WIRELESS WORLD
RESEARCH FORUM

White Paper on Meshing for Relay based Deployment Concepts

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***Abstract*— The goal of this White Paper is to establish a platform for the discussion of fixed wireless mesh networks and related technologies and to highlight the advantages of fixed mesh networks, showing the implementation challenges and potential solutions including traffic performance measures and its capabilities to guarantee QoS. The focus is on mesh networks with multiple nodes (Radio Access Points –RAP) to connect sources and sinks via a limited number of hops (e.g. =<4). This first version of the white paper provides an introduction to mesh networks and the ongoing activities in this field of research with its different application scenarios. The mesh technology will be introduced and with the W-CHAMB protocol a candidate solution is presented that allows for meshing with QoS support.**

***Index Terms*—Meshing, multi-hop, relay, deployment concept**

INTRODUCTION

THE advantage of using relays to allow for efficient radio network deployment has been shown in the respective WWRF white paper on relay based deployment concept [1][2]. The paper was mainly addressing the issue of two hop relays without a connection of relays of the same tire.

Meshing, which is a hot topic in the short range world, is nowadays also getting momentum as part of radio network deployment concept for infrastructure based networks using fixed relay nodes, such as the IEEE 802.16 mesh mode. This white paper on meshing for relay based deployment concept as a complement of [1][2] shall present and discuss innovative concepts and solutions in this rather new field of meshing in infrastructure based wireless networks.

In the context of this paper the mesh network is assumed to be a fixed wireless mesh network, i.e. it is based on fixed (or movable) relay nodes (RN) and Base Station (BS). Thus the UTs are most likely not involved in the mesh itself, but are connected to it as shown in Figure 1. The figure shows a mesh network where the Radio Access Points (RAP), which can be either a RN or an AP are connected with its neighbouring RAP. Thereby the AP denotes the RAP which is connected to the backbone network (most likely the Internet). For 4G deployment concept the technology of mesh is an interesting candidate to connect all cells of a cluster which would allow for an improved coordination across the radio access points (RAP) which could be either a BS or a RN. In such a scenario the RN would have to share its resources between the traffic caused by the actual UT and the network traffic which it has to forward to other RNs and BS.

Today's wireless market is split into Wireless Personal, Local and Metropolitan Area Networks. Short range communication is delivered by Bluetooth. Its main application is speech services for small battery driven devices. High speed Wireless Personal Area Network (WPAN) PHY technology is standardized by IEEE 802.15.3a currently. It introduces Ultrawideband (UWB) communication, which enables data rates of 480Mb/s up to 1Gb/s. In the field of Wireless Local Area Networks (WLANs) IEEE 802.11 is the dominating standard that replaced all other solutions on the market. Task Group "n" currently defines MIMO technology for WLANs to enable data rates in excess of 100Mb/s. For even larger covered areas, IEEE 802.16 is designed. It defines a centralized network architecture that enables Metropolitan Area Networks (WMANs).

All of the aforementioned technologies form lonely islands in an ocean of wireless networks. Without a wired backbone infrastructure, none of them is able to provide communication to devices, which are not part of the same service area:

- Bluetooth devices communicate with their piconet controller only,
- most the WLANs use an Access Point (AP) based structure, where all communication is possible via the AP only and
- IEEE 802.16 devices cannot communicate without the central controller.

However, users have a different understanding of communication services. The Internet is a meta-network of connected networks. Customers are used to be able to access any desired network and service anytime and anywhere. With the domination of Ethernet as the MAC and PHY technology and the Internet Protocol (IP) on the Network layer, plug-and-play access to Internet became possible. Wherever a user plugs in, a high speed connection is instantly available. Today's wired networks easily achieve data rates of 100Mb/s, 1Gb/s up to 10Gb/s. Standard Gigabit-Ethernet (GE) controllers are cheap and included with most of the current PC motherboards and notebooks. As a second key element of the success of the Internet, IP became the dominating de-facto standard. It replaced all other solutions.

To fulfill the demands of a wireless Internet, the aforementioned qualities of the wired Internet must be supported by any future wireless technology. In terms of high speed, current development in wireless technology increases the available data rates. However, coverage range stays hardly the same as for legacy wireless technology. There is always a tradeoff of coverage range data rate. IEEE 802.11n aims a 100Mb/s measured at top of the MAC at 15m distance e.g. Higher data rates of 480Mb/s, as UWB solutions will bring to the market, are limited to 2m and even less. To provide a sufficient coverage area and to enable a wireless Internet, future wireless networks depend on a large amount of Access Points (APs). However, the installation of multiple APs is costly and connection to the wired backbone often is not available. This condition is true especially for those areas, which are currently not covered with wireless services. Thus, to avoid the needs for a wired backbone, the backbone itself must become wireless.

In the following the paper will present a general introduction to mesh networks. The current activities towards mesh networks inside the IEEE 802 bodies are highlighted and some example scenarios as also discussed in the IEEE 802.11s group are shown. To demonstrate how a mesh network could work a candidate solutions will be presented with the W-CHAMB protocol before the paper will be concluded with an outlook on potential contributions towards future versions of the White Paper.

Mesh Networks

Roughly speaking, a mesh network is a network that employs one of two connection arrangements, full mesh topology or partial mesh topology. In the full mesh topology, each node is connected directly to each of the others. In the partial mesh topology, nodes are connected to only some, not all, of the other nodes. On the basis of this definition it is clear that mesh networking is not a new concept. In certain ways, the Internet is a mesh network. A Wireless Mesh Network (WMN) is a mesh network that handles many-to-many connections wirelessly and is capable of dynamically updating and optimizing these connections. An ideal WMN is a dynamically self-organizing, self-configuring, and self-healing network.

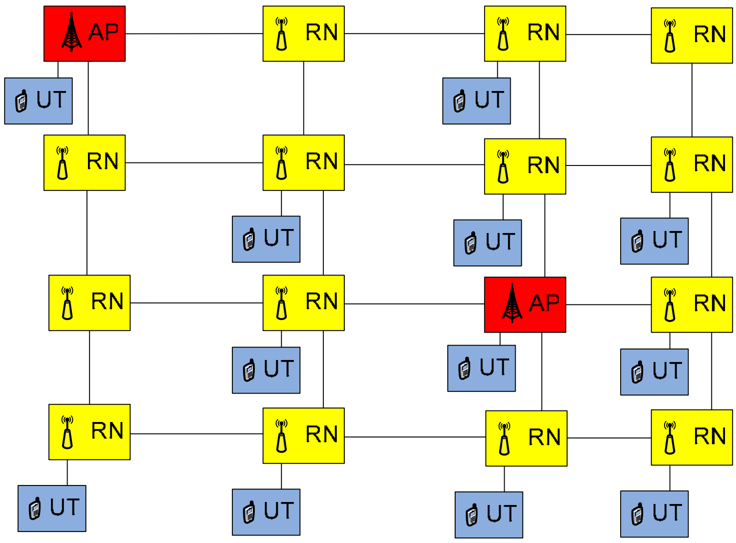

Figure 1: Mesh network based on fixed Relay Nodes (RN) with User Terminals (UT) connected to it. Access Points (AP) are connected directly to the Internet.

The certainly most evident advantage of the mesh deployment concept is the possibility of extending the range of a given radio access technology. The increase of the covering area allows consequently to serve a larger number of users and to better support the ubiquity of the applications. Many realizations of a mesh deployment can be envisioned, since a lot of parameters can be varied in accordance with the applications that the system is designed for.

Besides the technical aspects, the deployment easiness and cost-effective and the scalability provide to this mode an indubitable appeal with the respect to the operators, since these characteristics allow to reach and cover certain area that would normally be considered unprofitable as well as offering a solution for the easy deployment of high-speed ubiquitous wireless Internet. More precisely, the possibility of extending the range of a service without the need of expensive investments in infrastructures and equipments, is feeding the research in this domain.

So far the usage models and the radio access technologies that have been associated to this deployment approach have mainly concerned the domain of the LANs or the MANs, respectively involving evolutions of the IEEE 802.11 [7] and the IEEE 802.16 [8]standards. The latter has been approved in its latest version in 2004 and contains a mesh option for both MAC and PHY layers, whereas within the 802.11 committee the newly created task group *s* is in charge of the definition of the mesh extension for the most successful WLAN standard to date. However these two technologies rely on very different technical bases that seem to make them hardly compatible.

The mesh/relay deployment concept mainly refers to the design of the data link control and network layers and has been conducted on the related mechanisms usually located in these two layers. More precisely the impact on the above layers of issues such as the potentiality of the modulation scheme, the duration of the OFDM symbols (when this transmission technique is retained) or the sensibility to propagation condition of the transmission technique, can affect the deployment approach. Though all the PHY variants are still being considered, it seems evident that some configurations may ease the mesh deployment in certain scenarios. Typically, when the meshing terminals are fixes the usage of directive antennas to relay the information could be beneficial. Similarly, in wide area scenarios the use of those technologies or of MIMO ones could increase the coverage of the mesh network. Obviously techniques must be coupled with an adequate MAC scheme. On the contrary, in the mobile case a conservative choice may be to use the most robust transmission mode to avoid retransmissions. Finally, a strong influence on the deployment is performed by the working frequency of the network. It is well known that the high the frequency the shorter is the range of the transmission. This fact along with the rudeness of propagation condition in some scenarios leads somehow to the adoption of the OFDM transmission technique in relatively low frequency bands.

Generally it can be said that the mesh mode does not seem to be facilitated by one specific PHY solution. More precisely the mesh mode does not require specific PHY configuration but each one shall be investigated jointly with a specific MAC scheme and adapted to a specific scenario.

Hidden and exposed station problem

Implementation of an efficient multi-hop functionality needs solutions offered by a link layer protocol to properly handle hidden and exposed stations in a mesh network. Suppose an existing transmission between a sender A and a receiver B, a hidden station C is one that is within the interfering range of the receiver B but out of the sensing range of the sender A. Exposed stations are the complement of hidden stations. An exposed station D is one that is within the sensing range of the sender A but out of the interfering range of the receiver B. The well known decentralized Media Access Control (MAC) scheme IEEE 802.11 Distributed Coordination Function (DCF) [7] cannot function well in multi-hop networks since it cannot inhibit both the hidden and exposed stations in multi-hop environments. Centralized schemes like IEEE 802.16 [8]], Hiperlan2 [9] can handle the hidden stations and exposed stations well since a central controller knows and controls all the transmission details. But the excessive required control information for multi-hop operation leads to the significant reduction in transmission efficiency with the increase of forwarders. Transmission more than 2 hops in a centralized system incurs a large waste of bandwidth. It appears that a large scale mesh network can be constructed easily in a distributed manner than in a centralized manner.

QoS

Implementation of QoS in multi-hop operation is another tough issue. QoS requirements especially the delay metric is a great challenge for multi-hop operation. A high achievable network throughput not necessarily goes in hand with a low packet delay. For decentralized schemes, how to provision the bandwidth for a specific traffic to guarantee its QoS requirement while not waste the resource is not a trivial issue. IEEE 802.11e Enhanced Distributed Channel Access (EDCA) [10]] gives a primary solution on single hop environments, but the reported results are not so encouraging [11].

Mesh technology

Current research in wireless develops function to interconnect APs wirelessly. Interconnected APs share the wireless medium and enable a dense coverage area – A Mesh network is build. This paradigm shift is an evolutionary path for wireless technology. While traditional wireless networks operate in "island" mode –an AP is needed to connect wireless devices – Mesh networks are the counterpart to the wired Internet. Mesh networks offer the convenience and seamless services that wireless technology promises today, but cannot offer. Currently, the market for Mesh networks is still under development. A lot of small start-up companies have developed proprietary solutions. This situation usually indicates the beginning of a new market, where high increase in volumes and sales can be expected.

Mesh network environments

To allow for a performant packet transmission, the wireless medium must be used highly efficient. The node density is high, the cells covered by APs overlap at least partially. Thus, the spatial frequency reuse must be increased. Today's wireless technology is designed for single hop, Access Point centered communication. Centrally coordinated systems allow for high efficiency, since a global scheduling instance is able to use the available resources most efficient. However, multiple hops and neighboring interference are not considered. But especially interference limitation is a key element in Mesh networks. A cooperative

MAC design helps to improve the spectrum efficiency. It allows learning strategies, which determine when concurrent transmissions on the same frequency channel are possible. This greatly enhances the spectrum usage and increases the overall capacity. Hence, a distributed algorithm is needed to allow for spectrum efficient coordination of the medium channel access. Development of distributed algorithms that seamlessly support cooperative and self-healing network designs is a key element.

Mesh network applications

Users of home and CE are able to deploy full coverage wireless networks in their home environment with cheap mass market devices. The network supports auto-configuration and easy set-up. It delivers packets seamlessly to wired or wireless clients, hence allowing the customer to integrate Audio/Video, VoIP or any other CE devices to his network. Service is available without wiring. Enterprise and professional users of wireless networks benefit from cost effective setups, where no wiring is needed and ad-hoc installation are possible. in the home environment customers will demand replacement of wires, thus leading to a great success for wireless. Therefore, high capacity networks are needed that support >1Gb/s.

However, decentralized wireless networks cannot be controlled by a central coordination instance. A general solution for wireless ad-hoc Mesh networks, which are able to automatically set up a wireless infrastructure with high efficiency and good spatial channel reuse. The system shall support 1Gb/s and be able to deliver VoIP service in a wide area. The system shall dynamically use every allowed spectrum and behave cooperative to other devices. A seamless integration with different technologies shall be possible.

Wireless Mesh WPAN

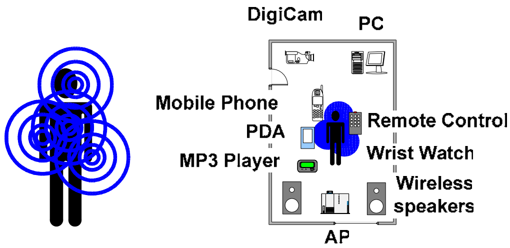

Figure 2: Mesh WPAN

In January 2004, the IEEE Working Group (WG) 802.15 formed a new Task Group (TG). TG 5's mission is the development of a recommended practice for Mesh WPANs. The group considers high and low speed Mesh WPANs. Due to their different nature, TG5 develops independent recommendations. The subset of common functions for high and low speed is expected to be small.

The documents, which TG5 received in accordance to the Call for Proposals (CFP), show a favorization for high speed WPAN solutions. Unlike the current 802.15.3 MAC, the TG5 proposal for a Mesh WPAN MAC is built on top of the distributed MAC of the Multiband OFDM Alliance (MBOA). MBOA, which has recently merged with the WiMedia Alliance, proposes an OFDM based PHY technology to IEEE 802.15.3a, too. Due to market orientation of its members, Philips, Sony, Intel, Panasonic, TI and many more, the most important application is to enable a wireless Universal Serial Bus (USB) 2.0, which support data rates up to 480Mb/s. Since USB devices can be set-up in a physical tree structure, a wireless USB network will need ad hoc networking procedures, which are provided with Mesh technology.

It is essential for the wireless USB market to provide seamless integration with wired USB devices and to deliver the same degree of easy set-up as the wired USB delivers already today. Due to the different nature of wireless networks, mesh technology helps to hide the fluctuation of performance and QoS in wireless networks and allows to support the ad hoc character of the USB.

Wireless Mesh WLAN

Since November 2003, IEEE 802.11 Task Group (TG) "s" works on Mesh WLAN. The 802.11s Mesh is based on Mesh Access Points (APs) solely. TGs defines the Wireless Distribution System (WDS) build by APs only. Explicitly the TGs PAR defines that “the proposed amendment shall be an extension to the IEEE 802.11 MAC. The amendment will define an architecture and protocol for providing an IEEE 802.11 ESS Mesh […] to create an IEEE 802.11 Wireless Distribution System […] over self-configuring multi-hop topologies.” Hence, the Mesh network interconnects APs to replace the wired infrastructure and to enable WLAN access where no AP can be connected to an ethernet. QoS in terms of throughput and delay is more important than energy consumption, since it can be assumed that the APs have sufficient computing power and are constantly powered.

Stations are not part of the Mesh. Hence, 802.11s does not define a MANET like peer to peer Mesh network. The size of the Mesh network is rather small. As a rule of thumb the TGs PAR states: “A target configuration is up to 32 devices participating as AP forwarders in the ESS Mesh.”

To seamlessly integrate Mesh technology to the wireless market, legacy compatibility is a major issue. “An Extended Service Set (ESS) Mesh is functionally equivalent to a wired ESS, with respect to the stations (STAs) relationship with the Basic Service Set (BSS) and ESS.” Therefore, stations associate with APs and use the Mesh network to perform services, which enable roaming etc. As TGs further defines that “The amendment shall allow the use of one or more IEEE 802.11 radios on each AP in the ESS Mesh,“ APs have to deal with legacy devices, which behave rather simple and inefficient. Therefore, the protocol must be able to deal with uncooperative legacy devices that constantly try to access the medium, as well as with hidden and exposed nodes, which are likely to cause harmful interference.

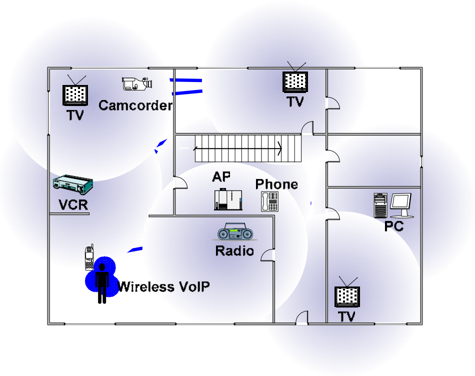

Figure 3: Mesh WLAN

The requirement “The amendment shall utilize IEEE 802.11i security mechanisms or an extension thereof […] in which all of the APs are controlled by a single logical administrative entity for security.” aims at a high reuse of 802.11i technology. The single logical administrative entity could be a common password used in all APs. Currently, there is no precise definition behind.

Summarizing there are the following key elements to develop, therefore:

- Backwards compatibility
- Multihop technology
- Interference awareness
- Spatial channel reuse
- Radio aware routing

According to its PAR and 5 Criteria documents, TGs has identified the following application scenario as in scope of its development:

- Consumer Electronics (CE)
- Home environment
- Office
- Public access
- Military usage
- Disaster field
- Public safety
- Campus networks

Since the covered range of usage scenarios is so broad, different proposals to TGs are expected. A good support for the upcoming High Throughput amendment of TGn is an important element. Since TGn does not only rely on changes to the Physical Layer (PHY) but on amendments to the MAC too, these new procedures as frame aggregation for example have to be taken into account by

TGs. With its sophisticated high speed PHY modes that support up to 500Mb/s, Mesh WLAN is a complimentary technology, which helps to reduce the gap in the coverage. As the Mesh especially carries the aggregated traffic from the APs, 802.11n is a major element in every Mesh WLAN.

Wireless Mesh WMAN

IEEE 802.16, mostly known as WiMAX, knows different mode of operations. The standard describes 802.16 primarily as a point-to-multipoint architecture; however an optional mesh configuration is foreseen. While WiMAX is centrally coordinated system, all Subscriber Stations (SSs) communicate with the Base Station (BS) only. It is the BS, which schedules all access to the Wireless Medium (WM). In a mesh topology all BS can act as SS to their neighbors. With Mesh technology introduction, WiMAX will be enriched by an important element, because networks operators are able to easily deploy cost-effective 802.16 networks with high flexibility regarding fixed backbone access.

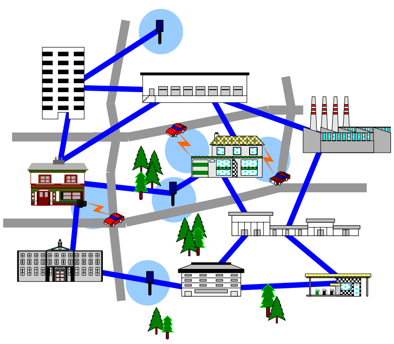

Figure 4: Mesh WMAN

IEEE 802.16 [8] Mesh mode is an optional feature of the WirelessMAN standard. In contrast to the mandatory point-to-multipoint (PMP) configuration where traffic only occurs between the base station (BS) and the subscriber stations (SSs), in the Mesh mode traffic can be routed through other SSs and can occur directly between SSs. Depending on the transmission protocol algorithm used, this can be done on the basis of distributed scheduling, on the basis of centralized scheduling, or on a combination of both.

Using distributed scheduling all the nodes including the Mesh BS coordinate their transmissions in their two-hop neighbourhood and broadcast their schedules (available resources, requests and grants) to all their neighbours. All nodes ensure that the resulting transmissions do not cause collisions with the data and control traffic scheduled by any other node in their two-hop neighbourhood.

Using centralized scheduling, the Mesh BS gathers resource requests from all the Mesh SSs within a certain hop range. It determines the amount of granted resources for each link in the network both in downlink and uplink, and communicates these grants to all the Mesh SSs within the hop range.

All the communications are in the context of a link, which is established between two nodes. Thus, the PMP frame structure composed of a downlink- and an uplink-subframe is replaced by a structure based on bursts scheduled for the transmission between two nodes. All packet data units, i.e. data and control messages are forwarded in the time domain by the Mesh SSs.

Quality of Service (QoS) is provisioned on a message by message basis. Guaranteed end-to-end QoS can only be provisioned by the Mesh BS in centralized scheduling mode.

Mesh systems typically use omni directional antennas. The standard does not integrate space division multiple access (SDMA) schemes in the Mesh mode.

Topology/Architecture Issues and Applicability to 4G Deployment Scenarios

Mesh Network deployment presents many characteristics that recall the well known Mobile (multi-hop) Ad Hoc NETworks (MANETs). MANETs are commonly defined as collections of mobile nodes connected together over a wireless medium. These nodes can freely and dynamically self-organize into arbitrary and temporary ad hoc network topologies, allowing people and devices to seamlessly “inter-network” in areas with no pre-existing communication infrastructure (e.g., disaster recovery and battlefield environments).

However, this type of network did not impact our way of using wireless networks. Users seldom operate 802.11 in ad hoc mode and, except in laboratory test-beds, never use multi-hop ad hoc networks. From the users’ point of view, scenarios consisting of a limited number of people wanting to form an ad hoc network for sharing some information or access to the Internet are much more interesting.

These considerations lead to relax one of the main constraints of MANETs, “the network is made of user’s devices only and no infrastructure exists,” toward networks neither isolated nor self-configured: mobile ad hoc networks rather emerge as a flexible and low-cost extension of wired infrastructure networks, coexisting with them. Indeed, a new class of networks is emerging from this view: mesh networks.

This brief explanation of the nature of mesh deployment gives a hint of the possible topology that this kind of network may assume. Mesh networks are built on a mix of fixed and mobile nodes interconnected via wireless links to form a multi-hop ad hoc network. Though several deployments of mesh network have been conceived by industry and academia, core building blocks and distinct features may easily be identified in mesh architecture. A wireless mesh network is a fully wireless network that employs multi-hop communications to forward traffic en route to and from wired Internet entry points. Users’ devices

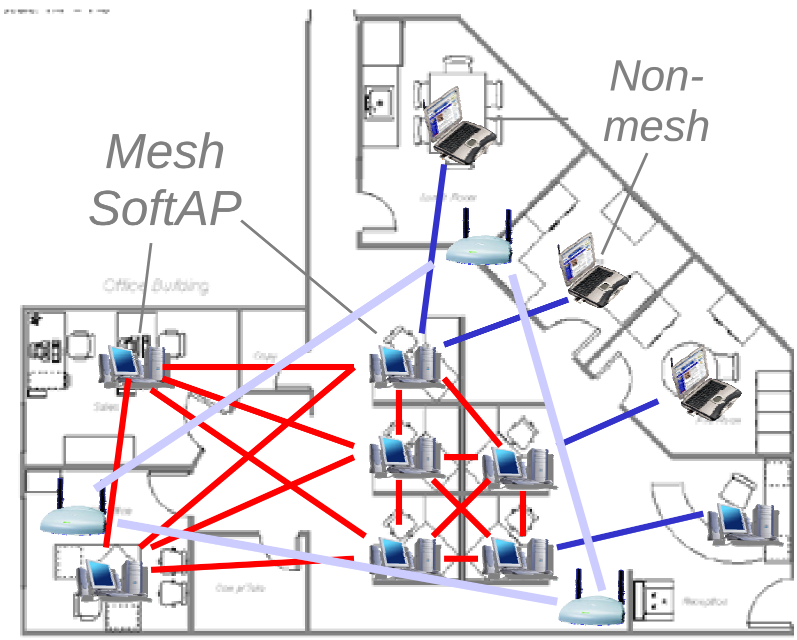

Figure 5: Small Office Home Office scenario

dynamically join the network, possibly acting as both user terminals and routers for other devices, consequently further extending network coverage. For example, indoor mesh networks can be set up by wireless interconnected access points that can create extended WLANs without a wired infrastructure. Outside buildings, mesh networks can be used to provide wireless access across wide geographic areas by minimizing the number of wired ingress/egress points toward the Internet.

Different from flat ad hoc networks, a mesh network introduces a hierarchy in the network architecture with the implementation of dedicated nodes (called relaying node in the WINNER context) communicating among each other and providing wireless transport services to data travelling from users to either other users or access points (in mesh terminology, access points are often special wireless routers with a high-bandwidth wired connection to the Internet backbone). The network of wireless routers forms a wireless backbone (tightly integrated into the mesh network), which provides multi-hop connectivity between nomadic users and wired gateways.

This topology paradigm can be easily applied to many area networks and precisely they can cover all scenarios of the WINNER project. Figure 5 and Figure 6represent typical mesh deployments proposed in the context of the IEEE 802.11s TG covering respectively small/medium office and Hotzone scenarios.

With respect to Metropolitan and Rural scenarios, WMN may represent an efficient alternative to the use of wired connection. The positioning of devices on top of the metropolitan building would allow covering areas that are usually served wirely. Moreover, the recently progress in the broadband wireless access systems and the research that the WINNER project will develop, will be able to satisfy the envisioned bit rate required in the definition of those scenarios

In Figure 6, the meshing among wireless routers and access points creates a wireless backhaul communication system, which provides each mobile user with a low-cost, high-bandwidth, and seamless multi-hop interconnection service with a limited number of Internet entry points and with other wireless mobile users. Roughly and generally speaking, backhaul is used to indicate the service of forwarding traffic from the originator node to an access point from which it can be distributed over an external network. Specifically in the mesh case, the traffic is originated in the users' devices, traverses the wireless backbone, and is distributed over the Internet network. This type of

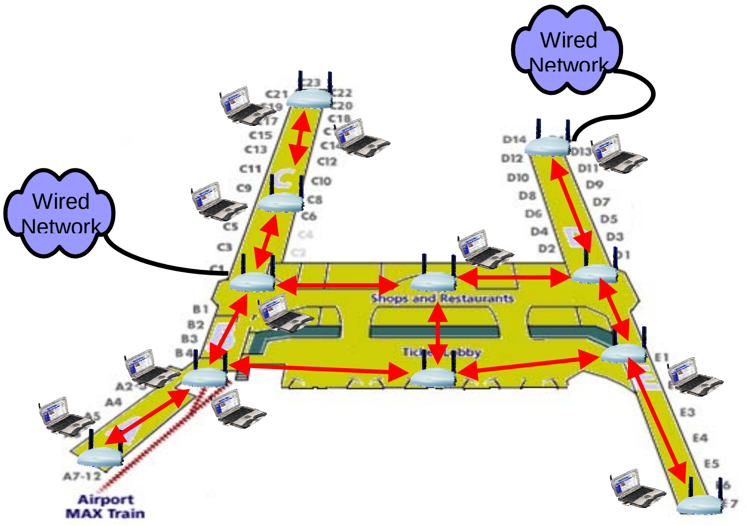

Figure 6: Example of mesh deployment in a Hotzone

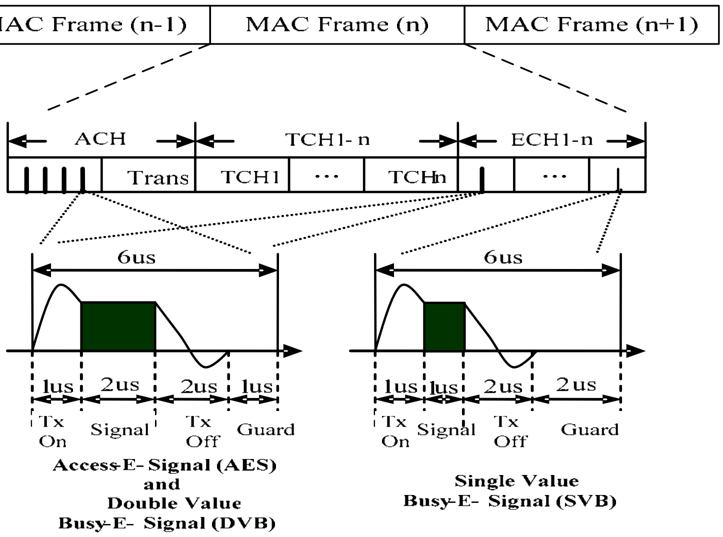

Figure 7: MAC frame and waveforms of energy signals.

configuration of a mesh network is often envisioned in the deployment of mesh systems[1].

W-CHAMB a Candidate Solution

We present a link-layer protocol named Wireless Channel-oriented Ad-hoc Multi-hop Broadband, or W-CHAMB, which is able to perform multi-hop delivery of multi-media services in mesh networks. The W-CHAMB protocol is based on TDMA/TDD technology, operating in a fully distributed manner on a single frequency channel. The W-CHAMB protocol is a candidate link layer solution for Task Group s (Mesh WLAN) of IEEE Working Group 802.11.

Possible applications include the next generation Wireless LAN (WLAN) and Wireless Personal Network (WPAN) systems. Due to the ability to quickly form a network in a fully distributed manner, the W-CHAMB protocol is also a candidate link layer solution for car-to-car communication and sensor networks.

The possible PHY layers include: IEEE802.11a/g PHY, Orthogonal Frequency Division Multiple Access (OFDMA) [14], Multi Carrier Code Division Multiple Access (MC-CDMA) [15], Ultra Wideband (UWB) [16] and forthcoming high data rate transmission schemes.

The part is organized as follows: First the W-CHAMB MAC protocol is described with its features for multi-hop operation, QoS support and synchronisation. Then the Radio Link Control (RLC) protocol and Radio Resource Control (RRC) are briefly outlined.

The W-CHAMB MAC Protocol

MAC frame and energy signal

Unless otherwise stated, the time-related parameters in this paper are example values assuming the IEEE 802.11a PHY [8].

The W-CHAMB protocol is based on TDMA/TDD technology. The operation of a network needs that the involved stations are synchronized. A solution for synchronization is given in [3]. The TDMA frame and waveform of energy signals are shown in Figure 7. Energy signals, in-band busy tones [17], play important roles in the W-CHMAB protocol. An energy signal occupies a short time slice, for instance 6 µs. Energy signals

[1] Moreover, the wireless backbone can take advantage of non-mobile powered wireless routers to implement more sophisticated and resource-demanding transmission techniques than those implemented in user devices. Consequently, the wireless backbone can realize a high degree of spatial reuse and wireless links covering longer distance at higher speed than conventional WLAN technologies.

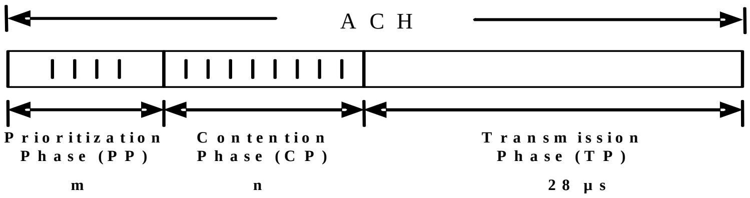

Figure 9: ACH structure.

are classed into two types according to the time slot in which they are used.

Each TDMA frame contains a number of time slots. Time slots are logically grouped into 3 types. The first type is the Access Channel (ACH), in which Access-E-Signals (AESes) are used to implement a two-stage prioritized access mechanism. The second type is called Traffic Channel (TCH), each slot carrying one data packet per TDMA frame. The third one is the Echo Channel (ECH). In a TDMA frame, the number of ECH slots is exactly same as that of TCH slots. Each ECH slot is paired with one TCH slot. An ECH slot is used by a receiving station to signal the occupancy of the corresponding TCH by transmitting a Busy-E-Signal (BES).

Busy-E-Signals are used in the ECH, while Access-E-Signals are used in the ACH. BESes are categorized as Single Value Busy-E-Signals (SVBs) and Double Value Busy-E-Signals (DVBs) according to the signal length as shown in Figure 7. An AES has the exact waveform of a DVB. A SVB is used by a receiving station purely for informing its nearby stations of the occupancy of a specific TCH slot. In case that a receiving station has data packets for its transmitting station, it will transmit a DVB instead of a SVB to request the reverse transmission opportunity, i.e. the TCH in TDD mode of operation, in addition to its basic function as a BES.

The parameters like the number of TCHs, waveform of an energy signal, number of energy signals and length of a MAC frame may be different with different PHY schemes and applications. All those parameters are never changed during operation.

Prioritized access

An ACH slot consists of three phases: Prioritization Phase (PP), Contention Phase (CP) and Transmission Phase (TP), as shown in Figure 9. A number of binary AESes are used in the first two phases to implement a prioritized access mechanism. The PP is the prioritized contention phase, preferable to higher QoS traffic. The setting of CP is to guarantee with a high probability

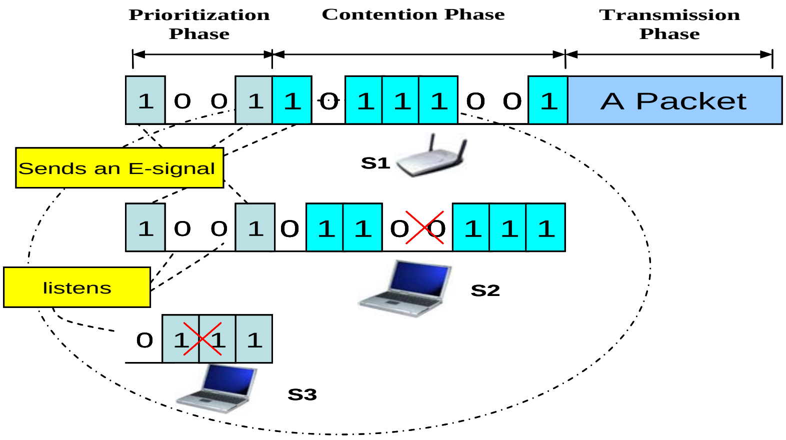

Figure 8: An example of contending for an access. Stations S1, S2 and S3 are in the transmission range of each other.

that there is only one winner under a heavy contention. Assume that the number of binary AESs in the PP and CP of an ACH is m and n, respectively. The number m is associated with the amount of contention priorities, n with the station density. As long as a station needs to reserve TCHs, or set up a link with the destination station, or broadcast Beacons or other packets in case that the station has no reserved TCH for use, it would contend in the ACH for winning a chance to transmit in the TP of an ACH.

The contention is performed as follows:

a) Each station uses the contention number selected according to the type of traffic and whether for the purpose of multi-hop forwarding. The amount of contention levels is up to 2^m. The higher the number, the higher the access priority would be.

b) A station checks the number bit by bit, when the bit is 1 it sends an AES, when the bit is 0 it listens. The most significant digit is transmitted first.

c) During a listening period, once hearing an energy signal, the contending station knows that it has lost the contention in the current TDMA frame. It must cancel the rest of its pending energy signals and contend again in the future.

d) Surviving stations of PP use the same listening and sending scheme again to contend in the CP by a number generated from $[0, 2^n-1]$ randomly.

e) The final winner of the previous phases then sends out the intended packet in the TP.

f) The losing stations contend again in the next TDMA frame.

Figure 8 illustrates a contention process. Stations S1, S2 and S3 are in the transmission range of one another. They happen to contend in the ACH at the same time. S1 and S2 want to set up a Voice over IP (VoIP) link with their partners, while S3 wants to initiate a video stream link. Assume that the QoS priorities of the VoIP and video stream are 9 (1001) and 7 (0111) respectively. Both S1 and S2 win in the first phase contention by means of listening and sending AESs. After that, each of them randomly generates a number and uses the number to compete again in the second phase. As shown in Figure 8, the generated numbers of S1 and S2 for the second phase are 185 (10111001) and 103 (01100111) respectively. S2 quits the second phase contention immediately since it hears an AES at the beginning of the phase. Finally, S1 gets the right to send out a request packet in the Transmission Phase.

TCH Reservation and Hidden Stations Solution

When a station wishes to transmit packets, it firstly checks the channel status. In case the amount of available TCH(s) observed at its own location meets the traffic need, it would contend for an access in the ACH and if it wins, it broadcasts a request packet for TCH(s) reservation containing the receiver address, the one hop connection ID, QoS-related traffic specification (QTS) and a list of

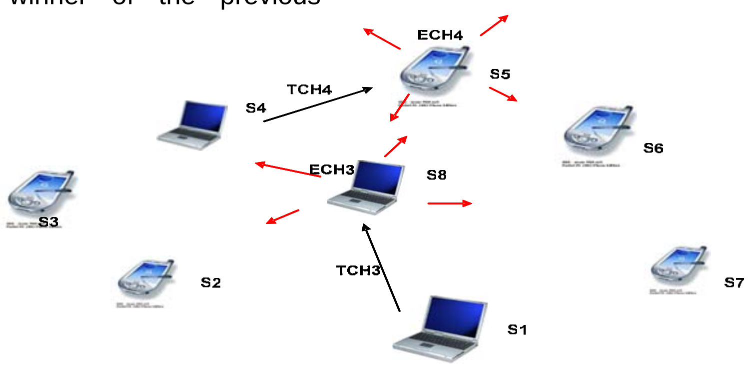

Figure 10: Calming down hidden stations by means of transmitting Busy-E-Signals

proposed TCH slots in the Transmission slot of the ACH. After receiving the request packet, the destination station makes the decision whether to accept the request or not by evaluating the received QTS and the free TCH slots available at its location. In case of acceptance, the receiver transmits SVB(s) in ECH(s) corresponding to the accepted TCH(s). Both the originator and nearby stations of the receiver obtain valuable information from the SVB(s). For the originator, it knows that the TCH(s) have been reserved. For the nearby stations, they know that the respective TCH(s) are in use and they cannot use them right now, therefore potential hidden stations are calmed down.

An example is given in Figure 10. The notation TCH n/ECH n means n^{th} TCH slot/n^{th} ECH slot in a TDMA frame in the following context. A one hop transmission is ongoing between the station S1 and S8. S1 uses the TCH 3 to transmit data packets and the receiving station S8 replies with Busy-E-Signals in the ECH 3 to inform its nearby stations that the TCH 3 is in use. S4 and S5 are potential hidden stations to S1. When they have data to exchange, they would select TCH(s) other than the TCH3 for transmission, since both of them know from the Busy-E-Signals in ECHs that the TCH 3 is currently in use. In this example, the TCH 4 is chosen by them.

Transmission and On-demand-TDD

Once TCH(s) have been reserved for a one hop connection, the sender uses one or some of them to send out its data packets. No matter whether the receiver correctly receives the packets or not, it replies with the SVB(s) in the related ECH(s) to signal the occupancy of the respective TCH(s) in its environment. In case the receiver has some data to send back, it transmits a DVB instead of SVB on the corresponding ECH. If the sender senses the DVB, from the next frame on, it stops the transmission in the respective TCH(s) and takes the charge of transmitting energy signals in the ECH(s). In reaction to this, the receiver shall send out packets via the reserved TCH(s).

Multi-hop Operation

A multi-hop connection consists of multiple one-hop connections in tandem that each is independently controlled. Owing to the TDMA structure, the hop-to-hop forwarding of a multi-hop transmission may take place simultaneously in the different TCHs of a MAC frame, achieving low end-to-end packet delays.

Packet Multiplexing

A TCH established between adjacent stations is used to multiplex any packets transmitting on the route. The sequence of transmission of packets competing for a TCH is according to their QoS priorities.

Synchronization

The design of a synchronization scheme for a distributed TDMA system aiming at high speed communication is really a challenging work. Rui et. al. [3] presents a primary solution for W-CHMAB networks. The scheme can be briefly described as followsr:

1) Beacon packets carrying time information are broadcasted periodically. Each station might be a potential Beacon generator. Recipients update their time by analyzing the received Beacons.

2) The access mechanism ensures that there is only one winner in almost every contention, which is important to guarantee that a Beacon appears timely over the air.

3) The clock shift compensation algorithm helps to mitigate the clock skews.

The W-CHAMB RLC Protocol

W-CHAMB RLC offers data transfer service to the upper layer. The RLC layer fragments the data packet from the higher layer into appropriate RLC PDUs and passes them to the MAC layer. The length of RLC PDUs depends on the PHY modes. There are two kind modes of service: The Unacknowledged Mode for connectionless point-to-point, multicast and broadcast applications and the

Acknowledged Mode (AM) for reliable point-to-point applications. In short, the AM provides the in-sequence error free data service to the upper layer. A selective repeat Automatic Request (SR-ARQ), by taking advantage of the On-demand-TDD feature offered by the MAC protocol, is designed as the link layer error and flow control scheme for AM [2].

Multi-hop Support

In the cellular networks like GSM, GPRS and UMTS, transmissions take place between base stations and mobile stations. Each station allocates and maintains only one ARQ entity. Various connections share the ARQ entity. However in multi-hop networks, the situation becomes more complicated. A station needs to maintain several one hop connections in the RLC entity in parallel. The counterparts of the station are located in different places. Therefore the channel environment of the connection pairs might be substantially different. In order to achieve high transmission efficiencies, a station should use different parameters like PDU length, the polling period for different ARQ entities.

Radio Resource Control (RRC)

After receiving a connection setup request indication from the RLC, the RRC entity would consider to accept the request only after it determines that the current available TCH(s) can satisfy the QoS requirement of the connection and setting up the connection would not corrupt the QoS of established connections. Multi-hop connection requests would be evaluated by accounting for that a multi-hop connection consumes a multiplex time radio resource than a single-hop connection does. A distributed Connection Admission Control (CAC) mechanism is used to make the decision to accept or reject a link setup request.

W-CHAMB Conclusions

W-CHAMB is a TDMA/TDD based wireless broadband system, operating in a fully distributed manner on a single frequency channel. It is able to implement an advanced QoS support in multi-hop networks. The possible PHY layers are: IEEE802.11 a/g PHY, OFDMA, MC-CDMA, UWB and forthcoming high data rate transmission schemes.

The W-CHAMB protocol has a good capability to handle multiple distinct traffic flows and types in parallel, meeting the particular QoS requirements in multi-hop operation, while achieving the high channel utilization. The W-CHAMB protocol is a suitable link layer solution for future mesh WLAN systems providing high quality multi-media transmission services.

Conclusions

This white paper has presented some initial thoughts on mesh networks including a candidate protocol solution that is able to solve the problems of a mesh network. The presentation of the current activities inside IEEE802 has shown the importance of mesh networks for ubiquitous wireless internet access.

The presentation of the W-CHAMB has shown that mesh technologies also allow for QoS support, which will be an important feature for B3G radio network deployment. For the future some more contributions on mesh specific solutions are planned.

One hot topic for mesh networks is ***self organisation*** allowing for plug and play integration of nodes or in order to react on topology changes. This makes mesh networks robust against node failure allowing to them to provide a high degree of resilience.

Mesh networks must allow synchronisation over several hops without a central coordinating instance, i.e. decentrally. Therefore ***Synchronisation*** is another issue to be addresses by this white paper. In this context also the efficient utilisation of directed antennas has to be taken into account.

Naturally a mesh network has to provide the means to allow for ***Forwarding*** in terms of routing (L3) or bridging (L2).

The high connectivity of RAPs in a mesh networks and its related capability to access the destination nodes via different routes provides a higher flexibility in terms of ***Radio Resource Management (RRM)*** compared to networks with unique routes. To exploit this flexibility efficient routing mechanisms are required allowing for load balancing in the mesh network. The respective resource reservation schemes must guarantee sufficient QoS support.

As Spectrum is a scarce resource it is consequent to address the ***spectrum usage*** in this white paper. The identified sub topics are frequency re-use, as one route in a wireless mesh network might re-use the same radio resource and interference avoidance (or mitigation), e.g. by the coordination of radio resource across mesh nodes.

To demonstrate the feasibility of mesh networks it is intended to show some ***traffic performance*** measure highlighting the QoS support of fixed mesh networks. The traffic performance measure should include some references on spectrum efficiency and show the suitability for real time services.

Other interesting research issues in the context of fixed mesh networks could be the integration of cooperative relaying, which could take advantage of the possibility to use different routes towards the same destination.

Readers who are interested to contribute please contact the editor (dcs@coments.rwth-aachen.de).

REFERENCES

[1] R. Pabst, B.H. Walke, D.C. Schultz, P. Herhold; H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott. W. Zirwas, M. Dohler, H. Aghvami, D.D. Falconer, G.P. Fettweis., "Relay-based deployment concepts for wireless and mobile broadband radio", *IEEE Commun. Magazine*, pp. 80-89, September 2004.

[2] Zhao, Rui and Walke, Bernhard, "Traffic Performance of the Wireless Channel-Oriented Ad-hoc Multi-hop Broadband System", In Proceedings of the 2004 IEEE 60th Vehicular Technology Conference, p. 5, Los Angeles, 09/2004,

[3] Zhao, Rui and Walke, Bernhard, "A synchronization scheme for the Wireless Channel-oriented Ad-hoc Multi-hop Broadband system (W-CHAMB)", In Wireless World Research Forum, Zurich, Switzerland, 07/2003,

[4] Dirk Galda, Niclas Meier, Hermann Rohling and Martin Weckerle: System Concept for Self-Organized Single Frequency OFDM Network, Proc. of the 8. International OFDM-Workshop,Hamburg, Germany, 2003

[5] IST-2003-507581 WINNER "D2.3: Assessment of Radio-link technologies", Feb. 2005-06-13

[6] IST-2003-507581 WINNER www.ist-winner.org

[7] IEEE standard for Wireless LAN- Medium Access Control and Physical Layer Specification, P802.11, November 1997.

[8] IEEE 802.16-2004, "IEEE Standard for local and metropolitan area networks --- Part 16: Air Interface for Fixed Wireless Access Systems, October 2004.

[9] ETSI, Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Data Link Control (DLC) Layer.

[10] IEEE 802.11e/D8.0, Medium Access Control (MAC) Quality of Service (QoS) Enhancements, Feb. 2004.

[11] S. Mangold, S. Choi, G. Hiertz, O. Klein and B. Walke, "Analysis of IEEE 802.11 for QoS Support in Wireless LANs," In IEEE Wireless Communications, Vol. 10, pp. 2-12, Dec. 2003.

[12] B. Xu and B. Walke, "A New Air Interface Concept for Wireless Multimedia Communications beyond the 3rd Generation," Wireless Personal Communications Vol. 23, No.1, pp. 121-135, Oct. 2002.

[13] M. Lott and B. Walke, "Performance of the Wireless Ad hoc Network W-CHAMB," in Proc. European Wireless (EW'99), Munich, Germany, Oct. 1999

[14] W. Rhee and J. M. Cioffi, "Increase in Capacity of Multi-user OFDM System Using Dynamic Subchannel Allocation," in Proc. IEEE VTC Spring 2000 Tokyo, Volume: 2, pp. 1085 -1089, May 2000.

[15] S. Hara and P. Prasad, “Overview of Multi-carrier CDMA,” IEEE Comm. Magazine, Vol.35, no. 12, pp. 126-133, Dec. 1997.

[16] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs): Multi-band OFDM Physical Layer Proposal for IEEE 802.15 Task Group 3a. 10. Nov. 2003.

[17] F. A. Tobagi and L. Kleinrock, “Packet Switching in Radio Channels: Part II—The Hidden Terminal Problem in Carrier Sense Multiple-access and the Busy-tone Solution,” IEEE Trans. Commun., Vol. COM-23, pp. 1417–1433, Dec. 1975.

[18] RFC 2598 - An Expedited Forwarding PHB, June 1999.

[19] IEEE 802.11a: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-speed Physical Layer in the 5 GHZ Band.