favor routes with diverse channel assignments over routes where only a single channel is used.

A similar approach is adopted in [129], where the idea is also to utilize the benefits of using multiple channels and radios without modifying the MAC layer. The proposed architecture includes the channel assignment problem and it is considered jointly with the routing. However, the assumption is that the channel assignment and routing is solved by a centralized algorithm, which is being executed based on link load measurements at a time scale of hours. For the channel assignment problem two heuristic algorithms are proposed. The routing metric is based on knowledge of the traffic matrix, which is used to obtain a metric reflecting the expected amount of traffic flowing through a given link for a given routing pattern. Under this metric, both shortest path routing and multipath routing for achieving load balancing are considered.

A more elaborate multi-radio routing protocol is given in [90]. The MAC layer is based on a more advanced multi-channel protocol, where channel assignment is dynamically solved by a distributed heuristic algorithm, which aims at a balanced allocation of channels that minimizes interference. The MAC layer assumes that part of the radios are tuned to fixed channels, while the rest are called switchable radios. Associated with the switchable channels is a channel switching delay. The routing protocol is similar to the one considered in [40] with the modification that the WCETT metric is generalized so that it also includes the channel switching delay.

Directional antennas: A routing protocol supporting the use of directional antennas is considered in [32]. The MAC layer uses the DiMAC protocol (by the same authors), where the RTC/CTS frames are sent in the directional mode (a node is assumed to know its neighbors and through which beam form they can be reached). Reception of the RTS frames is done in the omni-directional mode, i.e., an idle node is always in the omni-mode. The MAC protocol does not include any special functions for dealing with deafness. The used routing protocol is a modified DSR protocol. The main modification concerns the method to broadcast route request messages (which are used to discover routes to unknown destinations). To perform the broadcast the route request is separately transmitted sequentially on all the different beams of the antenna. For an antenna with n beams, this incurs an increase in the broadcasting delay by a factor of at least n times. On the other hand, with the use of directional transmissions the transmission range may be increased resulting in routes with longer hops and hence a smaller total number of hops. The idea in the paper is to explore this trade off, along with some optimizations in the routing protocol (e.g., delayed route replies to inhibit a node from replying too quickly to a route request before all information has arrived and limited broadcast to limit the transmission of redundant route requests). However, the results show that the benefits are not always so easy achieve. For example performance in random topologies is typically much better than in regular topologies (e.g., grids).

DOLSR [37] (Directional OLSR) assumes that each node may have several radios of which one is with an omnidirectional antenna and the other radios use directional antennas. DOLSR extends OLSR by including new functionality to solve the directional channel assignment problem, i.e., in addition to being able to separate signals in the frequency domain, the nodes can also separate signals spatially. To this end several heuristic distributed combined direction and channel assignment algorithms are evaluated.

Multipath routing: Multipath routing is another mechanism for increasing the utilization of the network. Especially, if the topology of the network is relatively dense, i.e., any given node has typically many neighbors within its transmission range, multipath routing can be very efficient in increasing the capacity of the network.

- Multipath routing in a single channel mesh network is considered in [112]. The authors compare the performance of randomized multipath routing against single shortest path routing. Multipath routes are can be discovered basically using any protocol capable of determining multiple routes through the network without regard to the routing cost, e.g., with AODV it is possible to determine routes with a given maximum hop count. For the discovered paths traffic is distributed in a randomized fashion. Two randomization schemes are proposed: in the simplest one, only the measured link loss rates are used to favor low loss links, and in the more complex one the loss rate information is coupled with information on the hop length.
- In [173] a multipath routing protocol is presented, which aims to avoid the need to construct the routes in advance. Instead the idea is to use local randomized forwarding based on the direction, where the packet is heading. Note that this requires geographic knowledge about the relative locations of the nodes. The randomization is made so that it takes into account both the direction and link loss rates. For routing a given packet, a packet carries a cost budget which is decremented each time the packet is forwarded, and the proposed routing algorithm tries to route the packet to the destination within the given cost budget. The cost budget represents a tuning parameter which controls in some sense the divergence of the forwarding paths compared with direct routes.
- ExOR [12] uses explicitly knowledge of the geographic locations of the nodes, including the intended receiver. It uses the 802.11 DCF MAC layer to broadcast the packet. After this there is a local coordination to determine, which node among those that successfully received the packet is farthest in the direction of the intended final destination node. This node shall then forward the packet onward. Essentially, ExOR performs opportunistic randomized local forwarding of packets and is able to utilize the existence of multiple paths very efficiently. However, geographic routing requires a separate mechanism to distribute the location information of nodes (similarly as routing table updates in proactive routing). This is not discussed in the paper.

4.1.3 IEEE 802.16 based networks

The research on 802.16 (WiMAX) networks is considerably more scarce than on 802.11 (WLAN) networks. One reason for this may be that 802.11 equipment is cheap and readily available. Also, none of the common network simulators, e.g., ns2, Qualnet or OPNET, include a module for simulating an 802.16 based network. Thus, experimental research to develop more efficient protocols can not be as easily conducted for 802.16 mesh networks as is the case for 802.11 mesh networks.

However, while the 802.16 capabilities of the physical layer have been defined to be highly dynamic, especially the allocation of resources, the 802.16 standard leaves unspecified a number of important control algorithms. For example, the scheduling algorithms to support the four QoS classes. Recently there have been a few papers addressing these MAC layer control algorithms in 802.16 networks. It is also highly likely that more papers on 802.16 mesh networks will appear in the next few years, especially on scheduling for QoS and fairness in the mesh mode. In the following some of the currently available papers are reviewed both in the PMP and mesh modes. Most of the algorithms presented here have not been implemented in a network simulation (as was required in this chapter). However, they are cited here since the approaches that are proposed are somehow specific for 802.16 networks.

Packet scheduling for QoS in PMP mode: Since 802.16 is a QoS oriented system, at the MAC layer the first scheduling functionality concerns the buffering architecture and scheduling algorithms to separate the traffic classes. This is studied for various traffic patterns via simulations in [34] by using standard fair queuing algorithms. In addition to the packet scheduling service for guaranteeing QoS, a connection admission control algorithm is required to protect the QoS of the connections that are already on-going in the system upon the arrival of a new connection. A simple connection admission control algorithm for all four traffic classes is proposed in [158]. An architecture combining both admission control and packet scheduling is given in [164] and also in [23].

Channel scheduling in PMP mode: The packet level QoS scheduling is used to maintain the QoS of the connections in the system, which needs to be done both at the base station and the subscriber nodes. The problem at the base station besides this upper layer packet scheduling is to also allocate the offered traffic to the mini slots consisting of frequency dimension, i.e., the subcarrier, and a time dimension, i.e., the symbol number within the frame. The base station determines the allocation based on knowledge of the traffic demands and the channel state of each node within the coverage area of the base station. From the performance point of view, this resource allocation problem is probably the most important, and it is made more difficult by the fact that the allocation is done in realtime at the time scale of some milliseconds (duration of a frame). In [65], the authors consider this scheduling to maximize throughput with fairness guarantees. The problems can be formulated as LP problems, and to lower the computational complexity also approximation algorithms with provable properties are given. The work in [136] extends the setting by presenting heuristic algorithms for solving the channel allocation to support all the four QoS classes of 802.16. To achieve dynamic slot allocation at such fine time granularity requires signalling overhead. The impact of this has been studied in [55].

Also the interworking functionality of 802.11 and 802.16 networks has been considered, when the two networks are operating in the same frequency range [9]. The interworking is achieved by introducing a central controller which is able to work with both 802.16 and 802.11e radios (recall 802.11e provides the QoS enhancements to 802.11). The framework assumes that the 802.11 radios are operating in the PCF mode (point coordination function mode), where the base station controls the 802.11 nodes explicitly by polling them.

MAC scheduling and routing for mesh mode: The 802.16 mesh networks are mainly used to provide a cost effective Internet access network for sparsely populated areas. Thus, the network topology is a tree rooted at the base station and the problem is to determine the routing and link scheduling for the tree, either jointly or separately. Also, the network is assumed to only carry data traffic and the use of the four QoS classes is not considered, and fairness is the only measure of QoS treated in the papers presently. The physical layer in the mesh mode is based on OFDM (not OFDMA), and thus there is no subcarrier allocation problem, as opposed to the case in the PMP mode. Instead, during a time slot all subcarriers are used by the transmitting node, and the duration of a time slot is several symbol durations. All papers available currently assume that the centralized scheduling method is used (recall that the mesh mode supports both centralized and distributed scheduling).

In [134], routing and scheduling are treated separately. The routing is solved by determining shortest path routes according to a given cost metric (the cost metric is not studied in the paper). For the centralized scheduling several algorithms are presented for the slot allocation problem to maximize the performance without any regard for fairness. Also, spatial reuse of time slots on non-interfering links is not considered. However, spatial reuse of time slots is an effective way to increase the capacity of the system. Scheduling to achieve spatial reuse of the time slots is considered in [51] and [162]. Both approaches separate the routing problem and the scheduling, such that separate algorithms are provided for constructing an efficient routing tree with minimal interference and for scheduling of time slots allowing concurrent transmissions subject to simple interference rules (typically by assuming that both the sender's and receiver's coverage areas must be free from other transmissions). In [150] only the construction of the routing tree is considered. All above works present entirely heuristic algorithms for achieving good performance, and the problems are not formally represented as optimization problems for which efficient solution methods would be proposed.

As mentioned above, most of the traffic in an 802.16 mesh network is data traffic and the QoS of the network is represented by the fairness of the scheduling (bandwidth allocation). However, none of the papers above specifically address the fairness aspect. Recently, this has been been considered in [20] and [82]. In [82], a heuristic scheduling algorithm has been presented to achieve hard fairness between the flows. In [20], a more formal approach is used, where the scheduling problem is formulated as an optimization problem and efficient algorithms are developed to solve the problem.

4.2 Analytical performance modeling of wireless mesh networks

In this section we provide a survey of papers dealing with analytical modeling of mesh networks and their performance. The topics in the section are divided into capacity related issues (asymptotic analysis and finite networks) and modeling of MAC layer protocols.

4.2.1 Asymptotic capacity analysis

A fundamental question related to wireless multihop networks is how does the network capacity scale with the number of nodes n in the presence of wireless interference. The well-known results in [57] show that network capacity scales as $\Theta(W\sqrt{n})$ for arbitrary networks and $\Theta(W\sqrt{\frac{n}{\log n}})$ for random networks, where W is the channel transmission speed.

These asymptotic results have been extended to the case of networks with multiple channels and multiple radios in [89]. The work assumes that the channel transmission rate W is divided into smaller rate channels. The nodes are equipped with radios and they are able to tune their radios. It is also assumed that the number of radios is significantly smaller than the number of channels (which is the case in practise). It is shown that in arbitrary networks there is always a loss in capacity, but for random networks it may be possible to to build multi-channel networks with a capacity that meets the Gupta and Kumar capacity with as few as one radio interface per node. In practise, this means that ideally having one or a few tunable radios may be enough to obtain most of the benefits of having multiple channels in a network.

The previous studies consider static network. However, in networks where the nodes are mobile the capacity can in fact be increased by exploiting the mobility. In the well-known paper [56], it has been shown that if nodes are able to buffer packets infinitely and one is not interested in the delay of packet forwarding, a constant capacity $\Theta(W)$ can be achieved. However, recently asymptotic results have been derived, which take into account the delay-capacity tradeoff [133]. The notion that is studied is called critical delay, which means the average end-to-end packet delay that users must be willing to tolerate in order to benefit from mobility. The critical delay depends on the nature of mobility (random walk type movement vs. random direction models) and in [133], the asymptotic behavior of the critical delay is analyzed for a class of parameterized mobility models. The results show that the critical delay behaves as $\Theta(n^\alpha)$, where $\alpha \in [0.5, 1]$ for random direction models and $\alpha \in [0, 1]$ for random walk models.

4.2.2 Capacity modeling in finite networks

While the asymptotic results are important and provide significant insights, it is also important to analyze the capacity tradeoffs is finite networks, where the topology of the network is fixed. Understanding capacity involves typically modeling jointly both the impact of wireless interference (scheduling) and routing. On the other hand, scheduling of the links involves modeling the behavior of the MAC layer.

In [78], wireless networks are categorized into scheduled and non-scheduled networks according to the fundamental nature of the MAC layer in a given network. Scheduled networks correspond to networks that allow the use of centralized scheduling according to STDMA [118]. For example, in 802.16 time slot allocations can be controlled at the time scale of milliseconds. In such networks, link scheduling requires in principle the enumeration of all conflict free link sets (transmission modes), which are then assigned time shares that can then be optimized to achieve optimal performance.

Non-scheduled networks correspond to random access, e.g., 802.11 networks where there is no centralized scheduling. Instead, the MAC layer relies on only local distributed coordination, which is typically optimized somehow to maximize local channel utilization. Interference can be modeled by using so called clique constraints, which consist of sets of links that mutually interfere each other so that only one of them can be active simultaneously. In these formulations, there is no need to solve an optimal schedule. Instead, one can rely on theoretical results which guarantee the existence of a feasible schedule, if the network graph satisfies certain conditions. From a modeling point of view this means that one is assuming that the random access MAC mechanism is able to somehow determine this schedule. Thus, it is still an optimistic estimate on the impact of interference.

Additionally, the modeling approaches can be categorized according to a more technological taxonomy, namely whether the problem formulations concern networks with single radio equipment, multiple radios (with multiple channels) or the use of directional antennas. This is the taxonomy we use below.

Multi-channel networks: The use of multiple radios is usually treated by assuming that the radio interfaces are fixed to certain channels and that this channel assignment does not change in a short time scale. Then it is natural to consider the joint problem of channel assignment, routing and scheduling (if assuming a scheduled network).

- *Scheduled networks*: In scheduled networks joint channel assignment, routing and scheduling has been addressed in [6] and [85]. The problems are formulated as LP optimization problems, which are NP hard to solve. In [6] provable approximation algorithms for the problems are provided, while in [85] an efficient heuristic algorithm is presented. Joint routing and scheduling is also considered in [84]. However, the channel assignment is not treated. Instead it is simply assumed that radios may operate in a duplex manner (i.e., it is assumed that the channel assignment problem to allow duplex operation is solved separately). For the routing and scheduling problem the authors derive efficient approximation algorithms. In [131] a fully distributed and dynamic link scheduling algorithm is provided that also enforces end-to-end rate guarantees.

- *Non-scheduled networks*: A decomposition approach is used in [146], where channel assignment is considered first and subsequently the routing. For the channel assignment, an algorithm is presented which seeks a K-connected topology for which also the maximum interference is minimized. The algorithm gives a heuristic solution to this problem, which guarantees K-connectivity, but not the optimality with respect to interference. Interference level of a link is given by the number of other links interfering with the considered link. The routing is subsequently solved as a flow allocation LP problem. The LP problem is solved upon arrival of each new connection to the network, and it seeks to allocate the new bandwidth request (flow) such that it minimizes the induced extra interference. In [147], only the routing problem is considered (channel assignment is assumed to be given). The routing problem is treated again as a flow optimization problem. Several optimization formulations (LP problems) are provided, e.g., to maximize the throughput, to achieve max-min fairness and to maximize throughput subject to a minimum flow allocation criterion.

- *Topology control*: The problem of centralized channel assignment is considered in [108]. The problem can be seen as a graph coloring problem with certain special features. These problems are typically NP hard to solve. Specifically, in [108] a heuristic algorithm is provided which solves the channel assignment by minimizing the maximum number of interfering links while maintaining a given requirement on the connectivity properties of the network graph. The centralized channel assignment problem is also considered in [126], and heuristic algorithms are provided for the problem. On the other hand, in [76], a completely distributed cannel assignment algorithm is provided.

Realtime algorithms that adaptively change the topology of the network to minimize the end-to-end packet delay in the network are considered in [8]. The approach uses a novel notion, called characteristic timescale, which is a property of a network when it is modeled as a specific type of linear system. The point is that the characteristic timescale correlates strongly with the mean packet delay of the network and can be obtained from realtime measurements of queue lengths. The provided algorithms essentially perform load balancing in the network by adaptively modifying the topology to minimize the characteristic timescale.

Single-channel networks: In single channel networks the channel assignment problem does not need to be addressed. Typical problem formulations again involve joint optimization of scheduling (involving wireless interference modeling) and routing. Some recent approaches are summarized below.

- *Scheduled networks*: Joint scheduling and routing subject to fairness constraints is modeled in [130]. The scheduling assumes that the network operates according to STDM, i.e., it includes spatial multiplexing (simultaneous link activations). A greedy approximation algorithm is also proposed to solve the optimization problem more efficiently. A similar modeling framework is presented in [78], but the optimization is formulated as a utility maximization problem. In [114] the joint scheduling routing problem is augmented with the possibility to use sub-channelization (i.e., it assumes an OFDMA physical layer). To make the scheduling problem easier, interference is handled partly by assuming that in the link scheduling all links are labelled as “even" and “odd". In the TDMA schedule only even links are active in the even time slots and similarly the odd links are active only during the odd time slots. The benefit (according to the authors) of the even-odd activation scheme is that it provides worst case guarantees for the packet delay through the wireless backhaul. The labelling of links as even or odd is part of the routing problem. The joint scheduling and routing problem is formulated as an ILP problem (integer-linear-programming), which is computationally difficult to solve exactly. Thus, also more efficient heuristic algorithms are provided. In [157], an LP problem formulation of the joint routing and scheduling problem is provided to compare single hop (directly from base station to mobile) and multihop routing in a tree type mesh rooted in a single WiMax base station. Also, heuristics are provided to select the most useful transmission modes (link sets) to be used in the scheduling (in order to avoid the inclusion of all possible link sets in the LP problem). The paper focuses on analyzing the impact of various radio related issues (e.g., narrow beam antennas, antenna height and antenna power) on the overall performance. A potential application of the ideas in all above papers would be in the context of 802.16 mesh networks using the centralized scheduling mode.
- *Non-scheduled networks*: Single path and multi-path routing in wireless networks are considered in [66]. The interference is modeled by considering cliques that are sets of links which interfere with each other. The paper discusses different approaches to modeling the interference, including binary type interference rules and continuous physical interference models (based on SINR values), as well as the impact of multiple radios/channels and directional antennas. Algorithms are provided that allow one to iteratively construct increasingly accurate lower and upper bounds for the capacity of the system. In [15] the topology design of 3G radio access networks is considered. The network is assumed to consist of 802.16 links forming a mesh network between the base stations and the radio network controller. The radio links are assumed to be non-interfering due to the use of highly directional antennas in the backhaul. The problem that is addressed is that given a layout of the base stations and the base station controller and traffic demands, what is the minimum number of 802.16 links needed. Additionally, the problem is augmented with constraints that guarantee network survivability in the presence of node/link failures. The problems are shown to be NP hard to solve and to facilitate numerical computations several heuristic algorithms are given.

Use of directional antennas: The use of directional antennas has been addressed both from the point of view of joint routing and scheduling, and topology control. In the following some recent papers are summarized.

- *Routing and topology design*: In [144], centralized routing algorithms are derived when new connection request enters the network. The wireless nodes are equipped with antennas that are divided in multiple sectors, and simultaneous interference free transmission/reception in multiple sectors is assumed. Interference is modeled by assuming a non-schedulable setting, i.e., scheduling of the links is not explicitly solved. Several LP problem formulations are provided with the general objective of minimizing the interference level along the path of the connection. Also formulations with requirements on node-disjoint routes are provided to address network survivability issues.
- *Topology design*: The problem of topology design is considered in [87], when the nodes are assumed to be equipped with multiple directional antennas. The topology design problem is formulated as determining a connected topology such that the interference along the shortest paths in the network is minimized. Specifically, the paper presents heuristic algorithms for solving this NP hard problem. A similar topology problem is considered in [59], where a heuristic algorithm is provided to construct topologies of multiple mesh networks. The idea is to construct the meshes such that they interfere minimally with each other. Assuming that the directional antennas are steerable in the nodes, upon a network failure in one mesh, the nodes may switch to the use of another mesh.

4.2.3 Performance modeling of MAC protocols on a shared channel

In the previous sub-sections we have basically considered the modeling of various performance aspects of multihop wireless networks but the specific impact of a given MAC protocol has not been in detail. In this section we review some recent papers that analyze the performance of a given MAC protocol. The performance questions of interest are then related to the mean delay and throughput of the network that can be achieved with a given MAC technology. Specifically, we focus on two MAC protocols: 802.11 and 802.16.

802.11 modeling: An early model on the performance of 802.11 DCF is in [10]. The scenario corresponds to the WLAN case with a fixed numner of nodes, where all nodes can hear each other (no hidden terminals), and it is also assumed that nodes are in a saturated state. The performance is then determined by the state of the backoff algorithm of 802.11 DCF of the nodes, which can be modeled as a bi-dimensional Markov chain. Since then numerous papers have given simplified versions of the model and also extended the model to the case of finite load scenarios. A recent model that extends the WLAN case to multi-hop 802.11 networks is in [120]. The multihop network is represented by a queuing network of M/M/1 queues and a product form solution for the multihop network is established.

802.16 modeling: There has been thus far very little literature on the performance of the medium access mechanisms of 802.16. A notable exception is in [19], which presents a stochastic analysis of the control channel performance in the 802.16 distributed scheduler. The control channel is used to make the reservation of actual data time slots in the next frame, and thus the performance of the random access mechanism on the control channel determines the performance of the channel allocation. The control channel access mechanism implements basically a distributed election mechanism for the control channel. The behavior of the algorithm is modeled by using renewal theory and from the model the mean access delay and throughput can be derived (after some simplifying approximations).

4.3 Cross-layer optimization of wireless networks

Cross-layer design has been recently received considerable attention in the discussion related to wireless access networks. By removing or redefining the layer structure of the traditional communications model, significant gains in the network performance may become available. The development is also motivated by the impairments of certain wireline network protocols, such as TCP, on unpredictable wireless links. Although the benefits of cross-layer designs are in certain cases clear, it is not obvious whether the benefits are sufficient to counter the inflicted loss in modularity. Careless cross-layer implementations may cause unintended interactions or harm the long-term development of wireless networking.

Cross-layer optimization is an analytical approach to cross-layer designs. By employing mathematical modeling tools and simulations, the aim of cross-layer optimization is *a)* to identify the potential gains in cross-layer designs and *b)* to devise algorithmic methods to utilize the gains. In the latter sense, the optimization approach is especially relevant to stationary wireless networks where the network nodes posses some computational capabilities. Mesh networks are a typical example of such a scenario.

In the following we review the recent development in cross-layer design in particular from the optimization viewpoint.

4.3.1 Overviews on cross-layer designs

While specific cross-layer proposals have been emerging in great numbers during the last few years, only a few articles attempt to review the concepts in a structured manner. Shakkotai et al. [132] discuss the basics of the cross-layer approach in general wireless networks. In particular, they focus on data services in the networks and review some research on TCP over wireless links and multi-user diversity. Also standardization issues are considered. More recently, Burbank and Kasch [16] discuss the cross-layer approaches from a military perspective.

When the number of proposals started to grow quickly, Kawadia and Kumar [79] argued against over-enthusiastic cross-layering. They warn that while the cross-layer designs are needed to satisfy capacity and QoS demands in wireless networks, some caution is needed with the proposals. Abandoning the layered structure may lead to spaghetti design, which can stifle further innovation in addition to being difficult to upkeep. Unintended cross-layer interactions can have undesirable consequences on the overall system performance.

The first comprehensive conceptual study of cross-layer design is by Srivastava and Motani [141]. Their classification of the designs summarizes efficiently the different possibilities of altering the current protocol stack. They identify the following alternatives:

- Upward information flow. Create a new interface to obtain parameter values from lower layers.
- Downward information flow. Set a parameter on a lower layer.
- Information exchange. Iteration of parameters on a lower layer.
- Merging of adjacent layers.
- Coupled design of layers. A layer functionality is designed to take into account the specific implementation of a lower layer.
- Vertical calibration of layers. Parameters are tuned jointly in all layers.

The authors present also the potential architectures of the cross-layer designs to replace the traditional stack where communication takes place only between adjacent layers. These include (see also Figure 10):

- Direct communication of different layers in the stack through new interfaces.
- Shared database. All layers communicate only with the database, which is responsible for collecting the information and setting the parameters throughout the stack.
- Completely new abstractions. For example, a general graph structure instead of a stack.

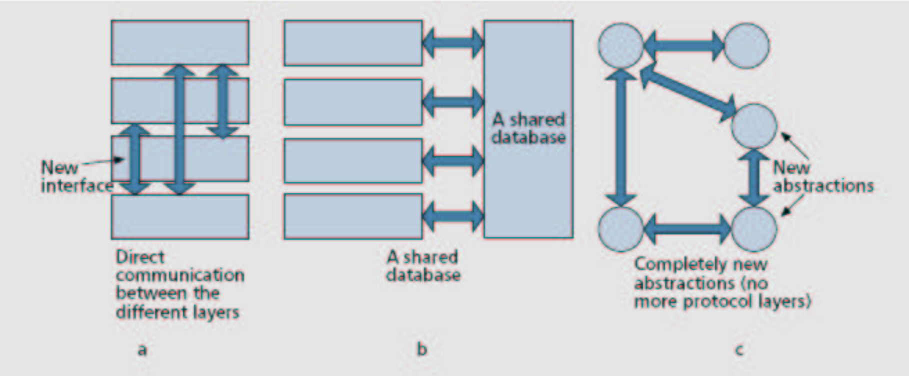

Figure 10: Illustration of cross layer architectures [141].

The article closes with a discussion of the open challenges in the field.

Whereas the article [141] provides an unifying conceptual view on the cross-layer design, ongoing work on layering as optimization decomposition by Chiang et al. [28], [29] takes an interesting mathematical perspective. The authors treat a communications network as an utility optimization problem along the lines of Kelly [80], and see the protocols as distributed solutions to the problem. Layering represents a decomposition of the problem. The authors argue that this mathematical view enables quantitative analysis of layering costs, and provides guidelines “how to” or “how not to” layer. The authors do not limit their approach to wireless networks, but address communications networks in general. However, the many of the examples related to the forward engineering are naturally related to the wireless networks. It is there where the layer structure is likely to be redesigned.

4.3.2 Cross-layer optimization proposals

Chiang et al. [29] provide a list of typical cross-layer optimization problems in the existing literature. Although the list is far from being exhaustive, it contains an edifying overview of different cross-layer optimization proposals also for wireless networks:

- Jointly optimal congestion control and adaptive coding or power control [27],[94]
- Jointly optimal congestion and contention control [93], [77], [161], [174].
- Joint optimal congestion control and scheduling [48].
- Jointly optimal routing and scheduling [83].
- Jointly optimal routing and power control [117], [167].
- Jointly optimal congestion control, routing and scheduling [99].
- Jointly optimal routing, scheduling and power control [36].
- Jointly optimal routing, resource allocation and source coding [171].
- Network lifetime optimization [113].

Most of the actual cross-layer proposals stem from a specific technology. Although the proposals represent maybe piecemeal advances, as criticized in [29], they provide often an implementable improvement to existing technology. Next we give a non-exhaustive overview of some interesting proposals which have emerged recently.

4.3.3 Cellular networks

Cross-layer optimization in cellular networks concentrates typically on the single wireless downlink. Accordingly, the link modeling is carried out in considerable detail. The studied features contain, for example, coding and modulation technologies, power control, antenna technologies, multiuser diversity and packet/user scheduling. Quality of service is represented by, e.g., bit-error-rates (BER) and throughput.

General studies. In [71] the authors describe different cross-layer mechanisms to achieve QoS targets in CDMA based cellular networks. As an overview of recent research efforts the authors discuss channel-aware scheduling, TCP over CDMA wireless links and joint source/channel coding and power allocation for video services. Schaar and Shankar [156] consider the multimedia transmission over WLANs on a conceptual level. They outline several issues related to joint optimization of physical layer, MAC layer and application layer.

Downlink with adaptive modulation and coding. In [102], a wireless link with adaptive coding and modulation and a single user is considered. The user's data packets arrive randomly to a finite buffer to wait for transmission. A cross-layer optimization scheme is proposed to minimize the packet loss rate (i.e. buffer overflows) and to maximize the throughput, while pertaining to a predetermined packet error rate in coding and modulation. In another paper [101], the same authors consider a multi-user scenario and combine packet scheduling and adaptive modulation and coding to meet prescribed QoS guarantees and to utilize bandwidth efficiently. Channel variations and status of users' queues are taken as the input when scheduling packets over a single wireless link. Most recently, in [100], they propose a MAC-layer scheduler for multiple connections with diverse QoS requirements, which takes into account the physical layer behavior and adaptive modulation and coding.

Johnsson and Cox [75] study packet scheduling of data traffic when channel condition is taken into account and compare such scheduling against two scheduling disciplines; weighted fair queuing and earliest deadline first. Haleem and Chandramouli [58] propose a stochastic control algorithm for selecting the modulation and coding and user scheduling. The goal is to maximize total throughput under short term throughput guarantees. Importantly, the proposed scheme does not require explicit channel state information from users, but the MAC-layer acknowledgments are utilized in the learning process.

Downlink in MIMO and OFDM networks. Song and Li [139] consider the optimization of OFDM wireless networks. By optimal subcarrier allocation and power allocation the authors take advantage of multiuser diversity and maximize the total utility of users. Cross-layer resource allocation in MIMO-OFDM networks is addressed in [148]. Xi et al. [175] model a point-to-point wireless downlink using a Markov chain model to capture the effects of MIMO technology and adaptive modulation and coding on packet level QoS parameters, such as delay-bound violation and buffer overflow probability. Toledo et at. [153] study the interactions of TCP and UDP over MIMO wireless links.

Uplink. Also uplink cross-layering has been studied. Jiang and Zhuang [70] study the uplink resource allocation in cellular CDMA networks with a DiffServ backbone. A cross-layer scheme merging the transport layer and link layer functionalities to guarantee QoS for heterogeneous traffic while and to achieve high utilization on the link layer. Li and Wang [97] study a multirate multiuser uplink system with low-density parity-check codes.

4.3.4 Multihop wireless networks

Multihop networks present an additional challenge for cross-layer optimization. Whereas in cellular networks one often concentrates on the operation of a single base station, in multihop networks the interference effects of different transmissions cannot be neglected. Furthermore, there are also additional degrees of freedom such as traffic routing. Finally, the performance is often measurable only for end-to-end traffic which further complicates the analysis.

Flow optimization. The performance is analyzed on the flow level in the form of end-to-end throughput. In a static scenario, the problem is often well-defined but computationally difficult and, hence, the contributions of the proposals are often related to computational methodology.

In [161] the authors develop two optimization algorithms that gives proportionally fair rates a set of end-to-end flows in a slotted Aloha network. For single hop-flows this is done in [77]. Wu et al. [166] consider a flow-optimization problem where the communication demands are defined for end-to-end multicast sessions. The approach then schedules a selections elementary capacity graphs (i.e. transmission modes) to meet the demands in bandwidth-limited regime and in energy-limited regime, respectively.

Johansson and Xiao, e.g. [73], consider cross-layer optimization of wireless networks with realistic power and rate control models. The goal of the work is to produce fair end-to-end flow rates. Despite the complexity of the the formulation the authors are able to obtain results for medium sized networks by utilizing a computational tool called column generation. Loretti et al. [104] extend the work to the scenario where the network nodes are equipped with multi-user detectors.

Lo Presti [103] studies a joint congestion control (as utility maximization problem), routing and media access control optimization and propose solving in using dual decomposition and a subgradient algorithm. Chiang [27] proposes an optimization method which solves power control and congestion control problems jointly in networks where link adaptation is used. In [145] the authors formulate problems for combined scheduling and power control. Shi et al. [135] study the rate vector feasibility in UWB-based sensor networks. A realistic network model is solved using branch-and-bound method and Reformulation-Linearization Technique.

Routing. Cross-layer optimization by routing corresponds to defining suitable routing metrics that incorporate information e.g. from the physical layer.

Iannone et al. [62] explore the use of cross-layer information in routing metrics in wireless mesh networks. In particular, interference, packet success rate and data rate are considered. The authors propose a routing heuristic for mesh networks in [61]. Fang and McDonald [50] propose a codeword routing scheme to account for MAC-layer interference on the routing layer.

Scheduling/MAC. Following the idea presented in [28] MAC-protocols can be seen as distributed solutions to the centralized scheduling problem. There are also close ties with the cellular network development.

Wang et al. [159] develop an analytical model to analyze the effect of directional antennas with CSMA/CA MAC-layer on the throughput performance.

The centralized scheduling is addressed in [99] (as continuation of their previous work [98]), where the authors pointed out that the global scheduling problem commonly appearing in the cross-layer optimization context, is hardly feasible in practice. To this end the authors study the effects of imperfect scheduling on congestion control.

Energy efficiency In [172] the authors study the cross-layer issues in a sensor network where virtual MIMO operation is assumed. In such a case groups of single antenna nodes co-operate in transmission and reception to achieve energy savings. Madan et al. [107] study the maximization of the time to the first node failure in a network with battery-operated nodes. The authors consider routing, power control, rate control and scheduling in their model. Kong and Hwang [86] consider additionally the reliability of transmissions.

Energy efficiency of a sensor network with interoperating forwarding and scheduling methods is considered in [31].

5 Products and test beds

5.1 Academic networks

The MIT Roofnet, see [11] and [4], is an experimental wireless mesh network at MIT with 37 nodes covering an area of approximately 4 km^2. Each node is equipped with a single radio and uses standard 802.11b hardware with an omnidirectional antenna. The routing protocol uses source routing with the ETT (Estimated Transmission Time) link cost metric, which depends on the retransmission probability of a link and the bit rates achieved on that link. The routing protocol contains measurement mechanisms to estimate the required parameters. The MIT Roofnet also has its own algorithm to adaptively change the coding and transmission rate.

Mesh@Purdue [109] is another relatively big test bed with 32 nodes (at the moment). The network uses both omnidirectional antennas and directional antennas. The routing algorithm is based on OLSR with the ETX cost metric. Recently, the network has been enhanced with support for multiple radio interfaces, at least under laboratory conditions, see [37].

UCSB MeshNet [105] is a 30 node test network at the University of California at Santa Barbara. All nodes have a single interface and for the routing AODV is used. The MeshCluster architecture [125] extends the original architecture of the UCSB MeshNet so that nodes may have multiple radio interfaces. Also, the routing protocol is modified to allow the use of more appropriate cost metrics, such as ETT or ETX. Mobility management schemes are also proposed.

Mesh networks are also being explored intensively as a means to provide networks that can be deployed easily and that provide a high degree of fault tolerance. The idea is that the mesh network functionality is designed so that the network can configure itself entirely automatically without any need for prior infrastructure. Such networks can be especially useful in emergency situations, where the normal fixed infrastructure has been damaged. In such scenarios, the networks are primarily used for carrying real-time traffic, both voice and video. Examples of such municipal emergency mesh networks are CalMesh [17] and RescueMesh [38].

5.2 Experimental test beds

Hyacinth [128] is a smaller scale test bed with 9 nodes. However, the architecture is quite advanced. It is designed to operate on top of a standard 802.11 wireless cards. Nodes in the network are equipped with multiple radios. The routing protocol implemented in the system solves in a distributed manner the joint channel assignment and load balancing problem by utilizing only local traffic load information.

Mobility management schemes have been evaluated in an experimental 6 node network in [116]. The two approaches that are compared are essentially a solution, where the network routers keep track of a client's location and route the packets accordingly via a “home" AP (access point), and in the other approach a standard ad hoc routing protocol is used, where each client device also has an IP address and takes part in the route construction.

A test bed for single channel directional antennas is discussed in [26]. The aim is to build a self-configuring wireless mesh, where nodes can be placed at street level and connected together using standard 802.11 radios equipped with highly directional antennas. One feature of the project is to use an addressing scheme based on IPv6 so that embedded in the address is also knowledge of the geographic location of the node.

In [43], the quality of VoIP traffic has been evaluated in a wireless mesh network with 15 nodes. Experiments were conducted to investigate the impact of using multiple channels/interfaces. Additionally, the benefits of traffic aggregation was studied to combat the large protocol overhead in VoIP traffic caused by the fact that the size of speech samples is very small. The idea is to allow some added packet delay at a router so that it can combine speech samples from many VoIP calls in a single larger packet.

A large scale simulation of a realistic urban area with mobile users has been conducted in [140]. The aim was to investigate the feasibility of 802.11 based mesh networking under realistic mobility patterns and realistic wireless signal propagation conditions on a real map of a part in London. The results showed, for example that considerably higher densities of 802.11 routers are needed than are typically planned to have adequate coverage also indoors.

5.3 Commercial products and community networks

Many companies have also developed their own solutions for mesh networks. Some communities and cities have used the available commercial products, or sometimes made their own, to deploy mesh networks.

Cisco Aironet[3] and Motorolla Motomesh[4] are combined hardware and software packages from established manufacturers. The solutions are vendor specific and specifications are not very open. Mitre is a research organization funded by the United States government. Their Mobilemesh[5] software platform is more open and available as IETF Internet Drafts and open source implementations. The software is used in 4G Systems[6] multinetwork roaming products. There are also companies, that are specializing on mesh products. Tropos Networks Metromesh[7] offers bundled hardware and software for metropolitan mesh networks, using IEEE802.11 and multiple radios. Strix Systems[8] also offer mesh routers using mimo. Strix Systems advertises 'highest performing' and resilient mesh networking platforms and proclaims to have solved the multi-hop 'dilemma'. MobilePro[9] provides products for WAZMetro[10] metropolitan networks, that are deployed in many cities through out the United States. Pronto Networks[11] with MetroZone is another supplier for metropolitan area mesh networks. Also MetroFi[12], based in Mountain View California, has solutions that are deployed in some U.S. cities. PacketHop[13] products offer, in addition to unlicensed band wifi mesh connectivity, communication using a 4,9GHz public safety frequency. Meshcom[14] has a driver for Windows and Linux and also offers a hardware testing kit with mimo radio connectivity.

There are also more community oriented mesh networks. Champaign-Urbana Community Wireless Network[15] coalition is maybe the most well known and one of the pioneers in the area of community operated mesh networks. They cooperate to deploy wireless networks in different communities and to develop open source hardware and software for others to use in their own projects. They have produced, among other things, their own routing protocol for mesh networks, called Hazy-Sighted Link State routing. Community Wireless[16] wants to be an umbrella organization for wireless community networks. Together with LocustWorld[17] they offer a MeshAP mesh router. An interesting development, though strictly speaking not yet a mesh, are Fon[18] wifi community routers. Private persons are offered wlan access points at a discount, if they make them available for other members of the community. As of yet the routers do not support mobility, but act as individual hot spots. Basic support for connecting routers through IEEE802.11 WDS is present however, and it is not unimaginable that global roaming could some day be supported by the geographically widely placed routers.

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6 Summary and conclusions

Wireless mesh networks are a recent architecture for multihop wireless networks. Also, standards for realizing mesh networks are being actively developed, especially in the IEEE working groups. In contrast with mobile ad hoc networks, mesh networks consist of static nodes communicating with each other over wireless links. The static nodes are essentially wireless routers. Such networks can be used, for example to provide a cost effective alternative to a wireline Internet access network. As opposed to the nodes in mobile ad hoc networks, the nodes in mesh networks are not energy constrained and node mobility is not a concern in protocol scalability. Instead, the main technical problems relate to achieving high user data rates over multihop wireless paths by using advanced MAC/routing layer solutions.

In this report a state-of-the-art analysis of wireless mesh networks has been presented. The analysis addressed the recent developments from the points of view of link layer and IP layer standardization activities, performance analysis of mesh networks and commercial products and test beds. In the following we present the summaries and conclusions from each of these areas.

6.1 Summary: Link layer solutions

The main link layer technologies for realizing mesh networks with relatively large coverage are IEEE 802.11 and IEEE 802.16. In both working groups the standardization is still partly incomplete, especially for 802.11.

The standardization work for 802.11 mesh networks is still in its early phases. a preliminary consensus has been reached which serves as a common starting point for the standardization process. The approach that has been adopted is to reuse the existing 802.11 standards as much as possible. The MAC layer mechanisms remain more or less the same with added capabilities to support the use of multiple orthogonal channels. In the routing, a link layer routing scheme will be used, so that an 802.11s network will appear as a single logical WLAN to an upper layer protocol, such as IP, effectively implementing a wireless distribution service for the 802.11 infrastructure mode.

On the other hand, the standardization of 802.16 is fairly complete, including support for mobility. However, the standards leave open the detailed scheduling algorithms used for resource allocation, leaving ample room for research innovations. The current standardization efforts focus on supporting so called multihop relaying.

6.2 Summary: IP layer solutions

The section presented several quite different solutions. None seem perfectly suitable and are certainly not tailormade for WMNs. Each of the solutions has some advantageous characteristics compared to the other ones. By comparing these attributes and combining features some WMN relevant qualities can be distinguished.

Routing: Two main categories, proactive and reactive routing, were presented. The reactive protocols AODV and DYMO use timers and soft state routes. This allows them to save resources, but the timers might be difficult to set correctly in a WMN environment. In a relatively stable WMN rapid expiration of timers is unnecessary. The presented proactive protocol, OLSR, creates stable, yet adaptive routes. The propagation of routes used in link state protocols does consume a certain amount of resources, but the use of multipoint relays greatly optimizes the behavior of the protocol. The hierarchical design is similar to that of the envisioned H-mesh and thus OLSR could be suitable in such a network.

Local mobility: Four different protocols for local mobility management were presented. Hierarchical Mobile IP is part of a very extensive and versatile protocol. It uses signaling to change host specific IP routes, but functions on top of regular IP routing and coexists fully with nodes without Mobile IP capabilities(/in a mixed network/a network with non MIP (routed) nodes). Mobile hosts can communicate with these using their local addresses. Cellular IP is designed to be very light with autonomous cooperation and no single point of failure. Routes are optimized after each handover. Brain Candidate Mobility Management Protocol uses tunneling and has a simple yet efficient design. It seems to best utilize a cross-connected mesh topology and conserves bandwidth with localized signaling. The NetLMM protocol is intended to work without any protocol specific changes to the mobile host. It represents an extreme approach to avoiding modifications in clients. It is however not yet clear, how well this will succeed, since the protocol is still in the making and all of the other standards it builds on are not ready either. In NetLMM the network is 'intelligent' and tries to work in an unified manner, while hosting mobile nodes that follow no specific mobility protocol. A protocol for mobility specific network nodes is defined but software requirements are defined for hosts as well. So in essence this approach strictly prescribes network behavior, while still not completely freeing up mobile host network stack implementation. It is reasonable to make some assumptions on host behavior. It is hard to imagine any current network, however intelligent, being able to co-operate with all known host mobility techniques.

Instead of strictly specifying an extensive mobility protocol for the network and specific requirements for hosts it could be worth considering directing the specification towards the interaction of the two. Defining only the interface between mobile host and network would free up both to implement mobility however they wish [72].

Some of the presented features could be deemed as especially important for WMNs.

- Autonomous and flexible protocol: The protocol should not require a specific modification to be present on all access network nodes. (Fulfilled by: HMIP, BCMP, NetLMM)
- No single point of failure: In a WMN any single node can become unreachable. If at all possible, this should not prevent other nodes from using mobility. (Fulfilled by: Cellular IP, others partially)
- Autonomous and flexible with regards to topology: No assumption for a specific routing protocol or topology can be made. Despite the fact that it is probable, that most traffic in a WMN AN is routed towards one or several gateways, a tree, or any other, topology should not be assumed. The ability to work on top of different kinds of routing, happening on different network layers, is central. (Fulfilled by: HMIP, BCMP, NetLMM)
- Modular and lightweight design: Richness in features makes for a complex design. The base protocol should be simple to implement. Additional features could be added as nonmandatory extensions. (Fulfilled partly by: CellularIP, BCMP)
- Lightweight signaling: As few messages as possible should be sent. This reduces delays and saves resources. Optimally the signaling should use the shortest path available. (Fulfilled by CellularIP, BCMP)
- Independence from global mobility solutions: Since no single global mobility protocol is yet overwhelmingly widely deployed, it is better to design local mobility without reliance on any specific global mobility protocol. (Fulfilled by: BCMP, NetLMM)

Autoconfiguration: In autoconfiguration several possibilities were presented. Depending on the structure of the network stateless or stateful autoconfiguration might be preferable. In a very volatile network completely distributed methods might be selected. Stateful configuration, i.e. DHCP, has the advantage of being widely supported. Stateless autoconfiguration requires less infrastructure, but is not available for IPv4. More exotic methods offer additional robustness, but are not yet deployed.

Our next step in designing the IP mobility management for a mesh network is to make a functional and requirements analysis. We already included some functional analysis in this section, but a deeper analysis is needed. Our initial conclusions already were that none of the present mobility schemes is really well suited for mesh networks.

6.3 Summary: Modeling and performance evaluation of wireless mesh networks

Protocol research: Many experimental protocols have been developed in the past two years addressing mesh networks with emphasis on reducing the impact of wireless interference on multihop communications, especially for 802.11 based networks. At the MAC layer the most effective way to increase capacity is to utilize many orthogonal channels and multiple radios. The results suggest that not that many radios are needed to obtain substantial capacity benefits. Approaches using centralized channel assignment or distributed have been proposed. The benefit of a centralized approach is that it can be used without modifications to 802.11 DCF. Also, directional antennas have been studied. At the routing layer the biggest problem is the determination of routing metrics that enable the routing protocols to discover routing paths with good performance (i.e., experiencing small interference). Also, new routing schemes can be developed, e.g., ones that would combine the MAC/routing so that a better coordination of the transmissions at the MAC layer would be achieved combined with a more efficient routing/forwarding of the packets, e.g., based on geographic location information of the nodes, similarly as in [12].

Performance and capacity: Various capacity issues in multihop have been investigated, both for scheduled and non-scheduled networks. Recent results on asymptotic analysis concern the impact of multiple channels and radios on the asymptotic per node throughput. In finite networks, the modeling involves joint modeling of routing and scheduling (wireless interference). For multi-channel/multi-radio networks both joint modeling of channel assignment and routing or decomposition approaches have been used. Similar approaches for the use of directional antennas have also been proposed. All modeling approaches employ either LP or ILP optimization formulations, and typically the research contributions also include heuristic algorithms to facilitate the numerical solutions. A new dimension in the resourceallocatio/scheduling problem is the subchannelization property in OFDMA systems, such as in 802.16 systems, which has not been explored that much yet in the research community. In general, scheduling in 802.16 networks allowing the exploitation of STDMA type mechanisms is still largely an open area, which is also beyond the scope of standardization,

Cross layer optimization: The overview of cross-layer optimization covers only the recent developments in the field as published in the most highly esteemed journals and conferences. The optimization decomposition approach [28] seems to be an interesting framework for further development of cross-layer designs. Open issues on the field are listed, e.g., in [29] and [141]. From the optimization point of view one of the key questions is to model the stochastic behavior of the network.

6.4 Summary: Products and test beds

There is a growing interest in applying wireless mesh technologies. The most typical examples include commercial products aiming at providing wireless Internet access. Another practical example is the development of products for spontaneous, autonomous mesh networks, e.g., for emergency workers and so called first responders that may need to work in an environment where all communications infrastructure has been destroyed. In such networks, mostly realtime traffic is carried, both unicast and multicast. Additionally, universities are developing various test beds for verifying and developing new experimental protocols.

All the current activities in mesh networks are using 802.11 based technology. Experimentation with 802.16 systems seems to be still quite rare, which is perhaps due to the expensiveness of the technology.

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