Towards Carrier Grade Wireless Mesh Networks for Broadband Access[1]

Nico Bayer, Andreas Roos
T-Systems Enterprise Services GmbH
Technologiezentrum
Deutsche-Telekom-Allee 7
64295 Darmstadt, Germany
{Nico.Bayer,Andreas.Roos}@t-systems.com

Roger P. Karrer
Deutsche Telekom Laboratories
Ernst-Reuter-Platz 7
10587 Berlin, Germany
Roger.Karrer@telekom.de

Bangnan Xu, Christian Esteve
T-Systems Enterprise Services GmbH
Technologiezentrum
Deutsche-Telekom-Allee 7
64295 Darmstadt, Germany
{Bangnan.Xu,Christian.Esteve}@t-systems.com

***Abstract*— Broadband wireless access networks have the potential to fulfil the vision of high-speed ubiquitous Internet access. Due to the unreliability and heterogeneity of the network, operators are particularly challenged to provide "Carrier Grade" services that ensure a secure, efficient and reliable access to users. This paper provides an overview of these challenges and presents a network architecture and overarching services that form a unified and reliable carrier grade wireless access network. Particular focus of the paper is on wireless mesh multihop networks as they are a viable solution to realise broadband wireless access flexibly and cost efficiently. Moreover, we describe a next-generation wireless access network testbed where the architecture and services will be deployed and provide initial simulation and measurement results.**

I. Introduction

Over the last century, the Internet has drastically changed our society. Wireless communication has now the potential to penetrate the communication capabilities into our everyday lives. Besides the well-known Internet applications, new services that are traditionally not associated with IP networks have been extended to be supplied via wireless networks, such as telephony via Voice over IP (VoIP) and television via IPTV. A deployment of these services provides the advantage of ubiquitous access and services for customers, which in turn provides new revenue opportunities for operators.

Unfortunately, a successful deployment is far from easy. First, a network is more than the sum of its parts. Thus, even though technology components may be ready for deployment, operators are challenged by the deployment of services that manage the network resources and the user access. In particular, operators are challenged to provide these services at "Carrier Grade", i.e. providing reliable, efficient and secure services. Second, the different services have different requirements on the underlying network infrastructure. Voice and video services are sensitive to delay, jitter and bandwidth fluctuations. Third, the rollout of new hardware and protocols provides new opportunities to support application constraints, but also requires a high degree of integration flexibility and management from an operator. Finally, the world is still divided into IP-based Internet services and cellular systems. A seamless availability of data, voice and TV (Triple Play) requires a convergence of the two worlds.

The contributions of this paper are four-fold. First, we present a network architecture for a carrier grade fixed mobile converged network. The architecture aims at integrating multiple wireless technologies, including cellular systems, WiFi (Wireless Fidelity) and WiMAX (Worldwide Interoperability for Microwave Access). We assess the fundamental structure to develop future networks over an all-embracing, IP-based network layer. Below the network layer, functionality is derived to integrate different wireless technology into the network and to abstract the details of the underlying technology. These abstractions allow the deployment of a common network management functionality on top of the IP layer.

Second, we describe the challenges of service deployment on top of the converged infrastructure. In particular, we focus on services that address the mobility, Authentication, Authorisation and Accounting (AAA), Quality of Service (QoS) and security demands in a wireless mesh network. Wireless mesh networks have the potential for rapid and cost-effective deployment, but are a challenging environment if the deployed services shall adhere to the carrier grade quality all the time. We present MAC and network layer changes to assist the deployment and maintenance of wireless mesh networks.

Third, we present a novel wireless mesh network simulation environment, which enhances the widely used NS-2 network simulator [2] with novel 802.16 mesh functionality. The modules provide the ability to test future mesh protocols in a simulated environment to assess their stability and performance and to compare their performance with related protocols.

Fourth, we describe Magnets [3], a wireless access network testbed that is currently deployed within the city of Berlin. The testbed is a semi-productive environment where novel architectures and concepts can be deployed. Magnets consists of three sub-networks: a high-speed WiFi backbone, a WiFi mesh network and a WiMAX mesh. We describe the planned deployment of the three networks in the city of Berlin. Moreover, we present initial results from the backbone. These results highlight feasibility and shortcomings of wireless technology to support carrier grade networks.

The remainder of the paper is organised as follows: Sec-

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tion II provides an overview of challenges for carrier grade wireless access networks. Section III describes the current status of wireless mesh networks as well as a concept to integrate them into a converged architecture. Section IV discusses concepts and solutions for overarching QoS, AAA and security. Section V describes the 802.16 enhancements for NS-2. Section VI presents the Magnets testbed and provides initial performance results from the WiFi backbone. Conclusions from the paper are drawn in Section VII.

II. Broadband Wireless Access in Next Generation Networks

Current deployments of wireless networks (WLAN and WiMAX) show that wireless technology can be easily and flexibly deployed at a fraction of the cost of fibre networks [4]. Unfortunately, the achieved rollout of wireless technology in e.g. HotSpots is not sufficient for operators that aim at deploying wireless access networks and creating revenues.

In this section, we first introduce the challenges in building wireless access networks that satisfy carrier grade network requirements. Then, we provide an overview of ongoing efforts to address these challenges, in particular Fixed and Mobile Convergence (FMC) efforts and the IP Multimedia Subsystem (IMS). Finally, we point out the short-comings of these efforts to meet the expectations.

A. Objectives of carrier grade wireless access networks

The fundamental challenge for operators is the ability to provide carrier grade services to their users, i.e. a reliable and secure infrastructure that supports precise billing as well. The following list highlights some of the operator-specific challenges that must be addressed to achieve carrier grade services:

- Reliable and vendor independent access infrastructure to guarantee low infrastructure costs and to avoid service disruptions in order to enhance user acceptance
- Service provisioning for fixed as well as mobile users
- QoS provisioning in order to support Triple Play services
- Secure communication links in order to protect the network and the user data against misuse
- AAA mechanisms adapted to the specific characteristics of wireless access networks
- Integration into and interaction with future ISP core networks to realise overarching management functionality

Operators are currently working on several architectures to achieve the above objectives. Here, we provide a detailed overview of two main projects operators are working on: Fixed and Mobile Convergence (FMC) and the IP Multimedia Subsystem (IMS).

B. Fixed and Mobile Convergence (FMC)

Traditionally fixed access networks (e.g. DSL, HotSpots) and mobile access networks (e.g. Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS)) have been developed independently and with different objectives. Mobile access was deployed for telephony while fixed access focused on data exchange, such as file transfers, but more recently also multimedia and video. As a result, two separate network types exist today, as depicted in Figure 1.

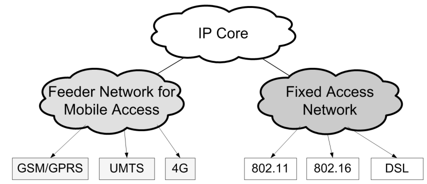

Fig. 1. Traditional access technologies

However, the distinction between data and voice networks is increasingly blurring. Technological advances in the network and in end systems provide the feasibility to interchangeably use the different services over either network. In fact, many devices today have multiple wireless interfaces. These multi-interface devices are attractive to users, as they limit the number of devices to be used and they increase the coverage by dynamically selecting the available access technology. However, users will only accept services that provide the same level of QoS, security and AAA independently of the access network. Therefore, operators are challenged to provide seamless services independent of the underlying infrastructure.

Moreover, the vision of merging the two dominant networks fixed and wireless into a single network is tantalising also for large-scale operators, as they are not only expecting the lower management costs of a unified architecture, but also an easier deployment and use of their traditional and future services. In particular, ubiquitous and location-aware services have the potential to open new sources for revenues.

To resolve the strict separation of fixed and mobile networks, network operators are working on Fixed and Mobile Convergence. FMC enables the combination of wired and wireless/mobile networks to provide services to customers without dependency on their location, access technology and device. The main objectives of FMC are service and network convergence. Service convergence enables the use of the same services independent of the access network. For example, the same service can seamlessly be used in fixed and mobile networks. Network convergence aims at connecting fixed and mobile networks via the same infrastructure to the operator's core network. Network services like mobility, QoS and AAA are managed by an overarching control system. The IP Multimedia Subsystem (IMS) architecture provides the basic platform to introduce service and network convergence.

C. IP Multimedia Subsystem (IMS)

The IP Multimedia Subsystem was initially developed as a call control framework for packet-based services over 3G mobile networks as part of 3GPP, i.e. an overlay over GPRS to provide IP services. It was then extended to include WiFi roaming and additional services such as presence and instant messaging in Release 6 (2004/5). The IMS introduces a common session control plane, suitable for any access technology capable of transporting SIP messages, providing an access-independent service delivery platform. The core of IMS is based on SIP entities called Call Session Control Functions (CSCF) and a central user database, the Home Subscriber Server (HSS). IMS extends SIP to be the signalling protocol for controlling real time and non-real time multimedia sessions offering carrier grade services. SIP as used in IMS provides a flexible distribution of functions and high scalability allowing the network i) to control the QoS of the bearer, ii) to invoke rich services on behalf of the user and iii) to support multiple business models (e.g. extended charging models, etc.).

The IMS is being standardised by the TISPAN (Telecoms & Internet converged Services & Protocols for Advanced Networks) in ETSI as a converged multimedia network and thereby as the core architecture of their next generation network. The standardisation process defines multiple subsystems that enable fixed access networks to interface the IMS. TISPAN closely interacts with 3GPP to leverage the IMS specification over wireless networks. In detail, TISPAN introduced the Network Attachment Subsystem (NASS) [5] responsible for authentication, authorisation and access management, and the Resource and Admission Control Subsystem (RACS) [6] which is responsible for QoS resource reservation, admission control and policy enforcement. The layered architecture of IMS allows the definition of service enablers (e.g. presence, group and list management) and common control functions (e.g. provisioning, security, charging and operation & management) that can be reused for multiple applications.

Therefore, IMS is a key enabler for Fixed and Mobile Convergence and a real technical architecture for network operators to compete against the growing Internet players. The main challenges of adopting IMS as the system for NGN are:

- Interconnection of legacy and non-SIP based services
- Roaming and interoperability with other IMS providers
- Interworking of the Internet
- Solving access technology specific functions

In this paper, we concentrate on the last issue. We discuss QoS and AAA challenges for non-3GPP access networks and propose some enhancements (overarching functions) to leverage IMS based converged networks.

D. Challenges

FMC and IMS address a number of challenges towards realising the previously mentioned objectives. First, wireless technology per se lacks reliability. In contrast to its wired counterpart, a wireless channel exhibits fluctuations and can even be entirely obstructed. Wireless networks must therefore be planned with enhanced resilience.

Second, the capacity of wireless ad hoc networks scales badly [7]. While this scalability is fundamental and unfortunate for ad hoc networks, it can not be tolerated in wireless access networks. The network must scale to a large number of users and to the increasing bandwidth demands of new applications. For an operator, scalability imposes a trade off between costs and carrier grade services. Current wireless technology, such as IEEE 802.11, provides a certain capacity within its transmission range. To avoid shortcomings, the wireless network would have to be overprovisioned. Overprovisioning requires more access points or more base stations. Each of these stations must be connected to fibre, which is responsible for a large percentage of the installation costs.

Third, a converged architecture needs to integrate heterogeneous access technologies. To provide carrier grade services in such a system, overarching management is essential. The management of a heterogeneous access network is by far more than managing the sum of the individual networks. Overarching management is required and influences several functions:

- Ubiquitous mobility supports mobility across converged heterogeneous access networks. An overarching mobility management must ensure seamless handovers among the different technologies. Besides the traditional terminal mobility new types of mobility like personal- and session mobility can be realised.
- Access management is responsible for the selection of the appropriate access. The term "appropriate" is a complex function of resource availability, application (QoS) constraints, AAA components and user preferences.
- QoS management is responsible for policy decision, policy enforcement, resource control and resource reservation of the access networks. QoS provisioning should interact with AAA functions to offer various service qualities at different costs. Furthermore, the QoS management needs to interact with the access network to get information about the capabilities and the available resources of the access network to decide whether the QoS constraints can be met.
- AAA and security control is needed to handle new service concepts that are independent of the access technology, such as a single signed on system.

III. Wireless Mesh Networks

Wireless mesh networks (WMNs) are regarded as a viable solution to provide broadband Internet access flexibly and cost efficiently. They have the potential to combine the coverage of mobile networks (UMTS) with the capacity of WiFi-based access points. Their ability to forward data over multiple hops at a high data rate eliminates the requirements to connect each access point to the wired infrastructure and therefore reduces costs. At the same time, capacity can be increased, either by deploying new wireless technology (WiMAX) or by equipping access points with multiple interfaces (WiFi). This section gives an overview about the current status of mesh networks and highlights the most important drawbacks for the application as a carrier grade mesh network. Finally a concept to integrate mesh networks into a converged network architecture is proposed.

A. Challenges of wireless mesh networks

The promises of wireless mesh networks have triggered advances at various levels. First, vendors are pushing their

WMN solutions with proprietary mesh protocols, such as SkyPilot [8], BelAir [9] and SaxNet [10]. Second, community mesh networks grow and provide connectivity and capacity. The MIT Roofnet [9] or the Freifunk in Berlin [11] are examples that have grown to a size of up to 200 access points and are continuing to increase. Third, research testbeds such as Magnets [3] and RescueMesh [12] are developed to experimentally evaluate mesh networks and understand their limitations and capabilities. Third, standardisation activities focus on multihop mesh networks, including the 802.11s for WLANs and IEEE 802.15 for wireless personal area networks (WPANs) and sensor networks. Similar efforts are on the way for future technology, such as IEEE 802.16, where the standard includes a mesh (multipoint-to-multipoint) mode next to the traditional point-to-multipoint (PMP) mode. In parallel a new group (IEEE 802.16j) has been established that focuses on the multihop relay specification.

Unfortunately, in spite of all the above efforts, the consideration of a carrier grade mesh network is still in its infancy. A first problem is the lack of a standard: proprietary solutions are already on the market while standardisation is still being debated. For an operator, it is vital to rely on standardised hardware and protocols, as solutions based on proprietary routing, QoS, AAA and security concepts are incompatible. Moreover, a standardised product simplifies the management and resource provisioning for an operator and it reduces capital expenditure (CAPEX) and operational expenditure (OPEX). A second, fundamental problem of mesh networks is that they have only been observed in isolation. However, to make mesh networks attractive for network operators and to provide end-to-end services with guaranteed QoS, security and reliability, an integration into the management system of the core network is essential. For a converged architecture as described in the previous section, this means that mesh networks need to be integrated into the overarching management system of IMS.

Though the integration into an overarching management system is essential, it is not sufficient to provide end-to-end services with guaranteed QoS, security and reliability. Therefore appropriate mechanisms within the mesh network are needed. The most fundamental drawbacks of mesh networks are that security and QoS provisioning are currently unsolved. The wireless links that form the mesh network ease miscellaneous attacks of unfriendly users. Thus mechanisms are needed to protect user data against misuse. Furthermore, QoS provisioning in WMNs is challenging. Problematics in this environment are for instance the often changing channel characteristics, along with the difficulty of sharing the wireless medium with many neighbours, each with its own potentially changing QoS requirements.

The subsequent section describes a concept to integrate mesh networks into a converged network architecture. The concepts to provide QoS, AAA and security mechanisms in mesh networks are handled in Section IV. Thereby the focus is on overarching mechanisms in conjunction with IMS as well as mesh specific functions.

B. Integration of Mesh Networks into a converged operator network

Here, we describe our effort to integrate wireless mesh networks into a converged network architecture. This integration is developed as part of the ScaleNet project [13] [1] by Deutsche Telekom AG, Germany. Due to their benefits ScaleNet views WMNs as one of the most important parts of its architecture.

Figure 3 depicts the concept of integrating WMNs into the ScaleNet FMC architecture. The integration must be made at three main layers: access, control and application layer. The converged access layer ensures that the access network that connects the user to the backbone is not restricted to any particular technology. Thus, WMNs seamlessly integrate into the architecture as other technologies, such as WiMAX, WLAN, DSL or even optics. Therefore, the access layer consists of two main parts: the Converged Access Aggregation Network (CAAN) and the Universal Access Nodes (UANs). The CAAN serves as connector between system specific last mile technologies and the IMS core and overlay networks and integrates all available access technologies within a single, fully converged access network domain. Wired as well as wireless access nodes are connected via a jointly managed transport network. The universal access node combines wireless and wired technologies within one single node and is treated as a single IP hop. It is responsible for the IP transport adaptation between access network and CAAN, QoS adaptation, traffic separation, mobility management, etc. Therefore access specific functions are integrated into the UAN to enable interworking with IMS. Depending on the topology, a mesh network is connected to the CAAN via one or multiple mesh base stations (M-BS). The M-BSs themselves are integrated into the universal access nodes UANs. Furthermore the Access Border Controller (ABC) which is also located within the CAAN contains management functions to handle mobility, security, QoS and AAA within the effective range of the CAAN. This converged access layer architecture is inspired by ETSI NGN.

The IMS platform is the heart of the control layer. The IMS is responsible for overarching functionality, such as session establishment and control, roaming, security, QoS and AAA. The control layer also contains overarching functions that span beyond the IMS platform, such as heterogeneous access management and mobility.

The application layer provides access to services independent of the access network. Thus services only need to be developed once and are introduced at a central point, e.g within the home network of the user. Furthermore different end user devices are supported thanks to the media adaptation technique.

Details about the integration of mesh networks into the overarching QoS, AAA and security architecture are described in the subsequent section.

IV. QoS AND AAA CONCEPTS FOR CARRIER GRADE MESH NETWORKS

This section presents QoS and AAA concepts for carrier grade mesh networks. Thereby the focus will be on the integration into the overarching management entity as well as on mesh specific functions.

A. *QoS and Service provisioning*

The ability to satisfy QoS constraints is vital to support Triple Play services. In particular, the network must support:

- real-time and multimedia services (e.g. VoIP, IPTV). QoS parameters such as maximum delay and minimum bandwidth must be guaranteed independent of the underlying network technology and topology.
- different traffic classes. Service level agreement (SLA) must be provided in analogy to fixed networks

A QoS provisioning concept for carrier grade mesh networks can be divided into two parts. First, an overarching QoS management must provide end-to-end QoS guarantees. This management combines the network-wide parameters and dynamically and opportunistically manages the resources. It addresses the following issues (as part of the RACS):

- Admission control based on policies and current traffic load.
- Policy enforcement and control.
- Resource control and reservation methods.

Second, QoS must be provided in the access network, in particular in meshes, to support Triple Play services. Due to the heterogeneous nature of wireless access networks, the key challenge is to provide the QoS guarantees as a function of the different technologies.

B. *Resource and Admission Control Subsystem (RACS)*

RACS hides the details about the access network from the application function (AF), e.g. IMS P-CSCF, as depicted in Figure 2 [6]. The RACS assumes that the policy enforcement RCEF (Resource Control Enforcement Function) ensures that the associated user traffic remains in accordance with the policy decision. The A-RACF (Access Resource and Admission Control Function) supports the resource reservation methods, admission control and final policy decisions. User traffic is only admitted if three constraints are met: (i) the user profile is stored in the NASS, (ii) operator-specific policies and resource availabilities are met, and (iii) border gateway functions (e.g. NAT) are cleared.

C. *Mesh integration with the RACS*

The current version of RACS has one drawback for the application in wireless access networks: the SPDF in conjunction with the A-RACF base the admission decision upon a static configuration. While the static configuration is feasible in wired networks, the lack of status information requires a modification of the RACS for wireless access networks to take traffic and QoS availability into account.

Therefore, we enhanced the RACS as depicted in Figure 2 to ensure carrier grade services also in mesh networks. We

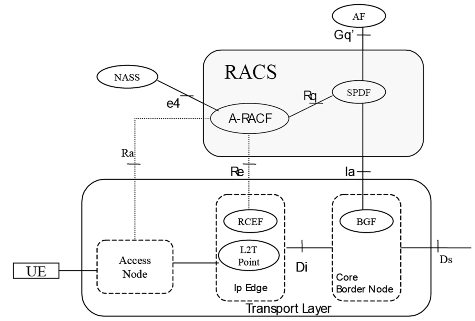

Fig. 2. RACS subsystem architecture

envision a Mesh-Ctrl function on the Access Node, e.g. the mesh base station. The Mesh-Ctrl function maintains relevant traffic and QoS information (e.g. free resources, delay) about the mesh network. The A-RACF requests traffic and QoS information via the Ra interface to decide whether a new stream can be accepted. As such, the Mesh-Ctrl function is strongly connected with the mesh MAC and routing layer functions. The integration of mesh networks into the RACS concept is shown in Figure 3.

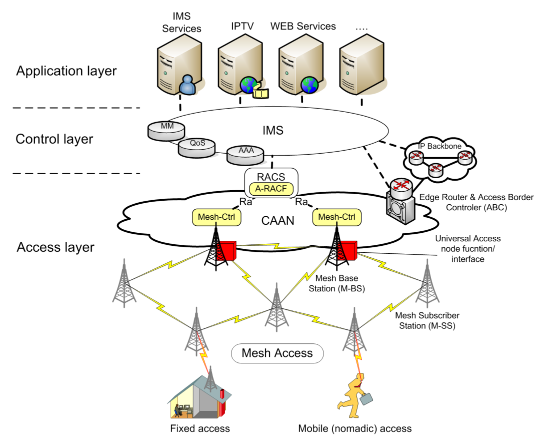

Fig. 3. QoS and service provisioning concept for carrier grade mesh networks

A possible user scenario for an overarching QoS management could be as follows. Assume that a user picks up the phone and dials a number. This action results in a call signalled via SIP to the Proxy Call State Control Function (P-CSCF). The P-CSCF contains the application function (AF). Before it forwards the SIP messages, it asks the RACS via the SPDF if the call can be admitted or not. The SPDF thereby translates the service level policy request from the application layer into IP QoS parameters. A G.711 call, e.g., is translated into real-time priority traffic with a bandwidth demand of 80 Kbps. The A-RACF then checks via the NASS if user and service policies allow the call, and the A-RACF collects information via the Mesh-Ctrl function if the network can support the QoS for the call. If so, the A-RACF reserves the required QoS parameters in the network. Once the reservation is completed, the policies are configured in the transport layer and the SIP session can be started.

D. MAC and routing layer requirements

The MAC and routing layer in the mesh network are responsible for providing end-to-end QoS within the mesh network. The MAC layer is responsible to provide differentiated QoS in the physical and link layers within one wireless router's neighbourhood in the wireless broadcasting environment, while QoS aware routing is responsible to find routes able to satisfy QoS constraints. Moreover, MAC and routing layer provide the information to the RACS about the ability to support QoS parameters in the mesh.

A resource reservation mechanism in the mesh network is essential to support Triple Play services. Typically, this process contains two parts: admission control and resource reservation. To satisfy QoS constraints, routing must be QoS aware. Unfortunately, QoS aware routing in wireless mesh networks is far from easy, as multiple paths exists through the network and the link characteristics changes faster than typical end-to-end delays. To include link information, novel cross-layer solutions must be derived with the ability to support multiple routing metrics. After finding a suitable route, the MAC layer must reserve resources on the route between source and destination. Depending on the traffic type, reservations can be temporary (e.g. for best effort traffic) or continuous (e.g. for realtime traffic).

Currently there are two trends of MAC protocols for wireless mesh networks. First, random access protocols, such as carrier sense multiple access with collision avoidance (CSMA/CA), are used in the IEEE 802.11 standard. However, CSMA/CA does not meet the requirements of carrier grade mesh networks [14]. TCP connections, e.g., suffer from instability and unfairness, mostly due to the the exponential backoff scheme, hidden terminals and exposed terminals [15], [16]. Unfortunately, attempts to support QoS using IEEE 802.11e failed [17], [18]. Therefore, controlled access protocols such as time division multiple access (TDMA) are currently under consideration for future mesh networks. IEEE 802.16 networks contain resource control and reservation mechanisms for QoS support. Unfortunately the 802.16 standard only provides a framework for the mesh mode, and at the current stage (too) many specifications are still undefined and need further investigations to ensure carrier grade quality.

E. AAA & security for carrier grade mesh networks

Today's fixed and mobile networks include their own AAA functionality. A precondition for FMC is the integration of current AAA systems to achieve an overarching AAA system. Currently independent and incompatible mechanisms, such as Point-to-Point Protocol over Ethernet (PPPoE) for DSL and EAP-SIM for GSM networks, are used to provide user authentication and authorisation. Overarching AAA aims to provide user access and service provisioning independent of the access network and the device by using one authentication mechanism, e.g. IEEE 802.1X - port based network access protocol. TISPAN defined the Network Attachment Subsystem (NASS) that provides access control and management entities for access networks. In this context, interface to the IMS architecture is provided as well. NASS and RACS are able to provide interconnection of QoS and AAA and thus to ensure policy based service provisioning. Moreover, flexible extended charging models and a fair payment depending on received services can be realised by such a joint approach. Carrier grade mesh networks need the integration of extended functionality to reach this goal.

1) Network Attachment Subsystem (NASS): The NASS describes several functions that are necessary for device configuration, network access control and service provisioning by interacting with the RACS and the IMS. An overview of the NASS architecture is shown in Figure 4. If a user equipment (UE) enters the access network the Access Management Function (AMF) requests for IP address allocation and user access information. UEs obtain their IP addresss from the Network Access Configuration Function (NACF). Additional configuration information is provided by the Customer Network Gateway Configuration Function (CNGCF) to the UE. The UE authentication and authorisation is done by the User Access Authorisation Function (UAAF) by requesting the Profile Database Function (PDBF) that contains all relevant user data. Association between allocated IP address to the UE and network location information are provided by the Connectivity Session Location and Repository Function (CLF). With regard to service and QoS provisioning the CLF contains interfaces to the service control subsystem and applications and the RACS.

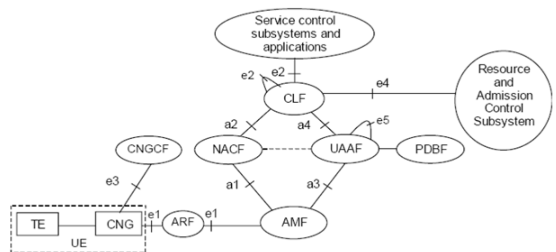

Fig. 4. Network Attachment Subsystem architecture

This approach contains several databases for user data, like the PDBF for network attachment and the home subscriber server (HSS) within the IMS core for service access. In order to provide real FMC, an efficient integration of the multiple user databases is required and very challenging. A central HSS allows the registration of multiple terminals and services belonging to the same user. This behaviour is also a precondition to provide Single Sign On (SSO).

2) Mesh integration with the NASS: Fundamentally, we can distinguish between centralised and distributed access control approaches. In Figure 5, a distributed access control function (ACF) for mesh networks is envisioned. The ACF is located in every mesh subscriber station (M-SS) to provide access control at each point of attachment.

In case a customer wants to get IP connectivity, its UE connects to the next M-SS. This initialises the access control

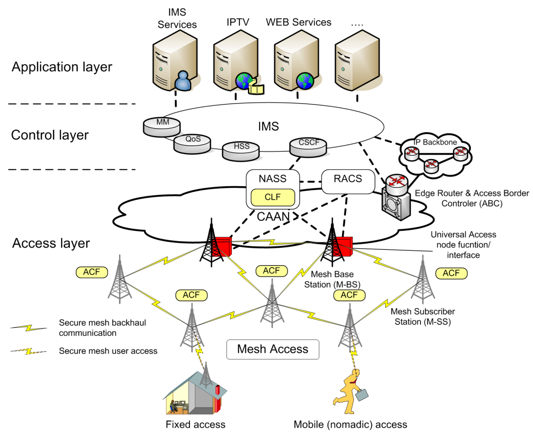

Fig. 5. ScaleNet AAA architecture with focus on carrier grade mesh networks

function in this particular M-SS. Our innovative approach proposes the ACF to initiate an IMS registration sending a SIP REGISTER message using the access information provided by the UE during the access authorisation attempt. The ACF needs to adapt the user registration data to generate an IMS conform SIP message containing a valid authorisation header (e.g. digest $username = "user1\_private@home1.net"$, $realm = "registrar.home1.net"$, $algorithm = AKAv1-MD5$,) that is directed to the IMS home network of the user. The authentication and authorisation data are stored in the user profile within the HSS. Furthermore, the user profile contains policies for service provisioning. Finally, the ACF executes the controlling of the access based on the success of the SIP registration procedure. This approach takes benefit of the application level signalling of IMS opening new possibilities to integrate distributed user data towards a carrier grade FMC network solution.

3) Security in Mesh networks: Security is a very important requirement for carrier grade networks and also for user acceptance. For that reason carrier grade mesh networks have to provide security mechanisms as well. These mechanisms prevent unauthorised user access, eavesdropping of user data and any form of attacks that inhibit the correct functioning of the mesh network. Furthermore, security functionality is needed within the mesh network backbone to avoid attacks on the infrastructure and eavesdropping. A first approach is data encryption among two mesh nodes. Second, mesh nodes must have the ability for mutual authentication of each other to prevent network attacks, like unauthorised traffic redirection or access by a malicious mesh node.

V. Wireless mesh network simulation environment

Network simulators are widely used to perform initial tests of protocols and services and to assess the performance in a controlled environment. We use the network simulator NS-2 [2] to evaluate the developed concepts and mechanisms. As the PHY layer of the current version does not consider interference, we enhanced the PHY layer towards interference awareness. Since no 802.16 based mesh module is available for NS-2 we have developed our own custom module. We paid particular attention to a high detail level and accurate programming in order to make the simulations as close to reality as possible.

A. PHY layer implementation

The current PHY layer of NS-2 relies on the distance between source and destination and the propagation model to decide whether a packet can be received or not. Interference is currently not considered. For realistic simulations of mesh networks, however, the channel model must be enhanced with interference awareness. Our enhancements consider the packet error probability by calculating the Carrier to Interference value C/I during packet reception, where C denotes the received carrier signal and I the received interference. C is calculated as a function of the distance between sender and receiver and the propagation model. The interference is the sum of a combination of individual interference contributions I_k caused by simultaneous transmissions of k devices and the background noise N, i.e.:

$$I = \sum_k I_k + N \tag{1}$$

Based on the C/I, the packet error probability is determined. Depending on the packet error probability, the node determines whether a packet can be received successfully. In general, packets with higher C/I have a lower packet error probability.

B. MAC layer implementation

Currently there is no IEEE 802.16 mesh module available for NS-2. Therefore, we started to implement our own costume module based on the 802.16-2004 standard that provides the following mechanisms:

- TDMA frame structure
- Sending/receiving of data and signalling packets
- Resource scheduling mechanism
- Multihop communication
- Base Station functionality
- Coordinated distributed scheduling

C. Initial simulation results

Figure 6 shows the TCP performance over a one-hop connection in IEEE 802.16 mesh mode. The simulation scenario is a grid with 4 and 64 mesh nodes and one mesh base station placed in the middle of the grid. A TCP session is started between the base station as destination and one of its direct (one-hop) neighbours as source. All other nodes do not transmit any data packets.

These initial results for different network sizes show that the IEEE 802.16 mesh mode in its current stage is not scalable. The TCP performance in the small mesh network exceeds that of the large network by a factor of 3.5. The reason for the lack of scalability is the transmission timing of signalling messages. If the node density increases, the number of competing neighbours also grows. Even if no neighbour transmits data packets,

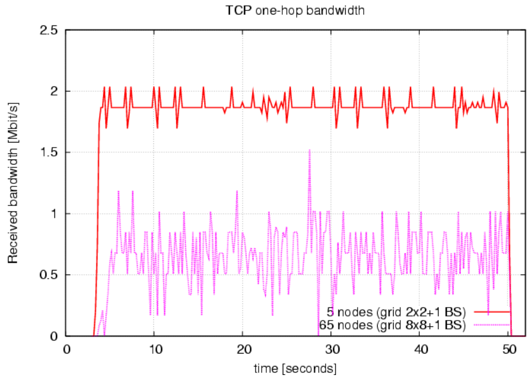

Fig. 6. TCP one-hop performance for grid scenario with 5 and 65 nodes

they compete with the "active" nodes for signalling message transmission opportunities. These signalling messages are used by the three-way-handshake to request, grant and confirm data transmission. If many neighbors compete, the transmission interval between subsequent signalling messages increases and with it the duration of the three-way handshake. As nodes in dense networks can not request bandwidth as frequent as in sparse networks, the TCP performance drops. Therefore, scalability of the 802.16 mesh mode has a non-negligible impact for QoS provisioning. Enhancements at the 802.16 mesh MAC layer are therefore needed to overcome these limitations. Further investigations, results as well as optimisations of the IEEE 802.16 mesh mode can be found in [19].

VI. The Magnets testbed

The ability to deploy and evaluate new technologies, protocols and architectures is vital for operators (and also researchers). Our understanding of the fundamental parameters of wireless access networks, ranging from capacity constraints, scalable deployment and efficient management, up to revenue potential for Telecom Operators is still in its infancy. The objective of Magnets is to develop, deploy and evaluate a next-generation wireless metropolitan area network that provides ubiquitous coverage at 100s of Mbps or even Gbps.

The design goals of Magnets are three-fold. First, we develop and deploy a semi-productive wireless access network using off-the-shelf equipment. Semi-productive denotes a testbed that provides access to a selected user group, in our case the students of the Technical University of Berlin. Access to the network is free, but no service guarantees are provided. Moreover, we take the freedom to deploy alternative protocols and study their effects on user traffic. Thus, we are able to gather realistic experience and draw conclusions for an extensive and fully operational deployment of broadband wireless access networks. Second, Magnets serves as a platform for investigating interoperability issues, such as the integration of different wireless technologies in a single network. Third, Magnets will leverage and help evaluate the multi-tier design approach in the context of mesh environments, a design trend that is also being followed in other fields such as peer-to-peer networks and sensor networks.

This section describes the Magnets architecture, shows initial performance results and draws conclusions from the 1-year between the project start and the first bits transmitted over the backbone.

A. Magnets architecture

The Magnets [1] architecture consists of 3 basic parts: a high-speed wireless 802.11 backbone, an 802.11-based wireless mesh network and integration points to alternative technologies (GPRS, UMTS and WiMAX).

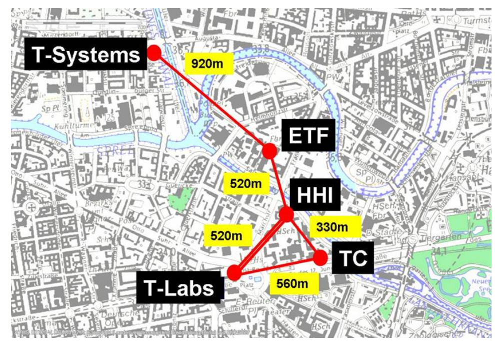

Fig. 7. Magnets backbone in the heart of Berlin

Figure 7 depicts the deployment of the Magnets backbone in the heart of Berlin. The backbone features wireless high-speed connection between 5 buildings, spanning a total distance between T-Labs and T-Systems of 2.3km. All nodes reside on top of high-rise buildings and have unobstructed line of sight, and all transmissions are in the unlicensed spectrum (2.4 and 5 GHz).

Each node along the backbone consists of a work-station with fast processor (3GHz) and 1 GB of RAM that acts as a router. Attached to the routers are 12 WiFi access points (APs) suitable for outdoor usage, mounted along the antennas to shorten the cable length between the antenna and the AP. The APs support the 802.11a/g modes at 54Mb/sec, and also a proprietary protocol called Turbo Mode, capable of providing raw bandwidth up to 108Mb/sec. The access points are connected to directional antennas, 8 of which operate at 2.4 GHz and the rest at 5 GHz. The link characteristics along the backbone vary in distance and capacity: the shortest link is 330 meters, and the longest being 920 meters.

The second part of the Magnets testbed is a WiFi mesh network deployed on the campus of the TU Berlin. In its final form, the outdoor testbed will consist of∼50 mesh nodes, targeting the areas of the campus where connectivity is currently sparse. For the selection of the hardware for the mesh nodes, we primarily opt for a platform that provides maximum extensibility (e.g. RouterBoards). In particular the ability to plug in multiple Mini PCI slots provides flexibility in connecting several wireless interfaces. The deployment planning attempts to strike a balance between achieving research goals and allowing practical use of the mesh network. Initially, a cluster

[1] www.deutsche-telekom-laboratories.de/∼karrer/magnets.html

of around 15 nodes will be deployed around a populated area of the campus, where several users are expected to connect. Each mesh node is equipped with several WiFi interfaces (between 3 and 6). Deployment is challenging because cards in the mesh nodes must be chosen to balance user access capacity (in the 2.4 GHz band, since users mostly have 802.11b/g cards) and capacity to forward traffic to the fixed network. Then, the ”diameter” of the mesh network will be extended in an ad hoc, less-planned fashion, to increase coverage and the number of hops traffic will have to traverse.

Finally, in a third phase, we will complement the networks with alternative wireless technologies to form a 4G heterogeneous network, taking advantage of the 6 Mini PCI slots of the mesh nodes. Some slots will be furnished with low-range Bluetooth and Zigbee communication interfaces for integrating sensor networks. Other slots will be equipped with wide-area wireless technologies, such as GPRS, UMTS, and WiMAX. Moreover, we aim at interconnecting the wireless mesh networks deployed in Berlin. For the interconnection, we will profit from the extended transmission range of WiMAX. Figure 8 depicts an initial plan to deploy the WiMAX backbone. The figure shows the 3 mesh networks that are currently deployed in the city of Berlin: the Berlin Roofnet at Humboldt University, the Freifunk.net and Magnets. We will deploy 3 WiMAX base stations at three strategic locations in Berlin to form a WiMAX backbone. Connected to the backbone are up to 5 subscriber stations located inside or near the WiFi mesh networks. Thus, the currently isolated WiFi mesh islands will be aggregated to a WiFi atoll.

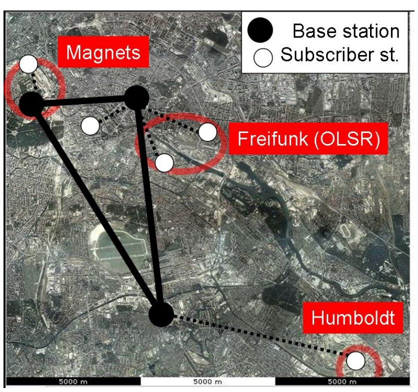

Fig. 8. Planned WiMAX backbone connecting Berlins WiFi mesh networks

Besides the traditional research challenges, such as TCP performance issues or handovers between multiple access technologies, interesting research questions arise when constellations of meshes are formed, in which mesh networks under different administrative authorities become interconnected. For example, integration of disparate mesh routing protocols with possibly different routing metrics is still an open issue. Specification of policies and their respective effect on intermesh routing, as well as mesh gateway functions have not been investigated either. Additionally, management of a large-scale mesh infrastructure is a challenging task and practical experience can prove invaluable.

B. *Initial performance results*

Link	Freq [GHz]	Ch	Level [dBm]	TCP [Mbps]	UDP [Mbps]	RTT [ms]
1	5	DFS	-49	26.3		2
2	2.4	7	-55	13.6	12.6	3
3	2.4	1	-58	12.3	15.3	21
4	2.4	13	-56	15.5	15.7	3
5	2.4	13	-80	6.4	2.9	10
6	5	DFS	-81	5.2	8.7	150

TABLE I

INITIAL MAGNETS BACKBONE MEASUREMENTS

Table I shows an overview of preliminary performance results from the backbone deployment. The first three columns denote the link (see Figure 7), the frequency and the assigned channel (5 GHz: Dynamic Frequency Selection). The remaining columns denote the measured level (dBm), the TCP throughput (Mbps), the UDP throughput with 1.5 kB packets (Mbps) and the RTT [ms] in each direction.

We stress here that the results are preliminary in the sense that we have not yet tuned the backbone parameters to achieve optimal results. Moreover, the results are counter-intuitive at some places, e.g. if the TCP throughput is higher than the UDP throughput. Some effects must be contributed to environmental factors, such as interference from neighbouring access points. We strive at investigating the causes for these effects and provide novel insight into wireless access networks over the next months (see e.g. [20]).

Nevertheless, we draw the following initial conclusions from the measurements. First, the measured throughput over links 1 to 4 achieves more than 10 Mbps throughput. For a wireless links that spans between 330m and 560m in a dense urban area, these results are promising. In particular, also integrating the measurements of [20], they show that wireless backbones are able to sustain a high data rate. Therefore, wireless technology can be considered a viable alternative for wired technology. This alternative is interesting for areas where no fibre is yet available (rural areas or 3rd world countries). Second, interference in a dense urban area is well known to cause severe problems. The node at ETF resides on a building that is not as high-rise as the others. As a result, the line of sight is not perfect such that the Freznel zone is not as free as on links 1 to 4. Moreover, due to the lower level, we measured up to 26 access points at one frequency that cause interference. As a result, the throughput of the links that converge at ETF drops by a factor of 2 at least. Moreover, recent experience shows that the links are even inaccessible for some times. A similar particularity is link 6 where the delay reaches up to 150ms. A detailed analysis showed that the firmware of the AP reacts to radar impulses. Radar impulses in the 5GHz range can be attributed to airports, weather stations or military. If the AP detects a radar impulse, it backs off and searches for an alternative frequency. Both results show the need to regulate the scarce spectrum for WiFi to ensure that scalable, high-speed WiFi networks can be deployed and run.

C. Lessons learnt

The deployment of the Magnets WiFi backbone, from its first idea to the first bit transmitted took a period of almost one year. Here, we highlight the key lessons learnt from the deployment.

- The deployment of high-speed wireless networks is feasible even in densely populated cities. The combination of high-rise buildings and directional antennas provide the potential achieving the maximal transmission rates of the access points.
- The key resources that will limit a deployment in the future are spectrum and roof space. The sharing of spectrum causes vast interference. Directional antennas provide spatial reuse, but their use is limited to point-to-point communication. Roof space to set up the antennas is getting sparse as well. Some roofs are already crowded with various antennas that may cause interference. Again, directional antennas reduce interference.
- The deployment of outdoor antennas is often slowed down by the connection to indoors facilities. Most Magnets backbone nodes deploy outdoor APs to reduce the cable length to the antenna. Outdoor APs are available off-the-shelf. However, eventually, a connection is needed from the AP to an indoor facility (router or network connection). This connection should be equipped with Power over Ethernet. For the deployment of the Magnets nodes, these connections required infrastructural changes (holes through the wall). These changes are expensive and must be done by experts, as the holes must be protected against water and lightning. New buildings should be constructed with the ability to easily lay new cables and deploy antennas on the roof top.
- A non-trivial task for a distributed deployment of nodes is the accessibility of the nodes. In addition to the wireless interfaces, each Magnets node contains a network card that connects the node to a wired management network. This connection is vital for maintenance, but also to provide a non-interfering connection to perform measurements. Setting up the maintenance connection is far from trivial, as IPs must be obtained from each site and a secure and robust routing infrastructure must be set up.

VII. Conclusions

For operators, the viability of wireless access networks depends on the ability to provide carrier grade service quality. Unfortunately, the heterogeneity of wireless technology and the lack of reliable channels requires an integrated architecture that allows an opportunistic usage of the different technologies.

The overarching architecture of ScaleNet combines traditionally separated fixed and mobile networks into a converged architecture and also integrates novel concepts such as mesh networks. The deployment of two specific services, QoS and AAA, show that a combination of technology-dependent functionality and technology-independent, overarching functionality is required. The presented architecture is the foundation for a future deployment of carrier grade networks.

In parallel, we are developing and deploying simulation and testbed environments to assess the functionality and performance of novel protocols for wireless access networks. The NS-2 extensions provide novel environments for simulating 802.16-based mesh networks. The Magnets testbed currently being deployed in Berlin is a testbed to test and evaluate protocols in a semi-productive environment. Advances in simulations and testbed environments are necessary to enhance our knowledge of designing, deploying and using wireless access networks towards a full deployment of carrier grade broadband wireless access networks.

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