

Towards Carrier-Grade Quality in Heterogeneous Wireless Mesh Networks

Johannes Lessmann, Paulo Loureiro
NEC Europe Ltd., Germany

John Fitzpatrick
University College Dublin, Ireland

Pablo Serrano, Albert Banchs
University Carlos III of Madrid, Spain

ABSTRACT

Current backhaul networks typically comprise a wired middle mile and a wireless last mile part. The wireless part is almost exclusively based on tree topologies. However, a lot could be gained by deploying mesh-based backhauls. Meshes allow better network capacity exploitation due to load balancing and offer inherent resilience to link degradations or failures. Yet meshes come with increased complexity in terms of radio configuration, routing or mobility management. In this chapter, we propose architecture and mechanisms for carrier-grade mesh-based wireless backhauls. One special focus of our solution is that it supports heterogeneous backhauls, which encompass multiple different wireless technologies. Our proposition has been successfully deployed in a test network.ⁱ

1 INTRODUCTION

Providing backhaul solutions for radio access networks with mobility support is very costly. Current solutions have significant limitations which will become even more pronounced with increased use of mobile data applications. New networking paradigms can result in a number of advantages when it comes to realizing such networks: mesh networks provide lower-cost solutions with greater flexibility, something that is highly desirable for operator deployments. The focus of the approach in this chapter, then, is on realizing backhaul mesh networks which can be used to deliver carrier-grade services to users, some of which are mobile.

Current backhaul solutions are largely divided into two categories: wired backhaul via leased lines (copper, fiber) or point-to-point, high capacity radio links. Both of these solutions have their limitations - in the first case, provisioning of the wired connection can take some time, be expensive and, in some cases, there are issues with availability of wired connectivity, especially in remote areas; in the second case, expensive radio engineers are required to install and maintain costly point-to-point backhaul links. Both of these solutions lack flexibility when it comes to deployment of new base stations in a radio access network.

Mesh networking technology represents a cost-effective and efficient alternative for realizing backhaul networks to provide mobile users with high quality services. The multi-hop wireless network architecture of mesh networks enables them to efficiently cover large areas without requiring many interconnections to a wired infrastructure. Further, mesh networks offer better capacity exploitation via statistical multiplexing effects as well as inherent resilience to link failures via higher path diversity, which ultimately results in reduced up-front cost (CAPEX) and lower network maintenance costs (OPEX) for the operator.

While mesh-based solutions can be highly beneficial for fixed backhaul scenarios, their usage is also advantageous in situations where the network infrastructure is only needed for short time periods, as is the case for large public events or emergency scenarios. In these situations, the deployment of a traditional backhaul infrastructure would require a very high investment which is usually uneconomical for such a short duration; a solution based on low-cost technologies such as WiFi, deployed in mesh topologies, provides a much more cost-effective way of satisfying this short-term demand.

A critical concern for operators is to provide access to the typical service bundle via all the radio access networks offered by the operator. Specifically, access to typical voice, video and data services must be provided. This imposes some constraints on the performance of the mesh backhaul: it must support *carrier-grade* service provisioning. While carrier grade, in general, has many aspects, including equipment reliability, security, AAA, QoS, management, standard's compliance, mobility support, service integration, etc., the contribution in this chapter will focus on those aspects that are most related to reliable service delivery: specifically, on issues related to ensuring that typical carrier service offerings, such as voice, video and data, are delivered with appropriate service quality to diverse mobile devices. This is a

real challenge which is not supported by current mesh network technology. Hence, we call our system approach a **Carrier-grade Wireless Mesh Network (CARMEN)**.

Generally, there is no single optimal wireless technology for all use cases at the same time. Backhauls for mobile cellular networks are well served with point-to-point microwave radios. Communication coverage in emergency scenarios is probably better provided with WiMAX or WiFi meshes. Hence, in this chapter, we propose a mesh solution that is able to combine different technologies in order to realize a **heterogeneous mesh backhaul solution** (see Figure 1).

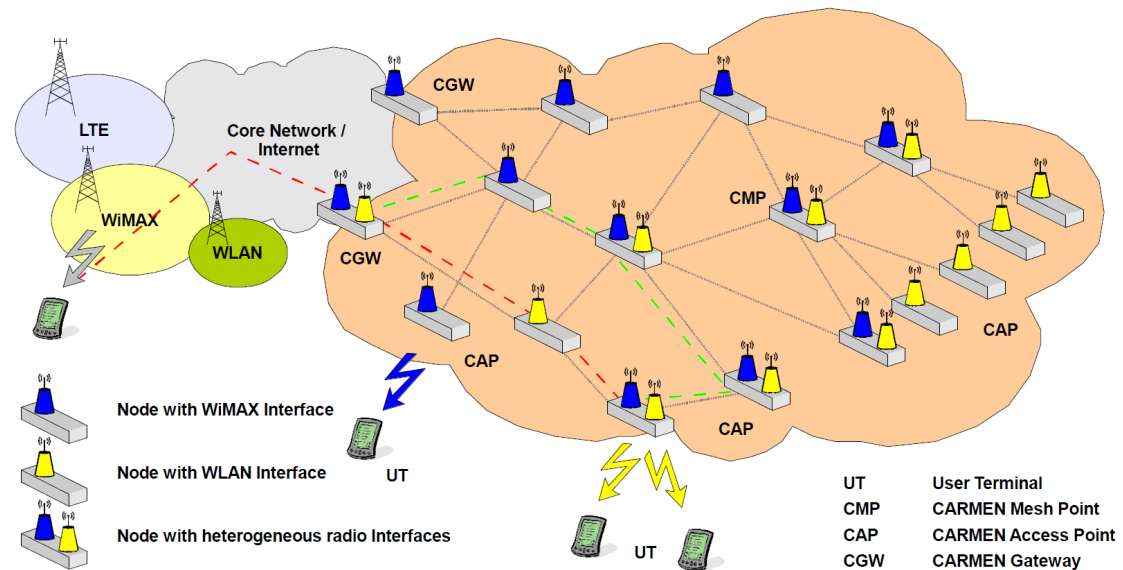


Figure 1: CARMEN's Heterogeneous Wireless Mesh Network Scenario

In our considered scenario in Figure 1, we distinguish between CARMEN Access Points (CAPs) which are nodes that (in addition to relaying traffic within the mesh backhaul) provide wireless access to user terminals (UTs), CARMEN Mesh Points (CMPs) that are pure backhaul router nodes and CARMEN Gateways (CGWs), that connect the mesh backhaul to the operator core network or the Internet.

In summary, then, the mesh based backhaul solution has the advantage of providing lower cost, more flexible backhaul for operators wishing to provide access to mobile users. Heterogeneous technologies can be used in the mesh to adapt to the various coverage/capacity requirements. The support for carrier grade services (including broadcast services) is a key challenge that needs to be addressed in order to realize this vision.

2 BACKGROUND

Clearly, there is a plethora of previous works in the general context of wireless mesh networks. It would not help the reader to list them all in this section, since the focus might be completely different, even though the overall subject is similar. Hence, to stay concise, we will limit the discussion to works specifically related to one of the individual key contributions of our CARMEN mesh backhaul solution.

2.1 Self Configuration

Topology Discovery and Formation

IEEE 802.1ab [1], link layer discovery protocol (LLDP), is a topology discovery protocol specifically designed for IEEE 802 standards. There are three distinct characteristics of LLDP distinguishing it from all relevant studies in this area. First of all, LLDP is a one way protocol in the sense that the announcements are connectionless, passive, and unidirectional. LLDP agents do not explicitly respond to any LLDP PDUs that they receive. This means that the only possible way to understand if any neighbouring device received a specific advertisement is to receive another advertisement from that device in which there is information related to neighbours. However, LLDP PDUs do not include any information about the neighbourhood either. The main idea behind this characteristic is that LLDP's target is to provide a central network administrator, not individual devices, with the topology information.

IEEE 802.11s [2] also defines mesh discovery, mesh authentication, peer link management and channel selection. IEEE 802.11s supports passive or active scanning to discover neighbour mesh points. However, the focus is on building an IEEE 802 LAN, i.e. a layer-2 mesh, while our work leads to layer-3 meshes. IEEE 802.11s does not consider heterogeneous technologies.

[3] introduces a neighbourhood information based topology discovery protocol that targets limiting interference as much as possible while keeping the communication graph connected with high probability. This protocol is called the *k-Neighbour protocol*. The focus is on transmission power control and optimization. The focus in our work is on capacity-optimality and stability.

[4] adopts a connectivity oriented approach to topology discovery in wireless ad hoc networks. They propose two localized topology control algorithms based on non-uniform maximum transmission power. Those algorithms are Directed Relative Neighbourhood Graph and Directed Local Spanning Graph. Both algorithms are based on the graph theory and the target is to adjust transmission power such that connectivity among mesh points and bi-directionality are guaranteed.

An overview of works for topology information dissemination can also be found in [5].

Radio Resource Management

Generally, one can distinguish between fixed channel assignment (FCA) and dynamic channel assignment (DCA). In FCA, the set of channels are

permanently allocated based on a pre-estimated traffic design [6], [7]. Here, we consider only DCA approaches.

DCA in cellular networks has been extensively studied and, as formulated in [8], is an NP-complete problem. Therefore, some heuristic assignment strategies and combinational optimisation tools such as Genetic Algorithms [9], [10], [11] Simulation Annealing [12], [13], multi-colouring schemes [14], [15] and neural networks [16], [17], [18] have emerged to deliver a near optimal solution.

For DCA in IEEE 802.11 WLANs, a well-known scheme is called Least Congested Channel Search (LCCS), which [19] showed to be not efficient with continued growth of WLANs. [19] formulates the channel assignment problem as a weighted vertex colouring problem and proposed two distributed algorithms that outperform the LCCS in terms of significant interference reduction. In [20], [21], the authors introduced additional techniques based on graph colouring algorithms. Other approaches are [22] (maximize per-user throughput), [23] (maximize fairness), or [24] (improve the utilization of wireless spectrum).

The existing channel assignment schemes in WMNs can be divided into three main categories — fixed, dynamic, and hybrid — depending on the frequency with which the channel assignment scheme is modified. In a fixed scheme the channel assignment is almost constant, while in a dynamic scheme it is continuously updated to improve performance. A hybrid scheme applies a fixed scheme for some interfaces and a dynamic one for others. [25] and [26] are examples for static schemes, [27] and [28] for dynamic schemes, and [29] and [30] for hybrid ones. Our approach is a dynamic scheme.

2.2 Radio Abstraction Layer

One of the fundamental contributions of our proposal is to introduce a radio abstraction layer in order to cope with heterogeneous wireless meshes. This layer is supposed to expose a number of technology-independent primitives to higher layers so that these can interact with the wireless interfaces in a homogeneous way.

IEEE 802.21

IEEE 802.21 [31] defines a standard for handovers across heterogeneous access networks, e.g. from an 802.11 to an 802.16 network or to a 3GPP network. Part of the handover process consists in preparing the target base station to accommodate the mobile terminal – ideally before the latter’s existing radio connection has been terminated. In order to enable these kinds of handovers involving multiple technologies, there must obviously be a media-independent interface allowing higher-layer functions (called “MIH Users” in IEEE 802.21), i.e. mobility management, to obtain information from the underlying involved radios about link state measurements or to tell the target base station to allocate certain radio resources for the new terminal. For this purpose, IEEE 802.21 defines a media-independent layer called Media-Independent Handover Function (MIHF). The standard also defines a mapping between the technology-independent handover primitives and their

technology-specific counterparts. Since in handovers, always multiple network nodes are involved, IEEE 802.21 also defines a protocol and transport mechanism over layer-2 or layer-3, via which primitives (i.e. handover signaling) can be transported between nodes. In Figure 2, this is called MIH_NET_SAP.

Our CARMEN radio abstraction solution is actually based on the IEEE 802.21 architecture. However, it significantly generalizes it, and adds a number of primitives to enable more comprehensive mesh functions beyond just handovers. This will be explained in more detail later.

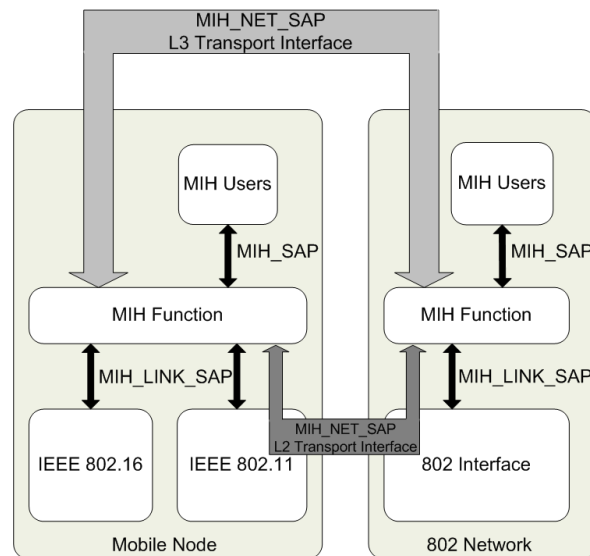


Figure 2: IEEE 802.21 Architecture

Ambient Networks

Ambient Networks (AN) is an EU project which focuses on technology which will allow people to communicate using the most cost-effective and appropriate combination of wireless networks and services (“always best connected”). Its goal is to provide seamless communication and entertainment through wireless devices of any sort. Since it is to support all wireless technologies, one part of its solution is a so-called Generic Link Layer (GLL) which has a similar function than the radio abstraction layer defined in this chapter. However, the focus is fairly different (it is not specifically targeted at mesh networks, or carrier-grade quality, it focuses on “user-centric” vs. our node-centric in-mesh communication).

2.3 Routing and Capacity Handling

Most of the existing works that consider routing in mesh networks are targeted at distributed routing approaches, where the goal is to find paths between source and destination that are optimal with respect to a number of metrics, by deferring decisions to individual intermediate nodes or groups of nodes.

However, for carrier-grade mesh networks, localized decisions may too easily lead to sub-optimal solutions on a network-wide level. Besides, we have performed studies comparing distributed with centralized routing approaches in wireless mesh networks and have come to the conclusion that convergence time after link state changes is likely to be too slow with distributed approaches. Hence, we have opted for a centralized routing solution where link state information is propagated to a centralized path computation element which then computes paths on behalf of the network nodes in a capacity-optimal way. The computation is done based on Integer-Linear Programming, i.e. leads to really optimal results for the given network situation.

Thanks to our radio abstraction layer, the central path computation element has an abstracted logical topology view of the whole network at any time. This means that its task is reduced to a pure algorithmic path search. Hence, the core contribution of routing, as far as heterogeneous wireless network support (the scope of this book) is concerned, is actually done by the abstraction layer, not by the computation element. For this reason, we skip going into long discussion of works on routing algorithms.

2.4 Mobility Management

Our mobility management solution is partly based on a well-known solution called Proxy Mobile IP (PMIP) [32]. PMIP is a variant of Network-based Localised Mobility Management (NetLMM) approaches, which, unlike host-based localised mobility where mobile terminals (MTs) signal a location change to the network to update routing states, provide mobility support to moving hosts without their involvement. A proxy mobility agent in the network performs the signalling and does the mobility management on behalf of the MT attached to the network. The core functional entities in the PMIPv6 infrastructure are (see Figure 3):

- Mobile Access Gateway (MAG). This entity performs the mobility related signalling on behalf of an MT that it is attached to its access link. The MAG is usually the access router for the MT, i.e. the first hop router in the LMM infrastructure. It is responsible for tracking the MT's movements in the access link. There are multiple MAGs in a Localized Mobility Domain (LMD).
- Local Mobility Anchor (LMA). This is an entity within the backbone network that maintains a collection of routes for individual MTs within the LMD. These routes point to the MAGs managing the links in which the MTs are currently located. Packets for an MT are routed to and from the MT through tunnels between the LMA and the corresponding MAG.

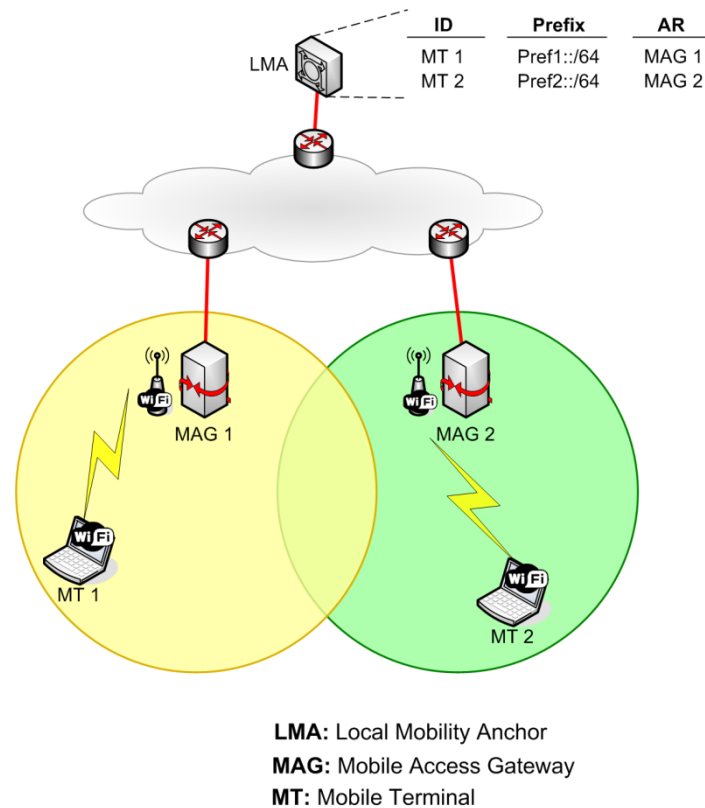


Figure 3: Proxy Mobile IPv6 Domain

Work on ‘MPLS Tunnel for PMIPv6’ proposes Multiprotocol Label Switching [33] as an alternative tunnel technology used between MAG and LMA beside IPv6, IPv4 or IPv4-UDP encapsulation headers. As MPLS has become quite popular and MPLS support is an important function for commercial edge and core routers, the integration of MPLS and Proxy IP Mobility can leverage operational PMIP deployment. Our work here would actually focus on MPLS usage between the MAG (on the CGW) and the so-called Point of Attachment (PoA) (on the CAP), i.e. be complementary.

Some proposed extensions to L3 mobility management protocol at IETF are based on approaches that distinguish between an upper hierarchical layer where wide area (macro) mobility is realised by Mobile IPv6 (MIPv6) [34], and a lower level of local (micro) mobility where all nodes maintain a soft-state routing cache, mapping the source address of received packets to the node forwarding them (this enables to learn a route to the originating node). The soft state information has to be renewed periodically.

Besides Hierarchical MIPv6 [35] which is specified in an RFC, there are other micro mobility protocols that were proposed at the IETF, but did not reach RFC status, namely Cellular IP (CIP) and HAWAII (Handoff-Aware Wireless Access Internet Infrastructure). Cellular IP [36], [37] was designed to complement and interwork with global IP mobility solutions, such as MIP or PMIP, and supports paging (location management across cell borders for idle nodes) and a number of (hard and semi-soft) handoff techniques. Both CIP functions are integrated with hop-by-hop routing along bi-directional paths. Cellular IP requires each node to use exactly one CIP gateway (towards the global IP network) at a time. This is due to the Gateway’s role to serve as a node’s Foreign Agent which has to relay its traffic in both directions up- and

downlink. It is also required to make uplink routing unambiguous. This is not suitable for mesh access networks.

Generally, the mobility management solution that we propose also distinguishes between macro- and micro-mobility. It uses standard PMIP in the operator core network (i.e. between LMA and MAG) and a PMIP-like but mesh-tailored solution in the mesh access network (between MAG and PoA). For the signalling between PoA and mobile terminal, we use IEEE 802.21, which was already introduced earlier. Details about our mobility solution will be explained in Section 3.5.

3 ARCHITECTURE

3.1 General Overview

In order to enable carrier-grade services over a wireless mesh network comprising of heterogeneous wireless technologies, one of the most fundamental contributions which CARMEN makes is the introduction of a technology-independent link (control) interface. Using this interface, higher-layer modules like Routing, Self-Configuration, etc. can interact with the individual interfaces (i.e. their drivers) in a homogeneous way. The technology-independent interface is also called Abstract Interface in this chapter, or *AI* for short. The AI can be used to obtain current parameters of interfaces like the currently used transmission power or modulation and coding scheme (MCS), but also to set these and other parameters, allocate resources in the underlying MAC layers, or obtain measurements from the individual radios. Figure 4 depicts the general architecture of a CARMEN node. Details of the AI will be presented in Section 3.3.

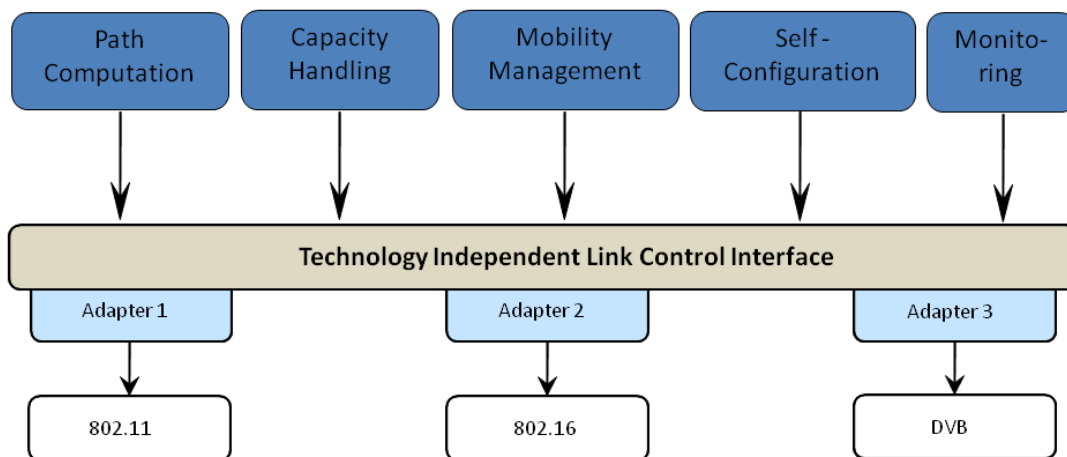


Figure 4: CARMEN Node Architecture

The AI is designed as an interface for the control and management plane of the network. The data plane in CARMEN is based on MPLS.

Generally, user traffic in CARMEN is transported in so-called *pipes*. A pipe is an end-to-end tunnel through the wireless mesh network associated with a specific QoS allocation (e.g. required bandwidth or delay). Pipes are usually dimensioned to be able to accommodate multiple user flows of a certain QoS class. This has the advantage that route discovery and resource allocation has to be done only once per pipe. Once a pipe p between a source node s and a destination node d is constructed and its resources in each intermediate node reserved, new flows between s and d (belonging to p 's traffic class) can simply be forwarded along the pipe without having to consult routing again. Also, doing explicit resource reservations for pipes instead of more opportunistic forwarding (as in the case of standard IP-routing) allows controlled traffic engineering and admission control of user traffic. This prevents the network from becoming congested.

In each CARMEN node, according to Figure 4, the five software modules routing, capacity handling, self configuration, mobility management and monitoring are running. In this chapter, these modules will generally be called *mesh modules*. Routing is responsible for computing and constructing path (i.e. MPLS tunnels) within the mesh network. Capacity handling keeps track of the available capacities in the network and decides which capacities to assign to new pipes, whether to increase existing pipes or construct new ones in case the existing ones are not sufficient anymore, etc. Self configuration is responsible for bootstrapping the network and continuously maintaining the network in terms of interface (de-)activation, channel/transmission power/MCS assignment, neighbor selection, etc. Mobility management handles flow-to-pipe bindings, IP address configuration and maintenance as well as handover execution of user terminals. Monitoring takes care of performing neighborhood scanning and obtaining measurement statistics about link qualities. These modules will be described later in more detail.

3.2 Self Configuration

The main role of Self Configuration is to provide the intelligence and configuration mechanisms to autonomously perform network setup and configuration, in particular node discovery and initial topology formation. Self-configuration also provides dynamic adaptation and optimization during regular network operation as well as during network failure.

Although the CARMEN architecture incorporates heterogeneous technologies the most difficult technologies on which to perform automatic configuration are those operating in unlicensed spectrum. The difficulty of self-configuration is further exacerbated when using low cost hardware and when co-locating multiple radios on the same mesh node.

For these reasons the CARMEN Self Configuration Function was developed to perform automated configuration for IEEE 802.11. The majority of 802.11 Access Points (APs) and User Terminals (UTs) operate in the 2.4GHz band; this can lead to high levels of congestion and would lead to poor backhaul network performance. An obvious solution is to use the higher Industrial, Scientific and Medical (ISM) spectrum at 5GHz and use 802.11a for the mesh network backhaul and the 2.4GHz band for user access; this helps to mitigate interference between mesh backhaul traffic and user access. Another advantage of using the higher 5GHz band is the larger number of available non-overlapping channels, which make it more suitable when multiple radios are co-located on the same mesh node.

However, deploying such a multi-radio 802.11 Wireless Mesh Network (WMN) would require individual manual configuration of each Mesh Node (MN) based on the radio environment and the level of interference from co-located radios; this requirement greatly reduces the cost-effectiveness of such deployments. For this reason a self-configuration framework can negate the need for manual measurements, radio planning and configuration of radio parameters such as channel, Transmission Power (TxPower), Modulation Coding Scheme (MCS) is required. As shown by Nachtigall et al. [38], the use multi-radio equipped 802.11a MNs for backbone communication can greatly increase the

overall WMN capacity. However, multi-radio equipped MNs suffer from significant levels of Adjacent Channel Interference (ACI); as investigated by [1], [39] and [40], as well as Inter-Channel Interference (ICI) described in previous work [41]. The SCF must consider each of these affects in order to compute the radio parameters for each node to minimize interference while maximizing system capacity.

Multi-Radio Interference Issue

Multi-radio CARMEN nodes utilize multiple 802.11a radios operating in close proximity and hence ACI issues are of particular importance.

Although channels in the 802.11a band are said to be non-overlapping there are still significant interference issues between neighboring antennas, even beyond channel separations of one. In order to demonstrate this problem, to figure out the impact of this interference and the required channel separations to mitigate it, throughput measurements were performed on multi-radio mesh network equipment. Other parameters including RTR, MAC layer loss and application layer loss were also recorded. Further information about these experiments and the experimental testbed can be found in [41] and [42].

A comprehensive set of experiments was performed on a dual radio mesh node with varying antenna separations and varying channel separations over all possible physical layer data rates. Each channel separation corresponds to a distance of 20MHz between the centre frequencies of each adjacent channel and each radio transmitting at the maximum transmit power of 15dbm to a third mesh node. In order to saturate each link, UDP traffic was generated using IPerf such that each radio was always trying to transmit at the maximum possible rate.

Figure 5, Figure 6, Figure 7 and Figure 8 show the results of these experiments. Each figure shows the aggregated throughput for both radios with a fixed antenna separation and operating at the maximum transmission power (Tx Power) with different channel separations over the range of available physical layer data rates. The aggregated throughput is the sum of the throughputs for both links; assuming no interference the maximum possible aggregate throughput would be approximately 82Mbps (twice the throughput of a single UDP connection).

The general trend of these results shows that the higher the channel separation, the better the aggregated throughput of the system is. However, in each experiment the maximal expected aggregate throughput of approximately 82Mbps was not achieved until a channel separation of 7 (e.g. Operating on Channels 36 and 64) This clearly demonstrates there are other interference factors that affect the system performance and not simply the ACI effect, since the side-band of a 20 MHz channel would only affect the adjacent channel.

These results also show that the higher the physical antenna separation between co-located antennas, the higher the achievable throughput. It should also be noted that during these experiments higher antenna separations also resulted in higher link stabilities. Both of these factors are of critical

importance for achieving a mesh network capable of carrying carrier grade traffic. Due to space constraints, only a small subset of the experiments performed can be presented here; further details can be found in [41] and [42]. However, the presented results demonstrate the importance of an intelligent, interference aware radio configuration mechanism for wireless mesh networks.

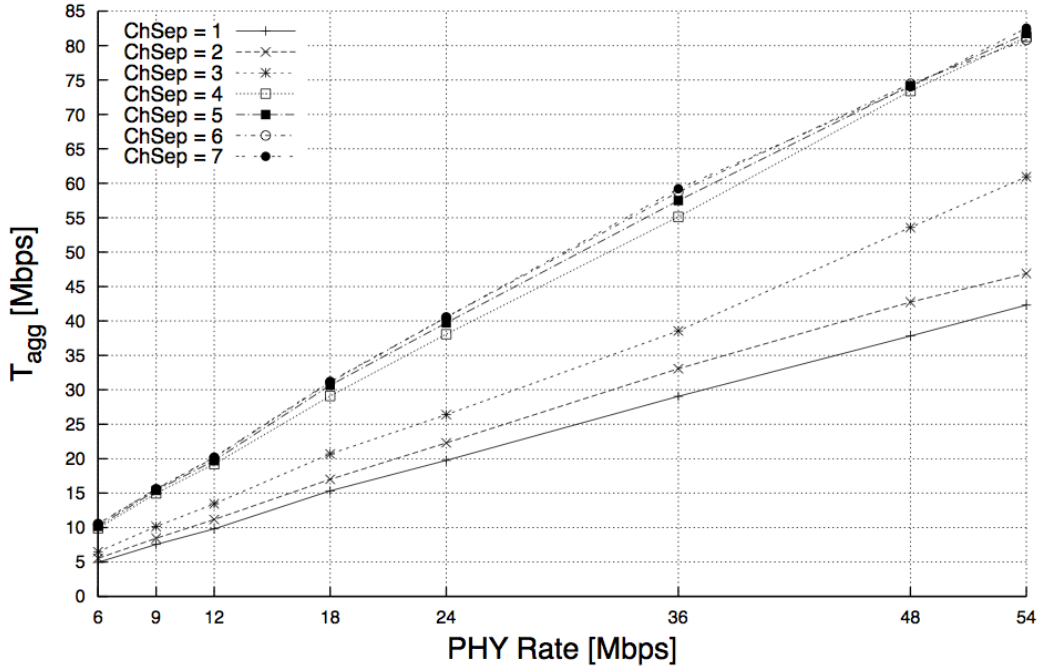


Figure 5 - Aggregated Throughput for Antenna Separation of 20cm with Tx Power of 15dbm

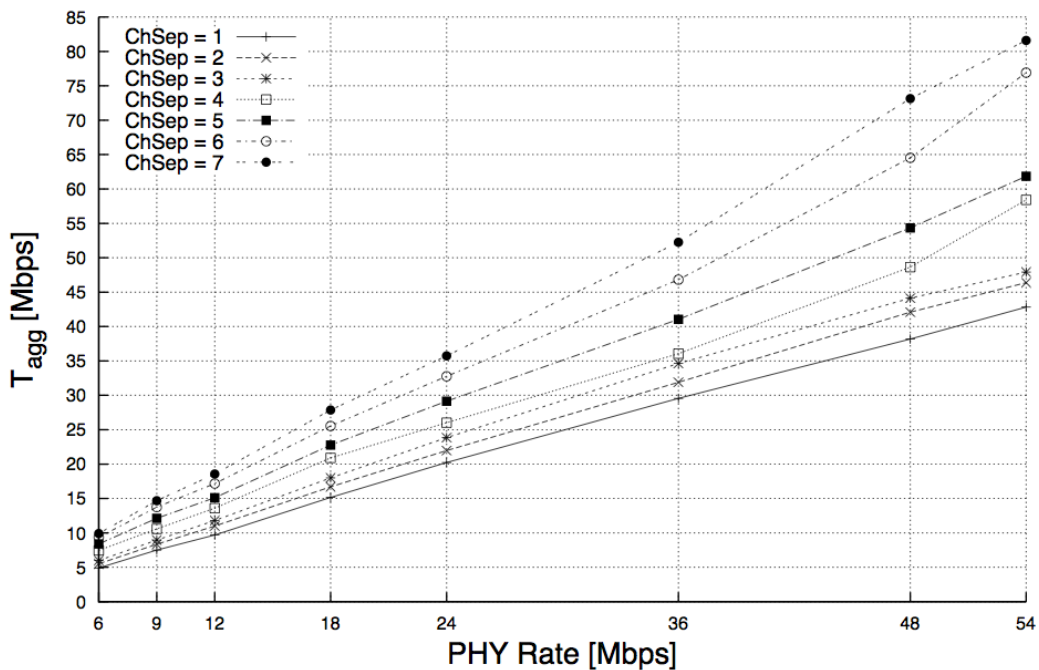


Figure 6 - Aggregated Throughput for Antenna Separation of 10cm with Tx Power of 15dbm

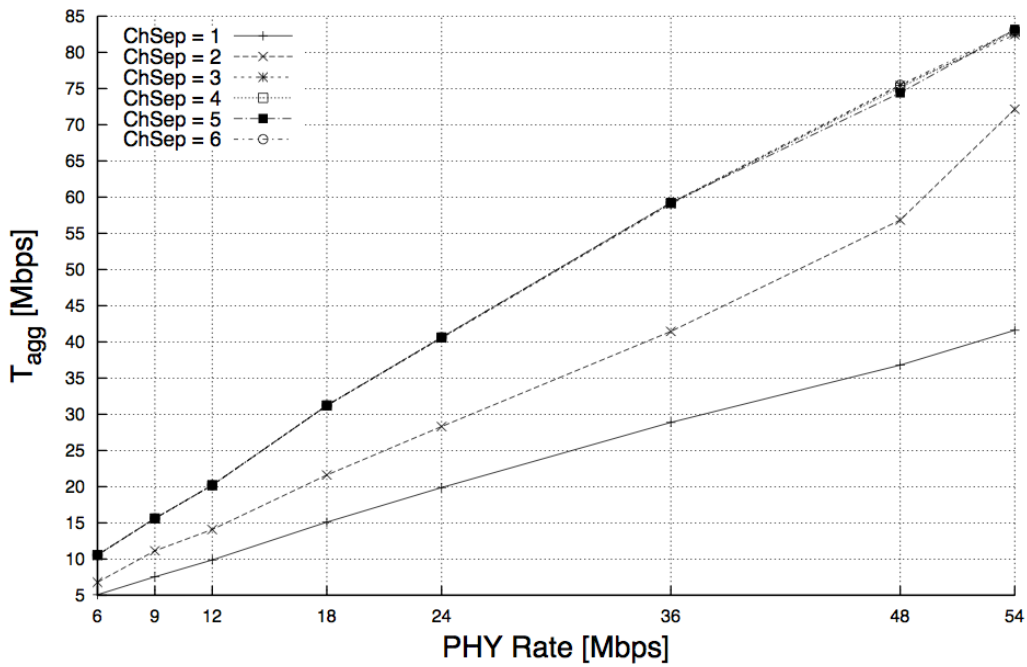


Figure 7 - Aggregated Throughput for Antenna Separation of 30cm with Tx Power of 15dbm

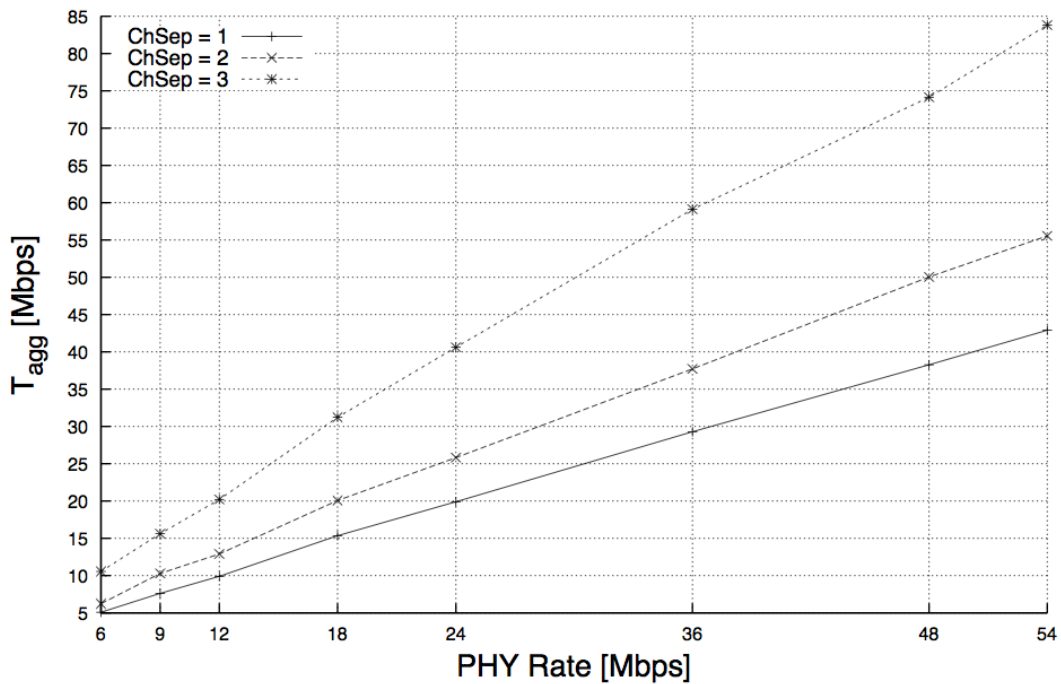


Figure 8 - Aggregated Throughput for Antenna Separation of 40cm with Tx Power of 15dbm

SCF Module

Within the CARMEN system there are two variants of the SCF; a CGW SCF and an SCF module for CAP and CMP nodes. The CGW SCF is significantly more complex than the non-CGW SCF; the SCF on the CGW can be seen as the centralized entity that is responsible for computing radio configuration

parameters for each node under the control of the gateway. Specifically, when computing radio configurations, the SCF must not only consider neighboring node radio configurations but also the interference between multiple radios on the same node as described above.

SCF Algorithm

In order to minimize complexity and maximize efficiency, the implemented radio configuration takes some offline planning assumptions into account.

Firstly, it is assumed that the node density has been planned such that there is a fair and realistic relationship between the total number of available channels and the number of nodes within a range of one another. This assumption is also taken as an input parameter into the decision on the size of a Link Group. Another assumption that impacts the link group size, channel assignment and radio configuration settings is that a large number of interfaces sharing the same physical medium will lower the overall performance within the Link-Group; this is due to the uncoordinated CSMA/CA procedure used in 802.11. Therefore, the SCF always attempts to minimize the size of each link group with the optimal result being the creation of point-to-point links between neighbors. Radio configuration is performed in a per-node fashion as the nodes bootstrap.

The SCF on the CGW will instruct the new node to set the Tx Power to the maximum possible level on all available 802.11 radio interfaces in the node. Based on the level of interference between the radios in each node, as described earlier, the minimal channel separation required between the co-located radios can be calculated in order to mitigate Adjacent Channel Interference and Inter-Channel Interference.

Based on both external users and other nodes operating the CARMEN mesh, the number of available channels may not be sufficient to completely mitigate these interferences. In this case the Tx Power is decreased such that at least one potential neighbor can be reached. Once the minimum channel separation is known the channel selection is computed using an Edge-coloring approach. If there are not enough available channels the assumption of creating point-to-point links is changed to create a link group of three radio interfaces or more.

3.3 Radio Abstraction Layer

Architectural Components

While Figure 4 showed a high-level representation of the AI, Figure 9 gives a more detailed depiction. As can be seen, the AI is internally more than a simple API exposing technology-independent event or command primitives. Rather, a significant part of the AI is defined by the so-called *Interface Management Function (IMF)*. The main features of the IMF architecture are

- Inter Process Communication (IPC) down- and up-calls between mesh modules (routing, self-configuration, etc.) and IMF
- IPC down- and up-calls between IMF and Interface Adapters

- Communication between different mesh modules via the IPC Mechanisms offered by the IMF
- Collaboration of the IMF Message Dispatcher and the IMF Node Manager Function
- Support for remote event subscription/reception

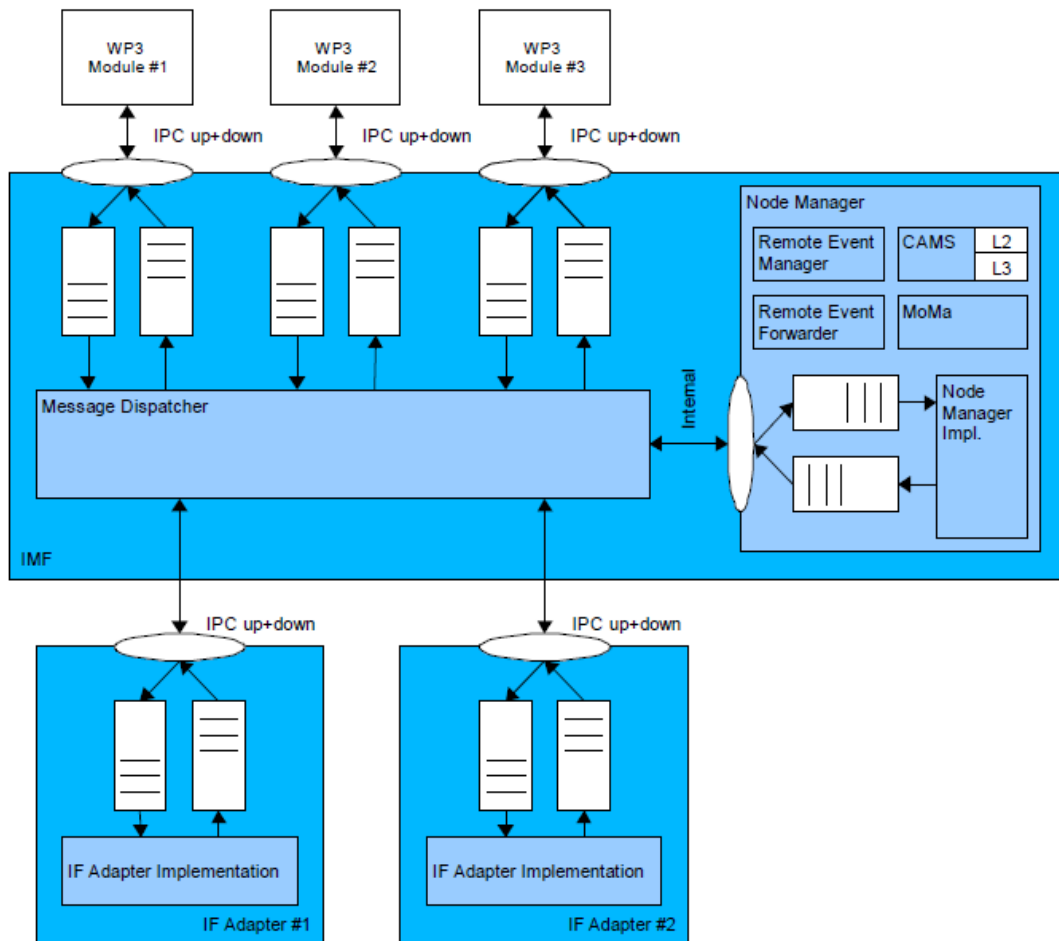


Figure 9: IMF Architecture and SAPs

The CARMEN IMF borrows concepts for linking modules inside a protocol stack based on adjacent layer protocols as this is described in the OSI Open Systems Connection Model [9], [10]. The IMF building blocks include Service Access Points (SAPs) to define service primitives issued by CARMEN mesh modules. Generally, two types of primitives which can be exchanged between mesh modules and wireless interfaces (via IMF) can be distinguished. These are event and command primitives. Examples for event primitives are LINK_UP (a new link to a neighboring node has been established), LINK_PARAMETER_CHANGE (the QoS parameters of an existing link have changed), or NEW_FLOW (a new user flow has been detected at an interface). Examples for command primitives are ALLOCATE_RESOURCES (reserve QoS resources like capacity in the MAC layer of an interface), or SET_RADIO_PARAMETERS (to configure the radio parameters of a radio card like MCS, channel or power).

Actually, it has been identified that some of the required primitives are already included in the IEEE 802.21 standard [31]. This standard also defines a media-independent interface, but is restricted in its scope to handovers across heterogeneous networks. Thus, the only expected user (mesh module in CARMEN terminology) of the IEEE 802.21 interface is mobility management. Hence, primitives beyond handover needs are missing and the interface management capabilities of IEEE 802.21 are not as generic as CARMEN's.

While event primitives are normally unidirectional by nature (i.e. going only upwards from the interface to mesh modules), command primitives are usually bidirectional and involve a request and a response part. Therefore, when bidirectional service primitives are invoked or received by mesh modules, they need to be accompanied by transaction IDs (correlators) for allowing mesh modules to relate responses with requests. This will be done by the mesh modules and transparently forwarded through the AI and included in responses. Furthermore, the IMF needs to attach SAP IDs to allow response and event service primitives to be forwarded to the originator of the request. Each mesh module has its distinct SAP ID which is assigned to it by the IMF upon IPC attachment. The validity of SAP IDs is for the time of attachment of the mesh modules. SAP IDs are not reused for a long time in order to avoid wrong assignments of responses, indications, and events to requests in cases where a more dynamic mesh node setup is used in the future.

The IMF Node Manager Function is a node wide information store for information pertaining to the node interface management, e.g. number and IDs of interfaces. This ensures the correct referencing of interfaces in the IPC communication with mesh modules. The Node Manager also hosts other node-wide functions such as Remote Event Managers, CAMS messaging service, and Monitoring aggregators (MoMa).

The Remote Event Manager is responsible for sending, relaying and receiving remote events and commands. In CARMEN, events can not only be received locally in a node. Rather, they can also be forwarded to arbitrary other nodes and received by those nodes' mesh modules. Likewise, commands cannot only be sent to local interfaces via the IMF, but also to interfaces of remote nodes. The Remote Event Manager is responsible for the remote communication. Generally, in order to receive events, mesh modules have to subscribe to them in the IMF by specifying the event type as well as the originating node (be it the local or a remote one). Then, once an event is received at the IMF, the latter will propagate it to all mesh modules which had subscribed for it previously.

In order to propagate events to other nodes, layer-2 or layer-3 transport is employed depending on whether the target node is a direct neighbor of the originating node or not. An entity called *CARMEN Messaging Service (CAMS)* (cf. Figure 9) is responsible for the transport of remote events or commands. Basically, CAMS is similar to the transport mechanisms defined in IEEE 802.21 where remote event signaling is also supported via the so-called `MIH_NET_SAP`.

Finally, the IMF encompasses an entity called *Monitoring Module Aggregator (MoMa)*. In the technology-specific Interface Adapter, there is a Measurement

Module (MeM) for obtaining measurement data in real-time about link stability, error rates, RSSI and SNR values, etc. The MoMa queries and aggregates this data in order to compute more expressive link and interface metrics out of sequences of measurement values. These metrics in turn can be queried by mesh modules for cross-layer optimization of protocols.

Mapping technology-specifics to technology independence

One of the most critical and difficult tasks of the radio abstraction layer is to map the technology-independent primitives to technology-specific ones and vice versa. This goes far beyond syntactical transformations, since, generally, it cannot be assumed that there is a one-to-one mapping for each event and command in each target technology. A fundamental problem in carrier-grade wireless mesh networks is, for example, the radio resource management and admission control. The admission control needs to have up-to-date information about the available resources in the network, in order to decide whether a new flow can be admitted to the network or not. However, the amount of available resources changes dynamically because of wireless link fluctuations and added or removed pipes (which have dedicated resources allocated to them). This means that admission control (as well as capacity-aware routing) needs a technology-independent link state model of the network topology. The link information includes at least the available (residual) link capacity, but could also include loss, delay or jitter.

In the following, we will present such a technology-independent link capacity model. This is to serve as an example for the general mapping complexity of the radio abstraction layer.

In our model, *logical links* are the technology-independent representation of radio links as exposed by the CARMEN AI to all higher layer functions. We use the term *logical*, because there need not be a one-to-one correspondence to physical links below the AI. We assume logical links are directional and point-to-point, as

- routing and capacity handling need to be aware if a technology only supports unidirectional communication (e.g. DVB-T) or if up- and downlink capacities are asymmetric (e.g. WiMAX),
- a point-to-point model simplifies link modeling and link QoS description (and thus the AI), and
- this model makes the mesh topology appear like a wired network, which enables the reuse of protocols designed for wired networks for benchmarking purposes.

A difference between a “wired” and a “wireless” point-to-point link is that in the former case a transmission is only received by the other end-point of the link, whereas in the latter case the transmission is often received by multiple (intentional or unintentional) receivers. This needs to be modeled, because it means the throughput capacity of a logical point-to-point link may depend on the traffic or resource allocation of some other logical point-to-point links. Here, this is modeled by the concept of a *logical link group* that describes the set of logical links that share the capacity available to the group as a whole.

More formally, we can model the CARMEN mesh network as a directed graph (=digraph) $G := (V;E)$, where V is a set of vertices (CARMEN Mesh Points) and E a set of directed edges (the logical links). A directed edge $e \in E$ is an ordered pair of vertices, i.e. $e := (v_1, v_2)$; $v_1, v_2 \in V$, and $p(e) := v_1$ is called the predecessor of e and $s(e) := v_2$ the successor of e .

A logical link group is a set of logical links and each logical link in E belongs to exactly one logical link group. In other words, E can be partitioned into a set of logical link groups Λ for which

$$\bigcup_{L \in \Lambda} L = E \quad \wedge \quad \forall L_i, L_j \in \Lambda, L_i \neq L_j: L_i \cap L_j = \emptyset$$

Let $L(e)$ denote the logical link group that logical link e belongs to and $C(L)$ the *capacity* of a group L . We measure the capacity of a logical link group in a technology-independent manner in terms of “scheduling units per second” ($\left[\frac{SU}{s}\right]$). These scheduling units could, for example, be TXOPs in IEEE 802.11 or time-frequency-slots in OFDMA, or could be just symbols and they can vary from link group to link group. The capacity should already be the net capacity, i.e. discounting for protocol overhead. Note that in one link group, as here defined, only one radio technology can be employed at any given time.

Further, let $c(e)$ denote the current cost of transmitting to the receiver $s(e)$ expressed in terms of “scheduling units per bit” ($\left[\frac{SU}{b}\right]$). This cost can be seen as the price paid, and deducted from the total wealth $C(L)$ available for that group, to transmit at link e at that particular instant. It includes the efficiency of the modulation and coding scheme used to match the current radio link e 's quality.

Finally, let's assume F is a set of flows already admitted to the network by admission control. Let L_f be the subset of links of logical link group L ($L_f \subseteq L$) that flow f needs to use to reach the intended receivers of a given transmission. L_f can then be used, for example, to model a multicast transmission directed to those receivers. Note that in this model a unicast transmission can be considered as a special case where the cardinality of L_f is 1. The traffic demand imposed by flow f will be defined as r_f (and measured in “bits per second” ($\left[\frac{b}{s}\right]$)). The *effective cost* of a flow to a particular set of receivers, assuming a particular admission control allocation, $c_{eff}(f)$, can then be computed and it depends on whether the underlying physical technology supports native multicast or whether multicast has to be emulated by separate unicast transmissions to each receiver. In the first case, the effective cost is equal to the highest cost of any point-to-point link in L_f , because the modulation and coding needs to support the weakest multicast receiver. In the second case, the effective cost is equal to the sum of costs of all point-to-point links in L_f . Therefore, we have:

$$c_{eff}(f) = \begin{cases} \bigvee_{e \in L_f} c_e & \text{native multicast} \\ \sum_{e \in L_f} c_e & \text{emulated multicast} \end{cases}$$

Given the information defined above, routing and capacity handling **can then test in advance and remotely, how an admission control or routing decision would influence the remaining capacity** in the network by computing a link group L 's remaining capacity $C^*(L)$ and available transmission rate for link e , $r^*(e)$, at cost $c(e)$ as:

$$C^*(L) = C(L) - \sum_{f \in F} c_{eff}(f) r_f$$

$$r^*(e) = \frac{C^*(L)}{c(e)}$$

A discussion how these values can be computed for specific technologies such as WiFi or WiMAX must be omitted due to space limitations here. However, concrete mappings have been done for WiFi, WiMAX and a non-standardized Soft-TDMA MAC.

3.4 Routing and Capacity Handling

This section provides an overview of the CARMEN routing function, the Capacity Handling Function (CHF) and the Forwarding Function (FF).

Routing Overview

Routing in a heterogeneous resource-constraint wireless mesh network requires sophisticated algorithms and mechanisms to efficiently manage the available resources and provide the high levels of guaranteed QoS required by end users. The CARMEN approach aims at reducing the CAPEX required to deploy carrier-grade networks by providing carrier-grade network availability and reliability utilizing lower cost “off the shelf” equipment.

For this reason CARMEN incorporates both an advanced admission control mechanism and a centralized QoS aware routing mechanism that is capable of providing the high levels of guaranteed QoS required by carrier grade services. The CARMEN routing function is responsible for determining how to populate and manage forwarding tables for different traffic classes and is responsible for the capacity management in the network. Unlike other mesh networks the CARMEN network must deliver carrier grade performance with guaranteed levels of QoS across heterogeneous access networks. Furthermore, to allow for triple-play service provisioning, the CARMEN routing architecture supports unicast as well as 1-to-N multicast path computation and setup. In order to support Mobile Terminal mobility and QoS differentiation while maintaining scalability, individual flows are aggregated into pipes, which are configured between any two CARMEN nodes. The routing mechanism must meet these requirements and therefore must have support for multipath routes, the ability to guarantee resources, and it must consider how traffic flows across different paths impact one another.

To achieve these requirements the CARMEN routing architecture must maintain real time up-to-date state information about the available links, their committed resources and QoS requirements and to efficiently route traffic across the network. Considering the relatively static (non-mobile) nature of a CARMEN mesh network and to reduce complexity in mesh points a

centralized routing mechanism was opted for. The centralized approach allows the gateway to have global knowledge of its routing area thereby allowing it to make informed decisions.

As stated earlier, a key requirement in CARMEN is the ability to meet carrier grade performance; this is a difficult challenge particularly when heterogeneous wireless technologies are being considered including contention based technologies operating in a shared medium on unlicensed spectrum. Specifically, CARMEN links have more dynamic behavior and are more susceptible to external interference when compared to wired or wire-like operator networks. Hence, when compared with traditional operator networks it is much more difficult to provide guaranteed QoS bounds in such a network. As any transmission using a contention-based mechanism can impact all users operating in the same medium, it is important that this is taken into account so as to minimize interference and provide a guaranteed level of quality. This leads to a global optimization problem for managing resources that can be solved by having global knowledge as in the centralized approach. The centralized approach to routing allows accurate determination of the impact a routing decision such as pipe setup/teardown has on other existing pipes. In the centralized routing mechanism each gateway acts as a network manager for its routing area and makes all routing decisions. The gateway maintains knowledge of the topology of its routing area, including link states, link groups, link group capacities and remaining link group capacities, as well as knowledge of all existing pipes.

Unlike a decentralized routing mechanism such as OSPF link state updates in the centralized approach do not require the flooding of messages in to the network, rather updates are transmitted directly to the default gateway of each node. This greatly reduces the overhead required for performing updates, particularly if there are a high number of pipes being setup. It also negates any problems that may be experienced with multiple nodes attempting to perform pipe setup simultaneously.

The routing architecture builds upon existing technologies such as MPLS-based Traffic Engineering and PCE-based path computation. CARMEN has incorporated adaptations to address the more volatile nature of the wireless technologies supported and to handle with the uni-directionality of links. Specifically, Pipe setup, teardown and modification are performed using RSVP-TE to establish MPLS labels at each node. When the routing function of a mesh node receives a pipe request it must forward the request to its default gateway. Once the gateway has computed a route it will reply, providing the path through the network over which the pipe must be constructed. The node can then establish the pipe over the route defined by the gateway using the optional Explicit Route Object (ERO) of RSVP-TE. This allows the pipe to be constructed over any route across the network and allows multiple pipes with different routes between the same endpoints.

Routing Architecture

Due to a centralized routing solution being used in the CARMEN network, the routing module being used in each node type has some slight differences, with most of the complexity existing in the routing module of each CGW. As

can be seen from Figure 10 each CARMEN routing module contains a management element and a path setup element, however only a CGW contains a routing database and the Pipe Computation Element.

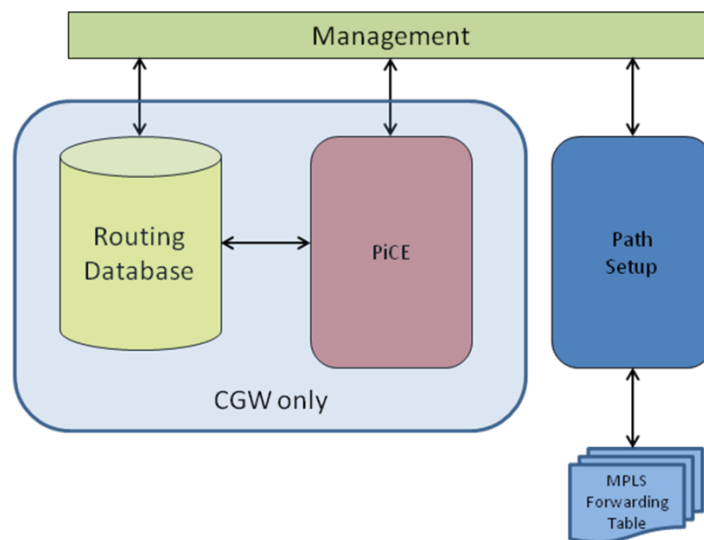


Figure 10 - Routing Architecture

The functionality of each of the routing components is summarized as follows:

- **Management** – The Management component is responsible for maintaining the system state and acting as the interface to receive and send primitives to the IMF. Essentially the Management block contains the event handlers for each received primitive.
- **Routing Database** – The routing database is present only in each CGW and must maintain an up to date logical link view of the network topology, including installed pipes and allocated and available resources. The data in the routing database is used by the PiCE to compute optimal flow distribution in the network and to serve pipe requests from the CHF. For this reason it is critical that the database always has accurate and up to date knowledge about link states within the network. This is achieved by having the routing management component subscribed to receive link events from all links within the routing area of the CGW and maintaining data of all installed pipes.
- **PiCE** – The Pipe Computation Element (PiCE) does not maintain any state information but rather utilizes the data in the routing database. When a request is received by the management component an up to date view of the network topology is passed to the PiCE, which computes a path through the network that can meet the requested traffic requirements. If a path can be successfully computed it is returned to the management component as a set of links through the network. It is then the responsibility of the management component to update the database and request that the pipe be installed.
- **Path Setup** – The Path Setup component is present in each CMP and CGW; it is responsible for the installation and teardown of CARMEN pipes between two nodes in the network as instructed by the Management component in the CGW. Each CARMEN pipe is

represented as an MPLS LSP; in order to setup a pipe the Path Setup component installs the MPLS forwarding state and resource allocations at each node through which the pipe traverses.

Capacity Handling

Although the Capacity handling Module (CHF) is a module in its own right and not a sub module of routing, there is a large amount of dependency and interaction between the CHF and routing. For this reason it is logical to include a description of the CHF in this section. It should be noted that the CHF module is present on every CARMEN Access Point.

In order to meet the strict QoS constraints required by carrier grade services explicit resource management techniques like admission control are needed to efficiently utilize network resources. It is the responsibility of the CHF to implement this functionality and act as the interface between the Mobility Management Function and the Routing Module. The CHF receives new flow requests from the mobility management module and must make pipe based admission control decisions for each new flow and to request new pipes from routing when required.

The CHF module has two primary functions; these are admission control and pipe initiation and maintenance:

Admission Control

CARMEN subscriber flows of the same traffic class and between common ingress and egress points are aggregated into the same pipe assuming that the pipe has available capacity. A flow request originates from the local Mobility Management Function (MMF) and then, on reception of this request the CHF checks if the flow can be admitted into an existing pipe, based upon the resources available. If so the CHF informs the MMF of the label to which the flow should be assigned; otherwise the CHF must request a new pipe from routing.

In order to be able to accurately assign new flows to existing pipes without invoking routing, admission control maintains a record of the available and allocated resources on all pipes which ingress or egress on the local CARMEN Access Point.

Pipe Initiation and Maintenance

Pipe Initiation and Maintenance is responsible for providing the pipe data rates satisfying predefined QoS requirements in cooperation with the Routing Function. On receipt of a new flow request from the MMF for which no available pipe exists, the CHF must request a new pipe from the routing function. This triggers the routing module to set up a new pipe or modify an existing pipe to meet the capacity and QoS requirements of the newly requested flow.

The Routing Function also signals the CHF when a certain pipe capacity or QoS has changed. This happens due to degraded or failed wireless links. Pipe Initiation and Maintenance then tries to redistribute the flows of this pipe

to other pipes of the same traffic class and with the same endpoint, otherwise it will request that the Routing Function set up of new pipe/pipes and/or terminates excess flows. Note that this recovery process is automated. While this may seem self-understanding for the wireless mesh networks community, this is actually a big step for network operators, who are used to static route placement and repair.

Forwarding Function

This function is integrated into all CARMEN nodes and is responsible for forwarding packets (deciding their next hop) based on information in its forwarding table. Entries in the forwarding tables are established, removed and modified on request from the Routing Module. Forwarding inside a CARMEN network is done on a per-pipe basis, thus all packets carried by a given pipe are forwarded in the same way, with packets assigned to pipes based on their class of service. Packets are forwarded differently depending on the class of pipe to which they are assigned thereby providing different classes of service to different user flows.

In order to avoid an overly complex solution the CARMEN specific forwarding functionality is implemented on top of existing implementations of the forwarding module in current Linux operating systems. This implies that the standard interfaces and protocols between layer 3 and layer 2 are left unmodified; including the IPv4/IPv6 addressing schemes, the standard address resolution protocols (ARP/NDP) and the control message protocols (ICMP/ICMPv6) and are therefore still part of the protocol stack in each CARMEN node.

As stated earlier, traffic in the CARMEN mesh is transported through pipes into which traffic with the same QoS constraints and endpoint is aggregated. Although in the current implementation of pipe traffic forwarding is done using MPLS, the architecture is general enough to support other tunneling schemes such as IP in IP encapsulation just.

The CARMEN Routing Function ensures the forwarding tables are built such that traffic aggregates will be forwarded to the next-hop based on the required QoS constraints. For this purpose the aggregates use MPLS labels which are also use as the pipe identifiers; these indicate to layer 2 the type of treatment a packet should receive in order to meet the QoS requirements. At intermediary mesh points, incoming MPLS packets are decapsulated from the MAC frames, passed through the look up process and delivered to the appropriate interface toward the next hop node. The outgoing interfaces encapsulate the packet into the specific data link technology. The MAC layer will map the pipe IDs (which in the current implementation correspond to the MPLS labels) to traffic classes and schedule the packets according to their priorities.

3.5 Mobility Management

Mobility Management has the tasks of maintaining radio link layer connectivity of a given QoS between UTs and their points of attachment (PoAs) to the network as well as re-establishing the UTs' network layer connectivity after a

change of PoA. A change of PoA may become necessary for various reasons such as:

- degradation of access link quality below a given threshold due to movement of the UT or channel fading
- a UT's demand for a change of radio technology, e.g. to obtain a higher data rate or to conserve energy by choosing a more efficient radio technology
- the need to load balance data traffic across PoAs for capacity reasons

In a carrier-grade mesh networking context, when backhaul is provided via multiple wireless hops, Mobility Management needs to further take into consideration the availability of capacity on the pipes between CAPs and CGWs as well as failures of backhaul links. To allow for an autonomous operation of the CARMEN Mesh in case of intermitted connectivity to the core network and to improve the scalability of Mobility Management, a hierarchical approach is considered, in which a micro-mobility solution handles mobility inside the CARMEN Mesh and a macro-mobility solution handles mobility across gateways to the core network. The latter should integrate well with existing macro-mobility solutions of the core network operator (e.g. PMIPv6).

As a result of the carrier-grade mesh requirements, as well as the fact that we consider heterogeneous mesh networks, the CARMEN Mobility Management solution

- supports micro-mobility operation despite possibly intermitted connectivity between CARMEN Mesh and the core network
- is network-centric, i.e. handover decisions are performed by the CARMEN mesh. To perform this task, information gathered by UTs is used
- considers both access link and mesh capacity in its management decision
- is based on a handover technology that supports heterogeneous technologies, i.e. IEEE 802.21
- supports seamless handovers for IEEE 802.21-based UTs
- incurs only low signaling overhead

Furthermore, our mobility management solution

- provides basic support for UTs without IEEE 802.21 functionality (e.g. using technology-specific solutions to enable interaction between UT and network during handover such as IEEE 802.16e specific mechanisms or IEEE 802.11k and IEEE 802.11v)
- decentralizes HO decisions.

The CARMEN micro-mobility solution requires several supporting functions

- an Access Status Input provisioning that reports the status of the access links from candidate PoAs

- a Handover Preparation function that collects the information required to prepare a handover, i.e. to create list of candidate APs and the correspondent resources
- a Handover Target Decision function that decides the target AP to which a UT should be attached and
- a Handover Execution function that performs all the procedures

The scenarios that we are considering in this chapter might be composed of up to thousands of nodes. Due to scalability and performance concerns, each CGW manages a certain amount of CAPs. CAPs are assigned to CGWs in such a way that the distance – in number of hops – between a CAP and its CGW is less than a certain threshold. This helps achieving a certain level of performance in terms of throughput and delay. The set of CAPs and associated CGW, together with the CMPs that interconnect them can be considered a different *Localized Mobility Domain (LMD)*. Support for a UT moving from a CAP belonging to one LMD to a CAP belonging to different LMD (that is, to a CAP managed by a different CGW), is provided by the hierarchical scheme adopted, in which a micro-mobility solution handles mobility inside the LMD and a macro-mobility solution handles mobility across gateways to the core network. Standard PMIPv6 is adopted as the macro-mobility solution, whereas an extended PMIPv6-alike solution is used as the micro-mobility domain.

Depicted in Figure 11 is an example of a CARMEN mesh network attached through several CGWs to an operator's core network. The CARMEN network uses several CAPs to provide access to UTs. The CMP's found inside the mesh network are transparent to the mobility management and thus the mesh path from CAP to CGW is seen as one single hop, from the mobility management point of view.

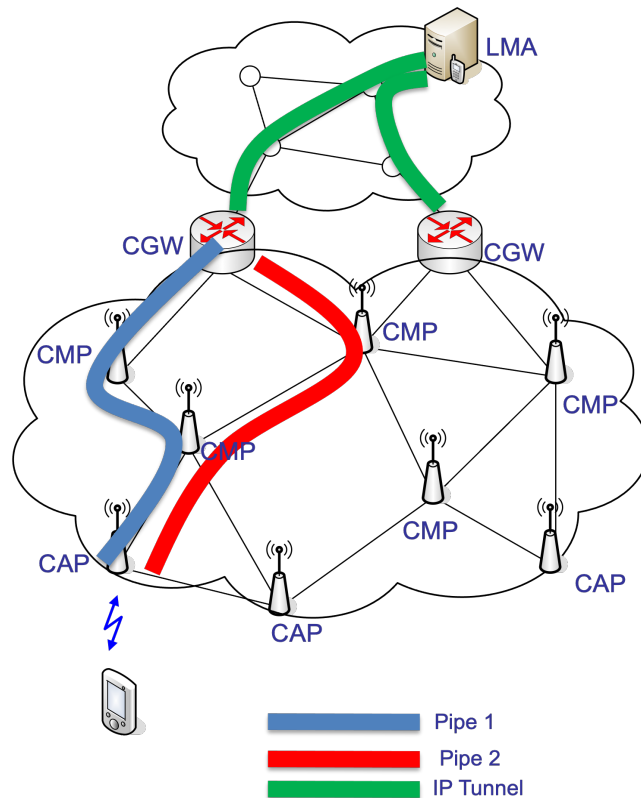


Figure 11 – Hierarchical approach solution based on PMIPv6

At the top level of the hierarchy we assume the operator runs standard PMIPv6 which deals with handovers between CGWs of the same CARMEN mesh network and it is also the point of anchoring of the UT's HNP (Home Network Prefix), keeping track of the corresponding CGW and establishing a bidirectional IPv6 over IPv6 tunnel between the Local Mobility Anchor (LMA) and the CGW, like in standard PMIPv6. This presents particular advantages from the point of view of an operator that already runs PMIPv6 in its core network, to which a CARMEN mesh network can be attached through several CGWs.

Below this level, there are the CGWs which have Mobile Access Gateway (MAG) functionality towards the core network and enhanced LMA functionalities towards the mesh network. The CGWs acts as the mid-level in the hierarchy and must anchor the location of the UT regarding to which CAP it is attached in the edges of the mesh and also the respective LMA located in the core.

Finally, at the bottom level of the hierarchy the CAPs run enhanced MAG capabilities.

Implementation Aspects

The implemented mobility-related modules consist of three main parts. The standard Proxy Mobile IPv6 (PMIPv6) protocol running in the core, the Mobility Management Function (MMF) running at the CGWs and CARMEN Access Points (CAPs) and an IEEE 802.21 stack running in the access part of the mesh (CAP and User Terminal, UT).

A detailed view of the MMF interactions with other modules, as well as with other mobility related modules is shown in Figure 12. It also depicts which parts of the software need to be running on different nodes.

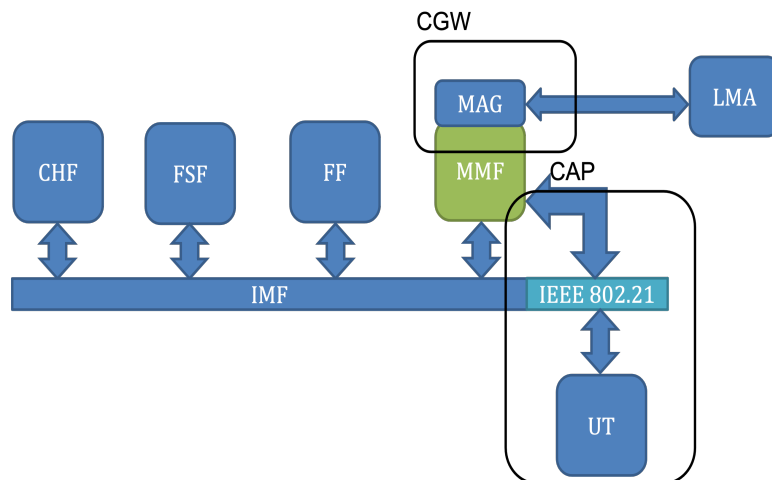


Figure 12: MMF Interactions

The IMF provides the interface to communicate remotely and locally with other mesh modules (cf. Section 3.2). From the IMF, the MMF must process and dispatch any arriving messages from other mesh modules and send any pending messages to be delivered by the IMF to other CARMEN modules. The MMF at the CAP can also receive events from the IEEE 802.21 submodule which assists in the handover procedure.

Apart from the protocol interface differences (PMIPv6 at the CGW and IEEE 802.21 at the CAP), the depicted generic architecture can be used on both the CGW and the CAP, with other small implementation differences. Namely, the internal implementation of the state machine must be different in order to handle the different messages to process.

Depicted in Figure 13 are the internal details of the functionality implemented for the MMF that runs at the CAP. Again, the IMF is used for the remote and local communication with other mesh modules. The IMF at the CAP is extended in order to support delivery of standard IEEE 802.21 primitives towards the access network (handover preparation and execution) and also other CAPs (resource query and reservation).

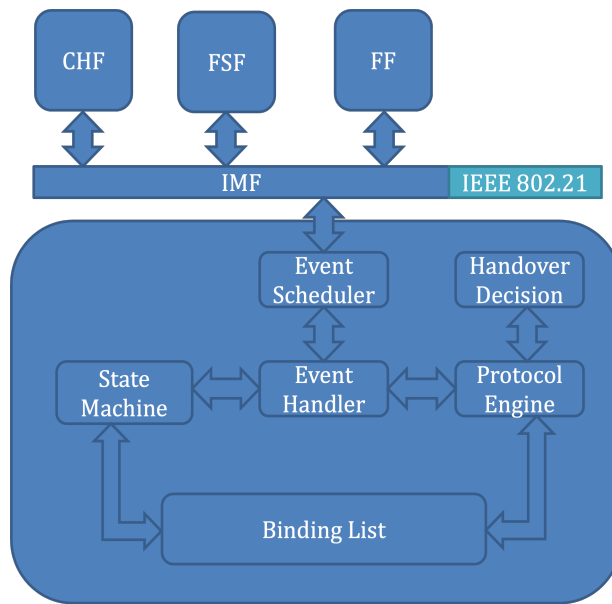


Figure 13: CAP Mobility internal functions

Also shown in Figure 13 is the Binding List, which consists of a conceptual structure that contains all the information relevant to tracking the User Terminal's (UT) movements as well as associated flows. Every time the UT changes point of attachment or initiates/terminates new flows this list is updated with the new information and the relevant states are also updated.

Depicted in Figure 14 are the internal details of the functionality implemented for the MMF that runs at the CGW. In addition to the IMF, another interface is used for the communication with the LMA residing in the core network and the MAG function that runs standard PMIPv6. More details on the mobility management solution are omitted here due to space limitations.

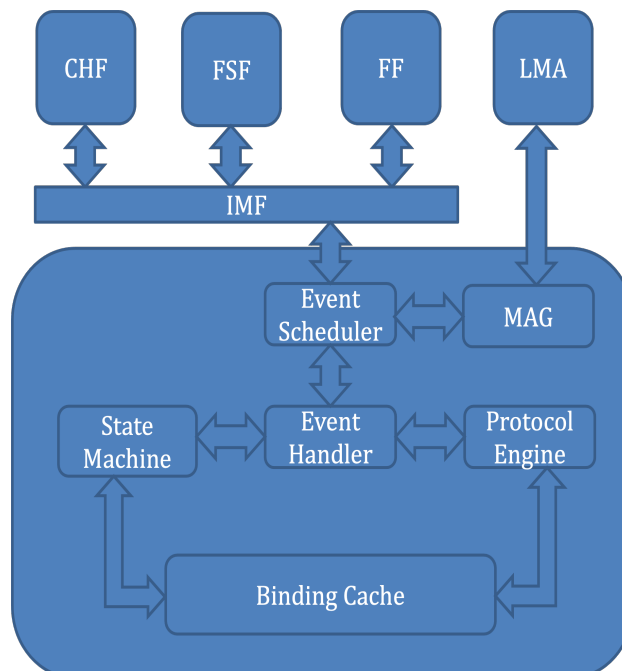


Figure 14: CGW Mobility internal functions

Similarly to the MMF running at the CAP, the MMF running at the CGW also stores a conceptual structure (Binding Cache) which contains all the information relevant to tracking the UT's movements, associated flows and respective tunnel endpoints towards the core network.

Summing up, the following concepts make our mobility solution specifically suitable for heterogeneous wireless mesh networks:

- the smooth and tight integration with IEEE 802.21 as the underlying handover mechanism
- the fact that not only the access, but also the mesh backhaul capacity toward the CGW is considered in the handover decision (this allows better load-balancing in resource-constrained wireless networks)
- the clear separation between macro- and micro-level mobility (while the latter is mesh-tailored, the former is well-established in operator networks)

4 FUTURE RESEARCH DIRECTIONS

While current wireless mobile backhaul networks are almost exclusively tree topologies (since no routing is required in that case), several factors make it likely that a migration towards mesh topologies will happen in the future. First, backhaul networks are already under heavy stress nowadays and investments to increase backhaul capacity are inevitable. Second, with the imminent rollout of next-generation access networks such as LTE, user traffic will again multiply, which will add to the load on backhuls dramatically. Third, the fundamental advantages of mesh over tree networks (such as load balancing and resilience gains) are more and more understood by network operators.

A next step to evolve our solution would be to study integration of our architecture and mechanisms for heterogeneous wireless mesh backhuls into the overall mobile backhaul context spanning access, wireless last mile, wired middle mile/metro network. The goal would be to understand the mechanisms that are required and potentially established in these different domains, find commonalities and identify possible problems and pitfalls when integrating them. Ideally, there would be a homogeneous end-to-end solution encompassing the whole backhaul.

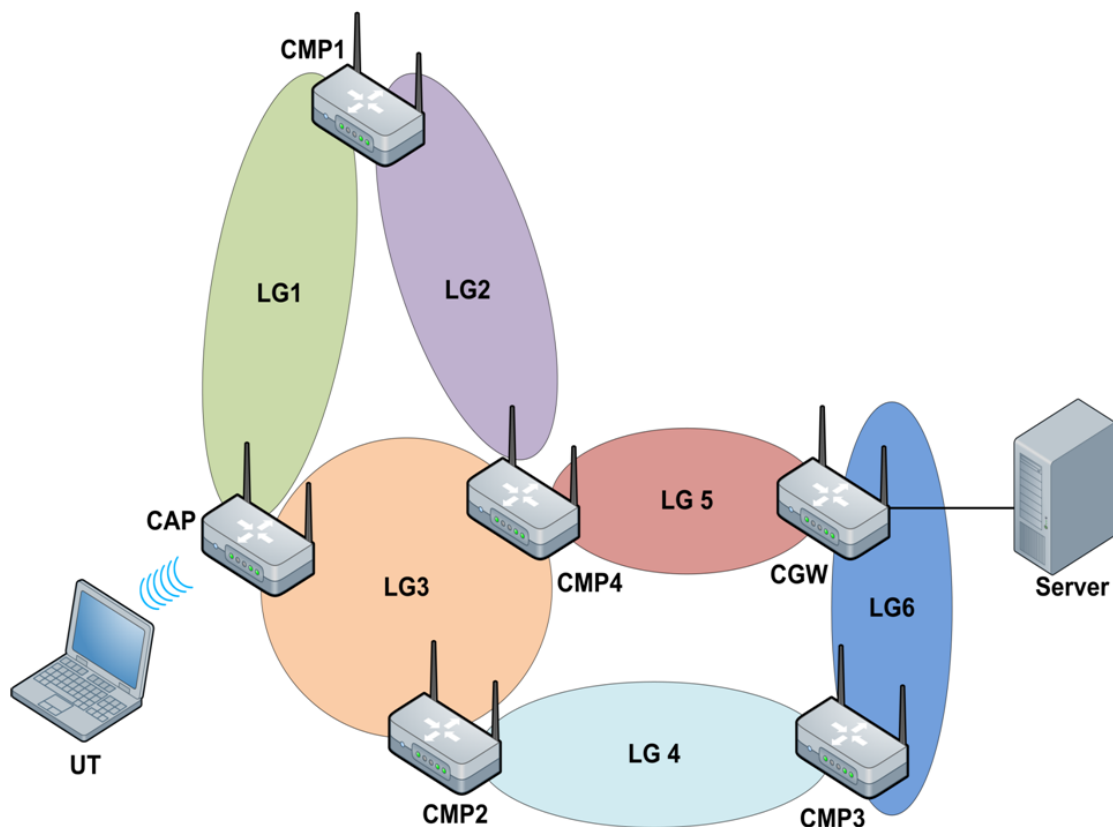


Figure 15: CARMEN Test Network

Our solution has been evaluated in a first test network which is depicted in Figure 15. It has 6 mesh nodes and 6 logical link groups (cf. Section 3.3). Logical link group LG3 comprises three links, namely the ones mutually connecting CAP, CMP2 and CMP4. The wireless technologies used in the network are standard WiFi, on the one hand, and a proprietary TDMA MAC,

on the other hand. Experiments have shown promising results so far. We could verify that our radio abstraction layer indeed works in a heterogeneous wireless mesh network. Routing, that operates on top of the abstracted logical topology made possible by the abstraction layer was able to place about four times as many flows in the network as standard shortest path routing. This result also demonstrates that resource management actually performs well even in the presence of link groups which include multiple links sharing the same spectrum (such as LG3).

Currently, we are deploying and testing our solution in a larger heterogeneous wireless mesh network to find out where individual parts or their integration could be optimized.

Mesh topologies in the wireless last mile backhaul come with increased complexity for an operator. First, meshes require routing instead of simple switching in trees. Second, cell site and frequency planning must be done carefully to maximize the usability of each wireless link, as installing such links in backhauls is very costly and meshes have more links than trees by design. Third, wireless links are more unstable compared to wired ones; this means that there must be failure recovery strategies, which should be self-organized to not unduly keep alarming the network management system in the operator premises.

In this chapter, we have presented solutions for these problems. Our routing solution is centralized, based on abstracted logical topological network views made possible by the radio abstraction layer, and has demonstrated superior performance in an actual test network. It can also recover from link failures by shifting affected flows to other links. Our self-configuration solution allows bootstrapping and reconfiguring of heterogeneous wireless networks. Our mobility management solution also supports heterogeneous networks since it is based on IEEE 802.21. Besides, it makes handover decisions based on both access and mesh load, thereby contributing to optimal load balancing.

By proposing a complete architecture, a radio abstraction layer, a self-configuration, routing and mobility management solution, we have gone far beyond the current state-of-the-art in the area of heterogeneous wireless (backhaul) networks. Our radio abstraction layer is a very generic approach which facilitates operation of heterogeneous wireless networks in many different use cases.

It must be said that the architecture and mechanisms which we presented are not restricted to pure mobile backhaul networks, they can also be used in more “community-style” or “best-effort” mesh networks, in order to increase their performance towards carrier-grade quality.

References

- [1] Congdon, P., Lane, B. 802.1AB - Station and Media Access Control Connectivity Discovery. Retrieved October 3rd from <http://www.ieee802.org/1/pages/802.1ab.html>
- [2] Wang, X., Lim, A.O. IEEE 802.11s mesh networks: Framework and challenges. In *Ad Hoc Networks*, Vol. 6, No. 6. (August 2008), pp. 970-984
- [3] Li, N., Hou, J.C. Localized Fault-Tolerant Topology Control in Wireless Ad Hoc Networks. In *IEEE Trans. Parallel Distributed Systems* 17(4): 307-320 (2006).
- [4] Hamida, E.B. et.al. Neighbor discovery in multi-hop wireless networks: evaluation and dimensioning with interference consideration. In *Discrete Mathematics and Theoretical Computer Science*, vol. 10(2), 2008, 87–114.
- [5] C. Ho, K. Obraczka, G. Tsudik, and K. Viswanath. Flooding for reliable multicast in multi-hop ad hoc networks. In *Proceedings of the International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communication*

(*DIALM*), pages 64–71, 1999.

- [6] K. Papagiannaki V. Mhatre and F. Baccelli. Interference mitigation through power control in high density 802.11 WLANs. In *Proceedings of IEEE INFOCOM 2007*, Anchorage, Alaska, USA, May 2007.
- [7] G. Li and J. Zhu. Performance analysis on utilizing directional antenna in high-density wlan. In *Proceedings of the Sixth International Conference on Networking (ICN'07)*, Sainte-Luce, Martinique, April 2007.
- [8] D. Beckmann and U. Killat. A new strategy for the application of genetic algorithms to the channel assignment problem. *IEEE Transactions on Vehicular Technology*, 48(4):1261–1269, July 1999.
- [9] G. Chakraborty and B. Chakraborty. A genetic algorithm approach to solve channel assignment problem in cellular radio networks. In *Proceedings of IEEE Workshop Soft Computing Methods in Industrial Applications*, pages, 34–39, Kuusamo, Finland, June 1999.
- [10] K. A. Smith. A genetic algorithm for the channel assignment problem. In *Proceedings of Global Telecommunications Conference*, volume 4, pages 2013–2018, 1998.
- [11] S. Banerjee S. S. M. Patra, K. Roy and D. P. Vidyarthi. Improved genetic algorithm for channel allocation with channel borrowing in mobile computing. *IEEE Transactions on Mobile Computing*, vol. 5(7):1536–1233, July 2006.
- [12] R. Mathar and J. Mattfeldt. Channel assignment in cellular radio networks. *IEEE Transactions on Vehicular Technology*, 42(4):647–656, November 1993.
- [13] D. Kunz M. Duque-Anton and B. Ruber. Channel assignment for cellular radio using simulated annealing. *IEEE Transactions on Vehicular Technology*, 42(1):14–21, February 1993.
- [14] P. Sparl and J. Zerovnik. 2-local 5/4-competitive algorithm for multi-colouring triangle-free hexagonal graphs. *Information Processing Letters*, 90(5):239–246, June 2004.
- [15] K. S. Sudeep and S. Vishwanathan. A technique for multi-colouring triangle-free hexagonal graphs. *Discrete Mathematics*, 300(1-3):256–259, July 2005.
- [16] N. Funabiki and Y. Takefuji. A neural network parallel algorithm for channel assignment problems in cellular radio networks. *IEEE Transactions on Vehicular Technology*, 41(4):430–437, November 1992.
- [17] D. Kunz. Channel assignment for cellular radio using neural networks. *IEEE Transactions on Vehicular Technology*, 40(1):188–193, February 1991.
- [18] K. A. Smith and M. Palaniswami. Static and dynamic channel assignment using neural networks. *IEEE Journals on Selected Areas Communications*, 15 (2):238–249, February 1997.
- [19] A. Mishra, S. Banerjee, and W. Arbaugh, “Weighted colouring based channel assignment for wlans,” *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 9, no. 3, pp. 19–31, July 2005.
- [20] J. Riihijarvi, M. Petrova, and P. Mahonen, “Automatic channel allocation for small wireless local area networks using graph colouring algorithm approach,” in *Proceedings of IEEE International Symposium on Personal, In-door and Mobile Radio Communications*, September 2004, pp. 536–539.
- [21] Janne Riihijärvi, Marina Petrova, Petri Mähönen. Frequency allocation for WLANs using graph colouring techniques. In *Proceedings of 2nd Annual Conference on Wireless On-demand Network Systems and Services*, January 2005, pp.19–21.
- [22] H. Luo and N. K. Shankaranarayanan. A distributed dynamic channel allocation technique for throughput improvement in a dense WLAN environment. In *Proceedings of IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 5, May 2004, pp. 345-348.

- [23] A. Mishra, V. Shrivastava, D. Agarwal, S. Banerjee, and S. Ganguly, "Distributed channel management in uncoordinated wireless environments," in Proceedings of The ACM Annual International Conference on Mobile Computing and Networking, Los Angeles, California, USA, September 2006.
- [24] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted colouring based channel assignment for WLANs," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 9, no. 3, pp. 19–31, July 2005.
- [25] M. Marina and S. R. Das, "A Topology Control Approach for Utilizing Multiple Channels in Multi-Radio Wireless Mesh Networks," *Proc. Broadnets*, Oct 2005, pp. 381–90.
- [26] H. Skalli, S. Ghosh, S. K. Das, L. Lenzini and M. Conti, "Channel assignment strategies for multiradio wireless mesh networks: issues and solutions," *IEEE Communications Magazine*, November 2007.
- [27] J. So and N. Vaidya, "Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals using a Single Transceiver," *Proc. ACM Mobihoc*, 2004, pp. 222–33.
- [28] P. Bahl, R. Chandra and J. Dunagan, "SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks," *Proc. ACM Mobicom*, 2004, pp. 216–30.
- [29] P. Kyasanur and N. Vaidya, "Routing and Interface Assignment in Multi-Channel Multi-Interface Wireless Networks," *Proc. IEEE Conf. Wireless Commun. And Net. Conf.*, 2005, pp. 2051–56.
- [30] P. Kyasanur and N. Vaidya, "Routing and Link-layer Protocols for Multi-Channel Multi-Interface Ad Hoc Wireless Networks," *SIGMOBILE Mobile Computing and Communications Review*, Vol. 10(1), (January 2006), pp. 31-43.
- [31] IEEE Computer Society. IEEE Standard for Local and metropolitan area networks - Part 21: Media Independent Handover Services. Retrieved October 3rd from <http://standards.ieee.org/getieee802/802.21.html>
- [32] IETF. Proxy Mobile IPv6. RFC5213, Retrieved on October 3rd from <http://www.ietf.org/rfc/rfc5213.txt?number=5213>
- [33] IETF. Multi Protocol Label Switching (MPLS). RFC3031 (Proposed Standard), January 2001
- [34] D. B. Johnson, C. E. Perkins, and J. Arkko. Mobility Support in IPv6. Internet Engineering Task Force, RFC 3775 (Proposed Standard), June 2004.
- [35] H. Soliman, C. Castelluccia, K. El Malki, and L. Bellier. Hierarchical Mobile IPv6 Mobility Management (HMIPv6). Internet Engineering Task Force, RFC 4140 (Experimental), August 2005.
- [36] Valko, A. G., Cellular IP: A New Approach to Internet Host Mobility, *Mobile Computing and Communications Review*, vol. 29, no. 1, January 1999, pp. 50-65.
- [37] Campbell, A., Gomez, J., Wan, C.-Y., Kim, S., Turanyi, Z., and Valko, A., Cellular IP, Internet-Draft (work in progress), draft-ietf-mobileip-cellularip-00, (work in progress), January 2000
- [38] Jens Nachtigall, Anatolij Zubow, and Jens-Peter Redlich. The Impact of Adjacent Channel Interference in Multi- Radio Systems using IEEE 802.11. In *2008 International Wireless Communications and Mobile Computing Conference*, pages 874–881. IEEE, August 2008. ISBN 978-1-4244-2201-2. doi: 10.1109/IWCMC.2008.151.
- [39] Vangelis Angelakis, Stefanos Papadakis, Vasilios Siris, and Apostolos Traganitis. Adjacent channel interference in 802.11a: Modeling and testbed validation. In *2008 IEEE Radio and Wireless Symposium*, pages 591–594. IEEE, 2008. ISBN 978-1-4244-1462-8. doi: 10.1109/RWS.2008.4463561.
- [40] Chen-Mou Cheng, Pai-Hsiang Hsiao, H. T. Kung, and Dario Vlah. Adjacent Channel Interference in Dual-radio 802.11a Nodes and Its Impact on Multi-hop

Networking. In *IEEE Globecom 2006*, pages 1–6. IEEE, 2006. ISBN 1-4244-0357-X. doi: 10.1109/GLOCOM.2006.500.

- [41] Sebastian Robitzsch, Christian Niephaus, John Fitzpatrick, and Mathias Kretschmer. Measurements and Evaluations for an IEEE 802.11a Based Carrier-Grade Multi-radio Wireless Mesh Network Deployment. In *2009 Fifth International Conference on Wireless and Mobile Communications*, pages 272–278. IEEE, 2009. ISBN 978-1-4244-4679-7. doi: 10.1109/ICWMC.2009.52.
- [42] Sebastian Robitzsch, John Fitzpatrick, Seán Murphy and Liam Murphy. Behind-the-Scenes of IEEE 802.11a based Multi-RadioMesh Networks: A Measurement driven Evaluation of Inter-Channel Interference. In *International Journal on Advances in Internet Technology*. ISSN 1942-2652. Vol. 3. No. 1 & 2. 2010

¹ The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 214994 (CARMEN).