WWRF/WG4 Relaying Subgroup

White Paper

"Relay-based Deployment Concepts for Wireless and Mobile Broadband Cellular Radio"

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Relay-based Deployment Concepts for Wireless and Mobile Broadband Cellular Radio

Abstract

In the last few years, there has been quite an interest in multihop-augmented infrastructure-based networks in both industry and academia, such as the “seed” concept in 3GPP, coverage extension of HiperLAN2 through relayers, user-cooperative diversity LMDS/MMDS mesh networks. This White Paper presents an overview of the concepts and applications of relaying. Its scope covers different approaches of exploiting the benefits of multi-hop communication via fixed or mobile relays:

- Multi-Hop Solutions for radio range extension in mobile and wireless broadband cellular networks (trading range for capacity)
- Multi-Hop Solutions to combat shadowing at high radio frequencies
- Multi-Hop as a means to reduce infrastructure deployment costs. (Relays can be assumed to be cheaper than Base Stations).
- Multi-Hop to enhance capacity in cellular networks
- Multi-Hop as a means to ensure connectivity in ad hoc networks is NOT in the scope of this White Paper. It is dealt with by the WWRF WG4 White Paper on Ad Hoc Networking [14].

Other multi-hop related issues like Security and Authentication are currently not in the scope of this White Paper, but may be included in later versions.

Content

1 Introduction

Future cellular networks are envisaged to be able to provide ubiquitous high rate services that are achieved by novel air-interface technologies as well as through novel network architectures such as pico-cells, hierarchical cells or multiple hops. Multihop wireless networking has traditionally been viewed in the context of ad-hoc and peer-to-peer networks. We consider the application of multihop networking in wide area cellular systems and look at potential capacity enhancements and other possible benefits.

Relays are network elements that are dedicated to storing and forwarding data received from the base station to the user terminals, and vice versa. Like user terminals, they are not connected to the wireline network through a back-haul connection, but have to rely on wireless transmission to communicate to the base station. Relays may have additional transmission power compared to terminals and yet be much lower in cost compared to a base station because of their very limited functionality. Deploying relays can clearly help improve the performance for users near the edge of the cell and have the potential to solve the coverage problem for high data rates in macro-cells. Since it is possible to have simultaneous transmission by both the base station and the relays, capacity gains may also be achieved. Cellular-relay networks could be such that the relay to user links use different spectrum than base to user links. For example the relays could communicate to the users through a wireless local area network such as the IEEE 802.11 network, in which case the relays are like access points and use the unlicensed band, while the base station transmits to the relays using the cellular network spectrum. Such a cellular-relay network has been proposed in [13] where the authors show significant gains from load balancing through the relays.

Relays can be viewed as a special case of ad hoc networks, which are networks where any network node can communicate with any other network node. In an ad hoc network every terminal in the network is allowed to transmit packets meant for other terminals in the network. In such a scenario the gains depend on the number of active terminals that are available and their locations. Furthermore, a distributed algorithm would be required for routing and scheduling of packets between different nodes of the network because of the large number of nodes involved. We envision the cellular multi-hop network to be one in which a small number of relays are made available in the network, presumably in the hot spots, by the wireless service provider. These relays can thus be more powerful than the terminal nodes and centralized scheduling is plausible. Since these relays are not tethered they can potentially be moved as the traffic patterns change over time. The asymptotic results on multi-hop networks thus do not provide any insight on the potential gains in the case of small number of relays that is of interest. We resort to simulations to evaluate the potential performance gain and its dependence on various system parameters.

Relays in a cellular system can enhance performance for two reasons. Firstly, distributed placement of relays within the cell reduces the propagation losses between the relay transmitters and the user terminals, resulting in larger link data rates. However, some of this gain can be somewhat offset by the fact that the base has to first transmit to the relay using the same spectrum. The other important reason for expecting performance gains is the reuse efficiency that comes from multiple simultaneous transmissions within the cell from different relays to users. The simultaneously transmitted signals do interfere with each other, thereby reducing the link rates. Thus a careful choice of which links (base to relays or user terminals and relays to user terminals or other relays) are active during each time slot is necessary for optimum performance, leading to further increased importance of the research in the area of Medium Access Strategies.

2 Cellular systems with fixed relays - infrastructure-based relaying

As a prototypical example for radio network deployments which use fixed relays, this section introduces a new radio access network architecture for a mobile broadband system that uses Fixed Wireless Routers (FWR) to provide radio coverage to otherwise shadowed areas. Highest spectrum capacity and lowest possible transmit power as main targets will be reached by using low power (1 W) pico base stations using a wireless or mobile broadband air interface at Access Points (AP) to the core network and at FWRs to trade the high capacity available at APs against radio coverage range. The Wireless Media System (WMS) will provide broadband access to terminals with medium velocity of movement and is embedded into a cellular radio network to support a high velocity of terminals with medium transmission rate. The low power used at the base stations leads to a pico-cellular concept relying essentially on multi-hop communication across fixed wireless bridges or routers and to some extent also on ad-hoc networking. The new concept to achieve broadband radio coverage in densely populated areas is described and first traffic performance analysis results of some crucial elements are presented. See [1][2][4][5][11][12]

The Wireless Media System (WMS) [1] is based on the integration of a cellular mobile broadband system for “hot area” coverage with a modern cellular mobile radio system for large area coverage. The WMS is aimed to have a very high multiplexing rate of about 100Mbit/s at the air interface for medium velocity terminals and high deployment flexibility through the use of mass production building blocks. The known candidate spectrum bands for operation of the new systems, e.g., beyond 3 GHz and most probably even beyond 5 GHz will allow an equipment size for pico cellular base stations (Access Points, AP) and Fixed Wireless Routers (FWR), including the antenna, so small that the radio network infrastructure can be termed more or less “invisible”. A FWR serves to extend the radio range and coverage of an AP to otherwise shadowed areas and will use either zentral or decentral control of the nodes involved, as described in [32]. Both, AP and FWR use 1 W EIRP transmit power outdoors and 200 mW indoors. The WMS will be embedded into a cellular high velocity supporting mobile radio network with medium transmission rate that will evolve from current 3G technology and is expected to use a new air interface and an IPv6 based fixed core network that is shared with the WMS. The discontinuous radio coverage available from the WMS will be hidden to a maximum degree to the users by an Intelligent Service Control (ISC) so that the subscribers are provided the contents they need within given time limits, however, the ISC description is not part of this presentation.

2.1 System Concept of the Wireless Media System

The Wireless Media System (WMS) [16][19][20][31][34] is based on Wireless Broadband System (WBS) technology that stepwise will be further developed to become a Mobile Broadband System (MBS). The WMS relies on multi-hop and to some extent on ad-hoc networking concepts in a pico-cellular infrastructure to provide a well defined Quality of

Service (QoS) to applications running on mobile terminals. Figure 2 shows by means of an example the discontinuous radio coverage available from the WMS in densely populated areas. The small pico cells highlighted around the pico base stations called Media Point (MP) shown in the circular areas called Media Point Sub-network represent areas where broadband radio coverage is available.

Narrowband and broadband access networks are integrated into a Beyond 3G system (shown by means of large hexagonal cells) with their characteristic functions like subscriber identity module (SIM), authentication, authorization and accounting (AAA) and localization available to both types of network. This is what the concept distinguishes from the Infostation concept [23] that considers a pure wireless broadband system deployment without integration into a mobile radio system.

The radio part of the WMS is characterised by

- A new air interface with data rates of up to 100 Mbps at terminal speed up to 60 km/h
- Dynamic channel selection, link adaptation, power control, smart antennas and re-configurable terminals
- Small (“Invisible”) base stations, called Media Point, “Hamburger sized” (including antenna) mounted below roof top (say on signal posts or in street lamps) with low EIRP used.
- Radio coverage provided by MPs operating either as Access Points to the core network or as Fixed mounted Wireless Routers (FWR) in a pre-planned multi-hop communication based infrastructure
- Multi-mode re-configurable terminals and base stations
- Smart antennas and beam forming at terminals and base stations (MP and FWR) for higher spectrum efficiency and lower radio exposition of humans
- Ad-hoc operation of the mobile broadband terminals at the periphery of the WMS.

The feeder systems connecting APs to the fixed network are either wire/fibre based or wireless, e.g., Point-to-Multipoint (PMP) LOS radio systems or HAPS (High Altitude Platform System) feeding MPs using directed (smart) antennas, see Figure 2 Some MPs are wirelessly connected to other MPs to reduce the number of Access Points (AP) needed to connect to the fixed telecommunication network. Wireless MPs are called Fixed Wireless Routers (FWR). In Figure 2 the radio coverage areas served by FWRs are shown in a colour different from that of the APs. Both, APs and FWRs appear to mobile terminals like base stations to connect to the WMS.

The WMS infrastructure is aimed to be very cost efficient and flexible to use, e.g. using multi-hop radio relays (bridges or routers) to connect MPs to the network, thereby trading the too high traffic capacity available from an APs against range of radio coverage.

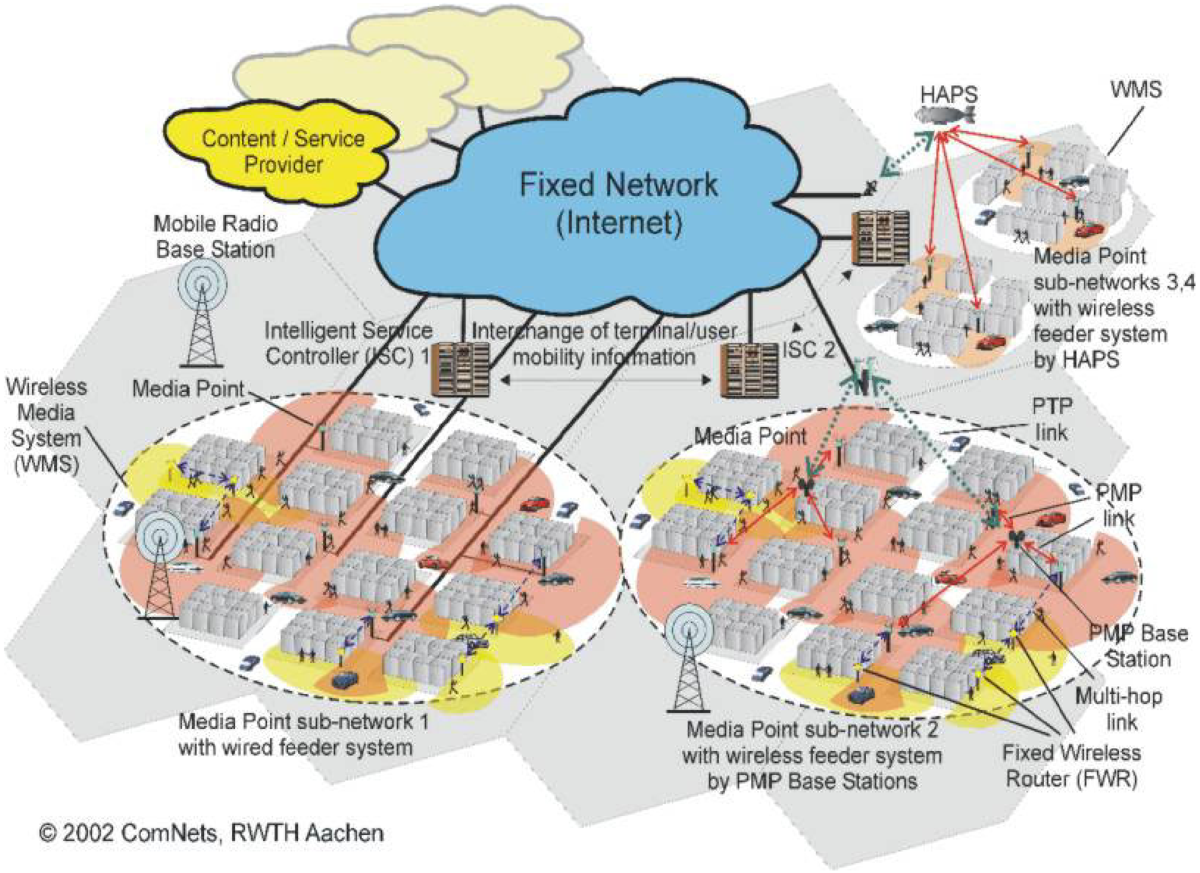

Figure 1: Wireless Media System and mobile radio integrated

2.2 Most Important Features of the Wireless Media System

The WMS will provide broadband radio access in densely populated areas using low power wireless/mobile broadband base stations (MPs) built up in a quasi-cellular radio network like layout to support mobile terminals. During a first phase of the system introduction, the speed of movement of terminals when communicating over the WMS, will be quite limited. In a second phase, after a new broadband radio interface has been developed, the speed of movement will be up to about 60 km/h or even more. The system will support any kind of communication service, e.g., voice, video, data with the appropriate service specific Quality of Service (QoS) parameters. This system will cover the needs of future mobile broadband systems that has been estimated to be characterized by a very high asymmetry of data traffic with an especially high load on the downlink, compared to the uplink, see Figure 2.

The high asymmetry shown comes from the transport of high bit rate multi-media contents and - to a small extent - from medium bit rate multi-media services. The goal is to carry in densely populated areas most of the high and medium bit rate multi-media traffic by the MPs of the WMS. In addition, some amount of the other traffic classes (like voice) also can be carried by the WMS. The WMS that relies on pico cells with a cell radius of a MP quite below 100 m (but a much larger range under line-of-sight (LSO) conditions up to 1 km) and is able to generate at least a ten to hundred-fold area capacity compared to 3G systems assuming the same width of the frequency band used.

Since the WMS will use a much wider spectrum range than cellular radio will ever get for operation, the capacity of the WMS will be multiple orders of magnitude larger.

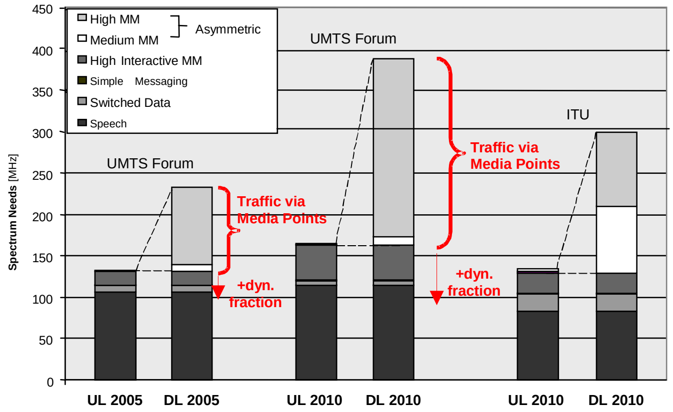

Figure 2: Predicted spectrum needs for UMTS per traffic class from UMTS-Forum and ITU-R

The mobile terminal which must be able to support both, mobile cellular radio and the WMS air interfaces, but not at the same time is shown in Figure 3. Instead of the two buttons (red and black) shown in the figure, a terminal internal agent will decide what air-interface to use at what location and for what type of service. The agent might decide to load high volume data preferably via the broadband air interface and wait for a radio connectivity for some time duration, since the broadband over WMS service is deemed to be much cheaper that over the 3G network. The agent also might decide that voice and other real-time oriented services will be provided via the WMS air interface if the mobile terminal has radio connectivity to it and is not moving very fast.

An operator of a WMS integrated to a cellular mobile radio system might apply a mixed cost calculation to be able to trade the low cost for transporting mass data via the WMS against the high cost of data transport across the cellular system. And he might end up with a very attractive tariff for all of its services compared to an operator purely relying on 3G technology.

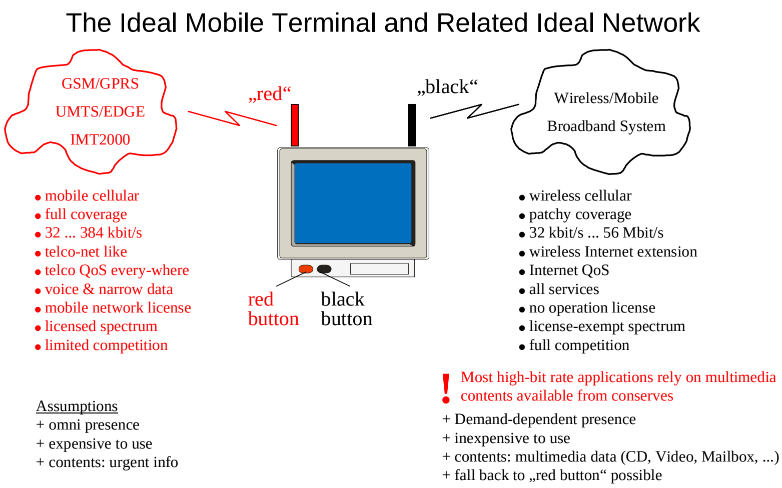

Figure 3: A multi-mode mobile terminal to support both, cellular mobile radio and the WMS

2.3 Multi-hop Operation of the Media Points

Multi-hop ad-hoc networking is under discussion to improve the range and radio coverage of mobile and wireless systems. Self-organization of mobile nodes is one big issue in current research, see [15],[32].

Figure 4 (left) shows a city scenario with

- one AP (providing radio coverage to the areas marked white) and
- four FWRs to provide radio coverage to areas “around the corners” shadowed from the AP, shown in grey .

According to the radio propagation conditions known for the 5-6 GHz frequency band [27], there is nearly no diffraction and waves reflected from obstacles have a much higher attenuation than with lower frequencies. Therefore, the intersection shown can be covered well by the AP but the close by streets can only be served if a line-of-sight connectivity is available between mobile terminal and serving MP. The FWRs allow to extend the radio coverage to the streets shadowed from the AP (around the corner).

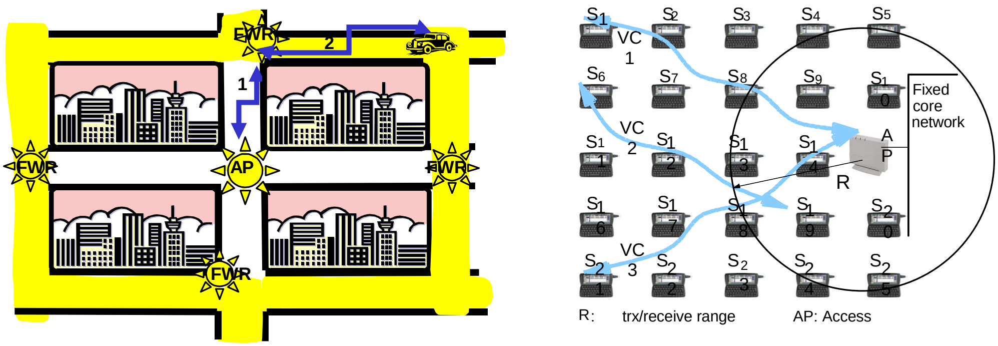

Figure 4: City scenario (left) with one AP (radio coverage in white area) and four Fixed Wireless Routers covering the shadowed areas “around the corners” shown in grey and schematic (right).

A schematic of this scenario - a multi-hop network with Access Point (AP) - is shown at the right hand side of Figure 4 where the transmit/receive radius R is shown to be the parameter determining the connectivity c of the nodes shown, where N is the total number of nodes and ni is the number of neighbour nodes to a node. A FWR (S1) would have to route the traffic of the wireless terminals it is serving (not shown) via the intermediate FWR (S8) using a low valued PHY-mode, or via S2 and S8 using a high valued PHY-mode, and so forth from S8 either via S9 or directly to the AP. The interpretation of the Figure 4 right hand multi-hop network is that all the nodes shown are either FWRs or APs and the invisible mobile user terminals roaming in the area are served by the nodes shown.

3 Cellular systems with mobile relays – Ad Hoc Relaying

3.1 Ad-hoc Network Operation in the WMS Access Network

An ad-hoc network has a completely distributed architecture with dynamic allocation of network and network node identifiers. In contrast to a wired network, self-organizing networks using the same radio channel cannot be separated from one another. The range of any node is restricted and networks can be fragmented under unfavourable propagation conditions. Independent ad-hoc networks do not communicate to each other and do not share the same communications medium, i.e. there is no interference between the networks. Overlapping ad-hoc networks share the same medium and contain some nodes being in the receive or interference range of the respective other network. Hidden stations can cause unpredictable interference that is difficult to control. Nodes may receive data with network IDs of a foreign network.

Multi-hop ad-hoc networks contain some nodes able to perform the function of routers. 4th generation systems will transmit packets multi-hop across mobile routers under multiple access conditions. Hidden stations are part of the concept. Applications running on nodes of ad-hoc networks in most cases need to be connected to wired networks to make a sense. This affects the network layer (routing) protocols.

ETSI-BRAN/HIPERLAN_1 and IEEE 802.11 contain the elements to operate ad-hoc networks, esp. addressing, forwarding, power conservation, security, routing information exchange, Hello procedures, topology control, multipoint relay functions. ETSI/HiperLAN_2 in the Home Extension contains an ad-hoc mode of operation that allows the nodes to agree on a Central Controller (CC) to take the role of an AP in a cluster of nodes, but no multi-hop functions are specified so far. Multi-hop operation based on wireless routers that operate alternating on different frequency channels to connect neighboured clusters has been proven to be workable, too [24]. In the HiperLAN_2 basic mode (using an AP) it has been shown that multi-hop operation is easy to perform without changing the standard [21]. ETSI/BRAN has not taken up ad-hoc networks so far as a working issue but has postponed the respective studies for later.

Neither measures to organize the coexistence of ad-hoc networks in a proper and well-defined way nor the network layer functions to be able to guarantee some quality of service are available so far; some first work on this has been published recently [28].

Studies on radio based ad-hoc networks for packet radio applications range back to the 70-ies, e.g., [TK1975], studies for telecommunication applications range back to the 80-ies, e.g., [32]. Besides others recent results have been published in [33], [30] and [36].

The WMS is also envisaged to allow an ad-hoc component of operation for its mobile terminals.

3.2 Mobile Relays to enhance Capacity and Range of cellular networks

3.2.1 State of the Art

No intelligent relaying concept has been adopted in existing cellular systems so far. Solely bidirectional amplifiers have been used in 2G systems and will be introduced for 3G systems. Yet, these analog repeaters increase the noise level and suffer from the danger of instability due to their fixed gain. Both drawbacks have limited their application to specific scenarios.

Most existing and standardized systems were designed for bidirectional communication between a central base station and mobile stations directly linked to them. The additional communication relation between mobile terminals in relaying systems, however, calls for resources to be allocated to this relation - one of the facts that have prevented the introduction of smart relaying concepts so far.

TDMA-based systems are especially suited for relaying as the existing time division scheme allows for an easy allocation of resources to the mobile-to-mobile links. One possible approach is to use the timeslot allocated to a relaying station for the communication with the associated remote mobile terminals. This essentially requires subdividing this slot [37] [1], which in turn causes a significant reduction of the system throughput [21] [2]. Another method proposed for F/TDMA systems is to reuse a channel (frequency and time slot) from neighboring cells [38]. Other publications complement the research for relaying in TDMA networks.

The possibility of relaying in cellular CDMA-based systems is investigated by Zadeh et al. [39]. Uplink and downlink are separated using frequency division duplex, as it is done in IS-95 or UTRAN FDD. Due to this limitation of the number of available frequencies, operating the relaying links at a different carrier is not possible. Instead, a time division scheme is introduced, in which a relay station transmits and receives at the same carrier in an alternating manner.

With respect to relaying in the UTRAN, Opportunity Driven Multiple Access (ODMA) was believed to improve system coverage and possibly enhance capacity [40]. Yet, ODMA content was removed from the specifications in the March 2000.

A completely different approach is considered in [41] by incorporating an additional ad-hoc interface into the GSM protocol stack to enable relaying through this newly created interface. Similarly, Wu et al. [42] employ relaying stations to divert traffic from possibly congested areas of a cellular system to cells that exhibit a lower traffic load. These relaying stations utilise a different interface for communication among themselves and with mobile stations, which could for example be provided by a wireless LAN standard.

Besides expected improvements at system level, relaying has the capability of significantly enhancing spatial diversity as discussed in [43].

To summarize, relaying is broadly considered as a method to complement capacity and coverage in cellular systems. Despite the fact that currently introduced systems are CDMA-based, there has been a strong focus on relaying in TDMA systems. But as CDMA systems will take over the role which 2G systems play today, this calls for more active research on the relaying possibilities in cellular CDMA systems.

3.2.2 Introduction

Simple calculations indicate that the provision of the very high data rates envisioned for the 4th generation (4G) wireless systems in reasonably large areas (i.e., beyond small disconnected pockets) does not seem to be feasible with the conventional cellular architecture due to two basic reasons.

First, the transmission rates envisioned for 4G systems are as high as two orders of magnitude more than those of the 3G systems; and, it is well know that for a given transmit power level, the symbol (and thus bit) energy decreases linearly with the increasing transmission rate. Secondly, the spectrum that will be released for 4G systems will almost certainly be located well above the 2 GHz band used by the 3G systems. The radio propagation in these relatively high bands is significantly more vulnerable to the non-line-of-sight conditions, which is the typical mode of operation in today's urban cellular communications. One very recent paper predicts that the above two conditions will impose a 30 dB shortage in the radio link budget of 4G systems to be deployed beyond 2010 [29].

The brute-force solution to the above described problem is to increase the density of the base stations significantly. However, this will result in a considerably higher deployment cost which will only be feasible if the number of subscribers also increase at the same rate. It should be noted that the rate of increase in the number of subscribers is expected to be rather mild since this number is upper limited by the population, and the penetration of the cellular phones is already quite high in the developed countries. On the other hand, that same number of subscribers will have a much higher demand in transmission rates. Consequently, the bottleneck in future wireless systems will be the throughput (aggregate rate) demand rather than the need for extra capacity. Under these conditions, a drastic increase in the number of base stations is not economically justifiable.

In recent years, there has been significant advances in transmission technologies (such as coding and modulation), as well as in collocated antenna architectures which are generally referred to as smart antennas (such as MIMO and adaptive antennas). Although incorporation of these techniques in future wireless systems is crucial, for practical reasons, these techniques alone do not seem to be sufficient for enabling almost-ubiquitous very high data rate coverage. For instance, in the presence of heavy shadowing, even the smartest antenna does not provide much help (besides, it may be infeasible to deploy complex antenna systems at wireless terminals). And, the performance returns due to advanced coding and modulation techniques do not go beyond a few dBs at most.

It is obvious from the above discussion that more fundamental enhancements are necessary for the very ambitious throughput and coverage requirements of the future systems. Towards that end, in addition to advanced transmission techniques and collocated antenna technologies, some major modifications in the wireless network architecture itself, which will enable effective distribution and collection of signals to and from wireless users, are sought. The integration of multihop capability in conventional wireless networks is perhaps the most promising architectural upgrade (in the rest of this contribution, the terms “multihop” and “relaying” will be used to refer to the same concept).

“It is worth emphasizing the basic difference in the fundamental goal of the conventional ad hoc and the described multihop-augmented infrastructure-based networks: while the defining goal of the ad hoc networks is the ability to function without any infrastructure, that goal in the latter types is the almost-ubiquitous provision of very high data rate coverage and throughput.”

In this section peer-to-peer relaying in cellular networks is considered due to the great appeal of avoiding seeds (which has the obvious advantage of not necessitating any additional infrastructure). Various relayer selection algorithms are considered and their high data rate coverage levels are evaluated through extensive simulations.

3.2.3 Observed Trends

Initial research [6] has indicated that with the proper relayer, relaying channel, and relayer power selection, a significant enhancement in high data rate coverage can be attained. The observed trends are:

- Performance returns due to relaying increases as the number of users in the system increases.
- Relaying with no power control is still better than no-relaying with power control. Employing power control in a relaying system further enhances the performance, especially as the cells get smaller; the returns due to power control become substantial in the interference-limited cells (400x400 m) in comparison to those in the noise-limited types (2x2 km).
- The maximum relayer transmit power level is an important factor only in large cells, where the higher this level is the better the performance is; but in small cells most of the benefits are gained with relatively small relaying transmit power levels.
- The performance returns are quite sensitive to the relayer selection criterion. If the relayers are chosen randomly, the performance gets worse in comparison to the no-relaying case (this is analogous to the case where a user is connected to a wrong base station). Yet, highly suboptimal (with minimal intelligence) but implementationally feasible relayer selection schemes (such as relayer selection based solely on proximity) still yield significant coverage enhancements.
- On the other hand, the performance returns are quite insensitive to the relaying channel selection criterion; the difference in performance between the random and smart channel selection criteria is insignificant (provided that the relayers are selected properly).

3.2.4 Conclusions

From the above trends the following encouraging conclusions can be driven:

- In systems with limited resources for monitoring and control purposes, the priority should be given to proper relayer selection rather than proper relaying channel selection. Since selecting a good relayer will most likely be much easier than selecting the best relaying channel, we may conclude that the relaying system will be quite robust. (For instance, through the use of the GPS data available at the base stations, distance-based relayer selection scheme can readily be implemented.)
- Power control should be employed whenever possible. Since power control is a very well understood technique which has been used in cellular systems for at least a decade, its implementation will not be a problematic issue. It should also be noted, however, that since the future systems be packet-based (such as TCP/IP), transmissions and interference will likely be relatively unpredictable and bursty. This will certainly influence channel selection, and may make power control unimportant.
- The impact of relaying on wireless terminals' batteries may not be that significant in microcellular systems.

The overall conclusion from the above stated trends is that equipping the wireless terminals with relaying (multi-hop) capability constitutes a very promising technology in delivering high data rates in a cost-effective manner in future wireless systems.

3.2.5 Future Work

A thorough investigation of the concept of relaying is an enormously complex task due to the very many parameters involved, including propagation and physical layer issues, systems issues including multiple access and radio resource management, networking and protocol issues, and finally implementation-related issues. Moreover, since there is still not too much material in the literature, the analytical understanding of the subject is also far from being comprehensive.

The following areas are considered to be of key importance in future research:

Virtual Arrays and Novel Diversity Schemes: The aim here is the possibility of developing novel diversity schemes. The concept of "cooperative diversity" (receiving the same signal from two or more routes) has already been discussed in the literature [8]-[10]. The idea of forming "virtual arrays" has very recently been addressed conceptually without any quantitative analysis [14]. In particular, we are interested in studying the feasibility of creating "virtual (distributed) MIMO systems", that is, a MIMO array created by utilizing the distributed relayer antennas in the network.

Multiple Access Techniques: Our intend here is to determine whether a particular set of multiple access and multiplexing schemes is inherently better suited for cellular relaying networks. He will consider both single-carrier (CDMA and TDMA) and multi-carrier (OFDM and MC-CDMA) schemes in the framework of non-random multiple access. We will also compare and contrast frequency-division and time-division duplexing techniques. All possible combinations (including hybrids) of these multiple access and multiplexing schemes will be studied. The terminal complexity will also be taken into account (e.g.: wireless terminals with relaying capability may be substantially more complex; in CDMA systems, for instance, an almost linear increase in hardware with respect to the number of simultaneous relayings is likely since parallel transceivers will be required).

Analog versus Digital Relaying: In digital relaying, the intermediate nodes detect and decode the received signal before re-encoding and retransmitting it to the next node. In analog relaying, on the other hand, the relayers just amplify and retransmit the received signal. Although one may be tempted to think that digital relaying would be superior to analog relaying due to the elimination of the noise propagation, our recent research [10] on the physical layer performance comparison of various multihop channels indicates that this is not necessarily the case since a digital multihop channel may be limited with the hard detection at the worst hop which may cause a bottleneck. Our goal here is to compare and contrast both types of relaying (i.e., analog and digital).

4 Forwarding Principles

This section presents a variety of technical options which are important in the context of relaying (see Figure 5):

Figure 5 shows the 3 basic options to choose from to implement relaying in a fixed infrastructure setting. The same principles apply to mobile relays:

a) Relaying in the time domain with both, AP and FWR, operating at the same carrier frequency f1

b) Relaying in the frequency domain where AP and FWR operate on different frequency carriers. The radio link between AP and FWR is based on LOS radio with transmit and receive gain antennas at AP and FWR. AP and FWR have to be in synchronous operation to be able to switch the frequency accurately.

c) Relaying in the frequency domain where a fixed mounted forwarding terminal that is in the range of both, AP and FWR, connects AP and FWR by store and forward operation and dynamically switches its membership to frequency carrier f1 or f2. AP, FWR and forwarding terminal might use both, transmit and receive antenna gain [24].

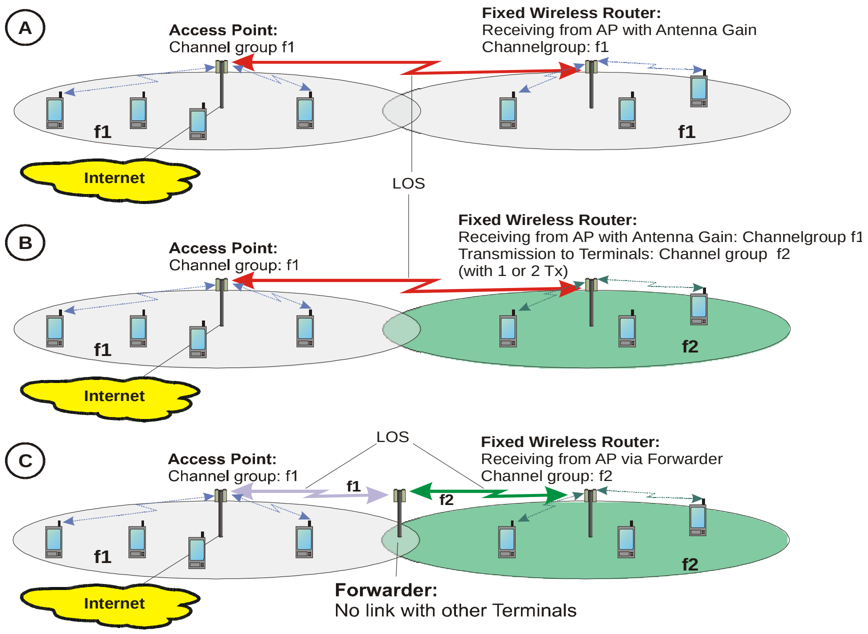

Figure 5: Various relay concepts based on Fixed Wireless Routers

All 3 forwarding principles are not exclusive to infrastructure based relaying but can also be applied with mobile relays. Also see [2]

The concept of the Fixed Wireless Router that also could be a Fixed Wireless Bridge (a Layer 2 relay) can be realized for example as described in [18][21] for the HiperLAN2 standard. Figure 7-Figure 10 show analytical and simulation results according to that solution. There are other possibilities to realize the FWR concept as shown in Figure 5.

A WMS architecture with one AP and four FWRs, as shown in Figure 4 (left), might be a basic architecture element used to cover a densely populated area. In that case, assuming a homogeneous distribution of user terminals in the service area, the capacity available from the AP would have to be shared with the FWRs: all of the mobiles roaming in the combined service areas of the AP and the four FWRs will have to share the capacity of the AP. This would mean that the terminals served directly by the AP would have available only a reduced amount of capacity, exactly what is aimed at by introducing the FWRs. Whilst the basic element shown in Figure 4 applies a maximum of 2 hops per connection, larger elements with one AP and 12 FWRs can be thought of using up to e hops, as shown in Figure 6.

There it is shown how the basic elements of Figure 4 are used to provide a city wide radio coverage. Of cause, the same schemes also could be used to provide a planned indoors radio coverage, e.g., for exhibitions, conference halls, hotels, etc. An AP is shown in the left hand side of the figure that serves four (twelve, in the second case) FWRs. The resulting element using one frequency (or frequency group) to cover a number of adjacent streets is applied in the right hand side scenario to provide a full radio coverage using this basic element and two (groups of) frequencies. It can be shown that this is already a workable wireless broadband system for outdoors, providing more or less the same throughput at any location in the basic i-hop cell element (i = 1, 2, 3,..) [22].

The bit rate over distance from an AP that is supported by FWRs to extend the radio coverage range for the approach according to Figure 5a) is shown in Figure 7, schematically. If the FWR1 would not have a receive antenna gain, it would have available only a bit rate equivalent to the value b [Mbps] instead a [Mbps] that would be available with receive antenna gain. A similar consideration applies to FWR2 and FWR 3.

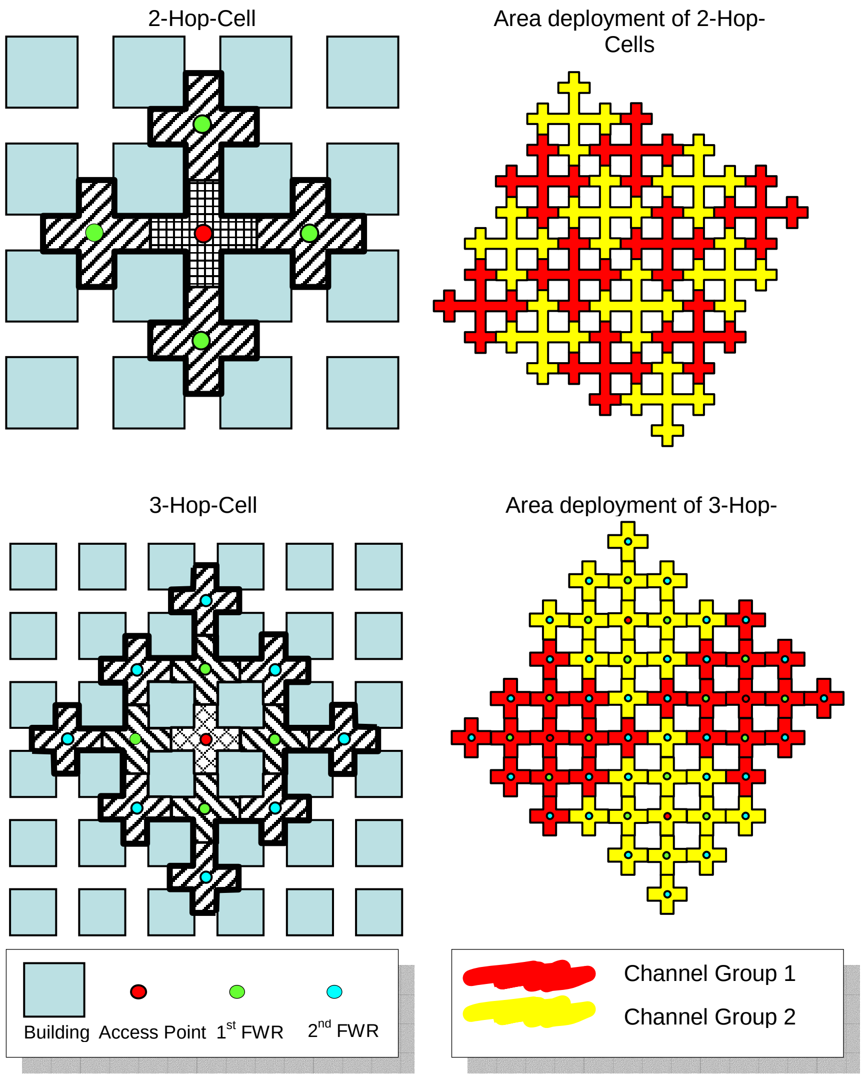

Figure 6: Full Manhattan city radio coverage based on the left hand basic element with one AP and multiple FWRs and two frequencies used [2][22]

Figure 9 shows for the approach shown in Figure 5a) the end-to-end throughput between an AP and a Remote Mobile Terminal (RMT) that is located in a distance d for different modulation and coding schemes known from the air interface of HiperLAN2 or IEEE 802.11a [22]. The RMT is shadowed by a building at the street corner and is therefore connected “around the corner” with the help of a FWR. The shaded area under the curves in Figure 9 shows the gain in throughput possible from the use of the FWR without which the RMT could not be connected to the AP. It can be seen that the range extension resulting from using the FWR is substantially large.

Recent work has proven that the capacity of an AP when using a modem as standardized for HiperLAN2 and IEEE 802.11a is much too large, compared to the communications traffic needs of mobile terminals expected in its pico cell area resulting from omni-directional or sector antennas and a power of 1 Watt EIRP allowed for these systems [29].

It is worth noting that smart antenna technology at the AP or mobile terminal cannot contribute to provide a radio coverage to shadowed streets: the FWR is the only technology able to do that.

The FWR concept can also be used to extend the range of an AP to non-shadowed areas as shown from our simulation results for HiperLAN2 according to the scenario in Figure 5a) in Figure 10. It can be seen that the radio range can be dramatically increased, especially, when using receive gain antennas at both MPs involved. Smart antennas and beamforming to reduce the path loss between AP and the FWRs and to support multiple FWRs to transmit(receive to/from the AP at the same time are known for a long time, see [BW1985].

From both, Figure 9 and Figure 10, it is apparent that the FWR based WMS architecture is scaling very well in that it is able to make available the traffic capacity of an AP to a small (pico) or much larger (micro) cell built up from many pico cells generated from the AP and its connected FWRs by using multi-hop communication. The results shown in Figure 9 and Figure 10 address the throughput available at remote MPs by extending the range of an AP to FWRs and does not say anything about the traffic capacity available to mobile terminals roaming around an AP or FWR.

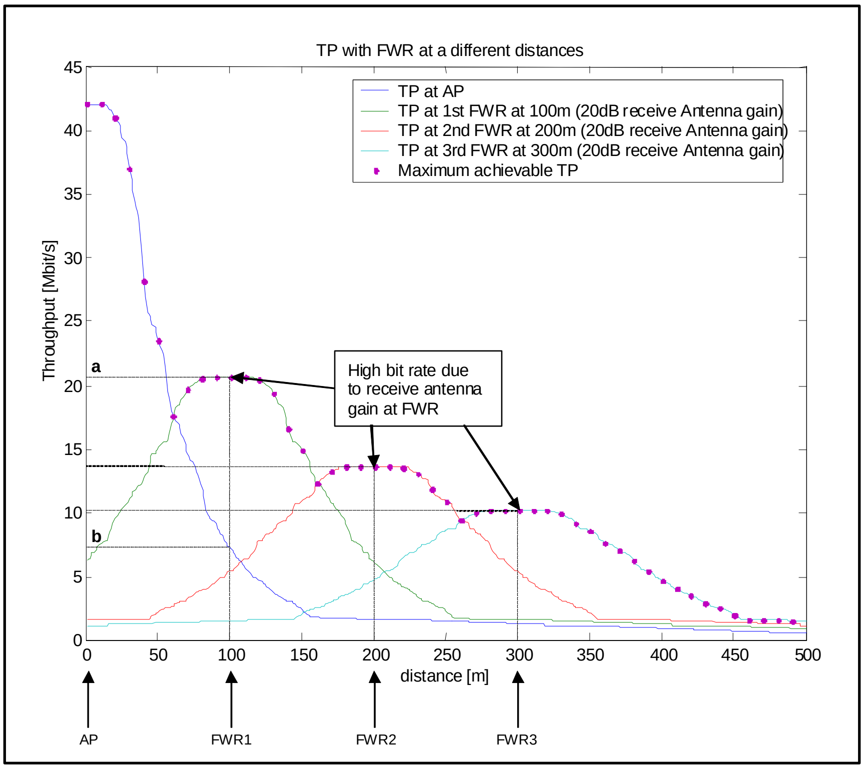

Figure 7: Extension of the radio range of an AP by Fixed Wireless Routers with receive antenna gain

5 Routing-, Protocol- and Performance-Issues

This section focuses on protocols for multi-hop networks and gives some insight into Traffic performance aspects. Of utmost importance for multihop communications are:

1) Routing protocols

2) Radio Resource Management (RRM) and Medium Access Control (MAC) Protocols:

3) Efficient Service Provisioning in Wireless/Mobile Broadband Networks with patchy radio coverage. See [3].

5.1 Routing

A routing protocol is required for establishing multi-hop paths in ad hoc networks. There are many IP-based protocols available for fixed networks e.g., RIP, OSPF etc but they are not well suited to ad hoc networking environment. Routing protocols for mobile ad hoc networks (MANETs) have to satisfy some highly contrasting requirements. Since there is no fixed infrastructure, the routing protocol should be distributed in nature.

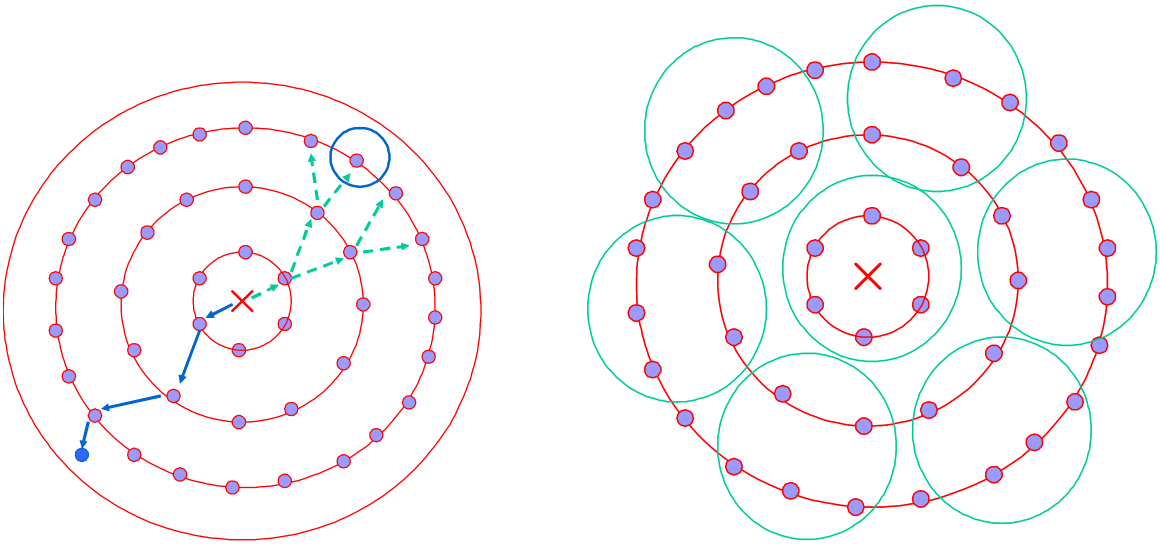

Figure 8: left: Regular Placement and Geographic Routing
right: Reuse Advantage - With increasing number of relays the size of each relay region decreases - transmit power can be reduced

Most of the publications state that the protocol overhead associated with establishing and maintaining the relaying routes may become severe, thus possibly eliminating the use of true *multihop* techniques. Limiting the number of hops, i.e. eventually employing just a *single intermediate relay* station, is expected to greatly simplify the associated design challenges.

5.2 *RRM and MAC*

5.2.1 Medium Access - Traffic Performance and Capacity Analysis for the WMS

A scenario according to Figure 4(right) has been studied in [35] where a new air interface has been developed of the so-called Wireless Channel oriented Ad-Hoc Multi-hop Broadband (W-CHAMB) system, formally specified using SDL [25] and analysed using stochastic simulation of the traffic load. Multi-hop links are established in the time domain, cf. Figure 5a). Two types of traffic are considered competing for the transmit resources.

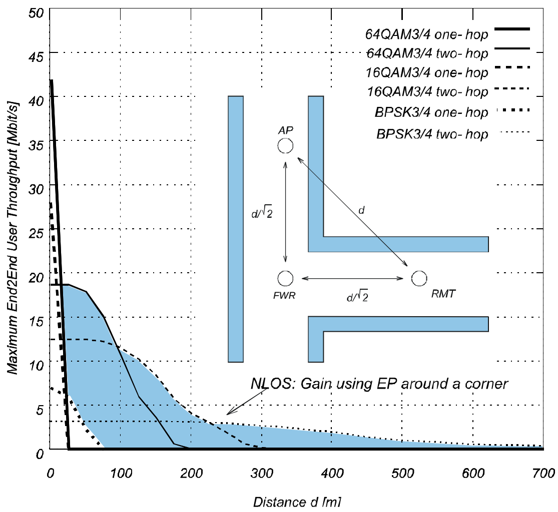

Figure 9: Fixed Wireless Router at the intersection (FMT) to extend the radio range of an AP “around the corner” into a shaded area to serve a remote mobile terminal (RMT)

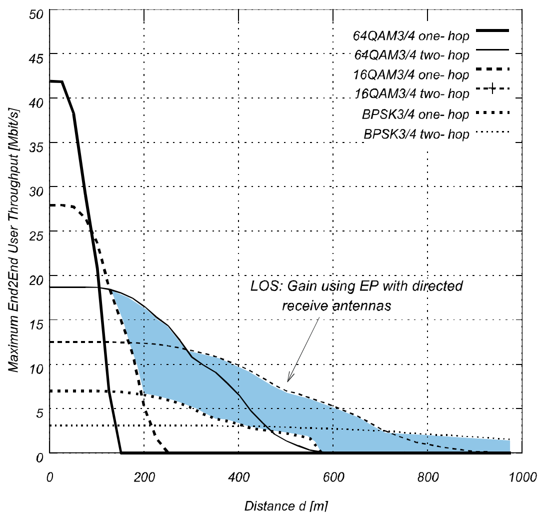

Figure 10:Maximum End2End throughput vs. Distance for Forwarding under LOS Conditions with directed receive antennas having a gain of 11 dB

The packet sizes of the Available Bit Rate (ABR) traffic are read from an Ethernet trace file. Data rates are varied to model different loads. The Packet size of real-time Variable Bit Rate (rt-VBR) traffic is modelled by an autoregressive Markov process with a mean of 3060 bytes and a maximum of 6120 bytes. 24 packets are generated per second by each rt-VBR source. The multimedia traffic load consists of five download rt-VBR sessions and 10 download ABR sessions from AP to nodes, five upload ABR sessions from nodes to the AP, and five direct link ABR VCs from WS to WS. The min-hop routing algorithm is used to established a multi-hop route. The transmission rate is 24 Mbit/s using the modem specified in IEEE 802.11a. The connectivity is an important parameter in that it relates the number of direct neighbour nodes to the total number of nodes in the network:

$$c = \frac{1}{N(N+1)} \sum_{i=1}^{N} n_i$$

If c = 1.0 the network is fully meshed and no multi-hop links are needed to reach any other node or the AP. If c is small, say 0.34, under equal traffic distribution probability the mean number of hops would be about 3. Figure 11 (left) gives a comparison of the throughput performance over load for varying network connectivity c=0.24..1 of the two concepts W-CHAMB and IEEE 802.11a. The prioritized rt-VBR traffic is completely served at all load conditions by the W-CHAMB system, whereas the throughput of the rt-VBR traffic decreases with the increasing loads in IEEE 802.11a. The maximum throughput of ABR traffic is higher than with IEEE 802.11a. This underlines some weaknesses of this broadly accepted protocol. These results have been gained assuming no antenna gain at any node to connect to each other.

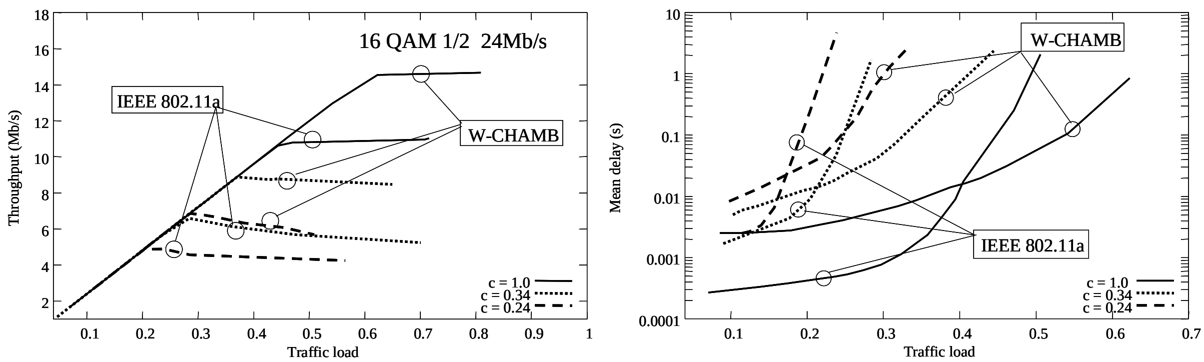

Figure 11: Multi-hop traffic performance under network connectivity c = 0.34 (about 3 hops on average); A throughput of 1.0 corresponds to 24 Mbit/s.

Much more interesting is the mean packet delay presented in Figure 11 (right) for both systems under c = 0.24..1.0 and variable total system load. It is visible that the W-CHAMB system is able to guarantee a small delay for rt-VBR traffic even at a heavy overload situation of 0.5. Since IEEE 802.11a is not able to differentiate rt-VBR and ABR traffic, the delay performance degrades rapidly with a increasing load and gains unacceptable results even under very low load, say 0.25.

The traffic performance in Figure 11 addresses the extension of the range of an AP to wireless nodes and shows that multi-hop really is able to provide a high throughput to multi-hop routes. It does not say anything about the traffic capacity available to mobile terminals roaming around any node. If one assumes another frequency channel to connect mobile terminals to the nodes, the respective results for one-hop networks can be found in [19].

5.2.2 RRM issues in the relaying context

Whenever relaying is performed, an additional channel will be required (for the second hop), since receiving and transmitting at the same channel will yield feedback loops (unless analog relaying is used with adequately separated distinct transmit and receive antennas [2], but this type of relaying is outside the scope of this contribution).

One strategy would be to reserve channels exclusively for relaying purposes. This is a conservative approach since each two-hop link will cost (in radio resources) the equivalent of two users to the system provider, which is obviously not desirable especially in busy systems.

If no channels are reserved for relaying, on the other hand, the system can search for a vacant channel whenever there is need for relaying, and relaying is performed only when such a vacant channel is available.

One possibility, for instance, is using the license-exempt bands for relaying. This seems to be a very promising idea due to the following two reasons: no expensive licensed band will be needed for relaying, and besides, if there happens to be major errors in relayer, relaying channel, and relayer power selection, this will only affect the terminals who communicate with the base station in two hops, which cannot be supported without relaying anyway, but not the other terminals in the system who are using the licensed band. This presents an appealing synergy between the concept of relaying and the efficient utilization of the license-exempt bands.

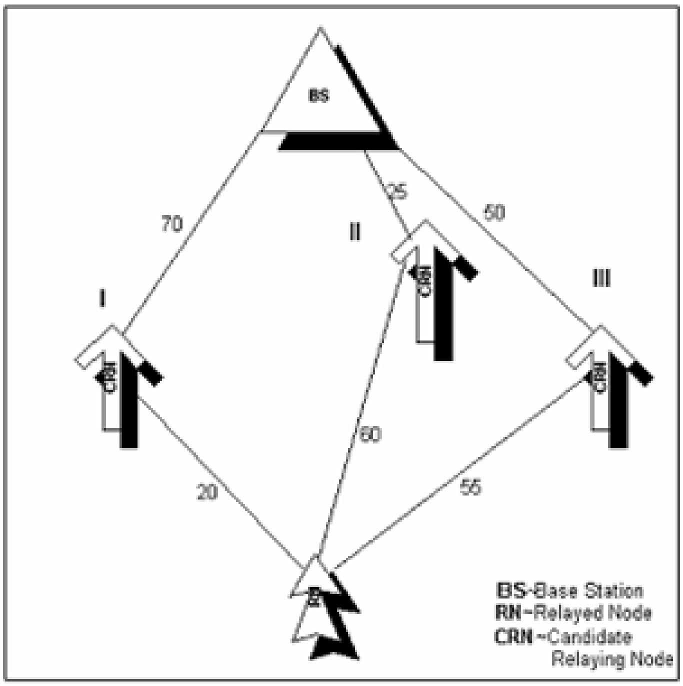

Figure 12: Mobile node selection in a cellular network for Ad Hoc Relaying (numbers represent pathloss of different paths)

Radio resource management deals mainly with the following three assignment problems: base station assignment, channel assignment, and transmit power assignment. In view of this, a major objective is to investigate the sensitivity of multi-hop cellular relaying systems to

- relayer selection,
- relaying channel selection, and
- relayer power selection and control.

Various relayer and relaying channel selection schemes, from random to smart selection, with and without power control, have to be considered.

5.3 Efficient Service Provisioning in Wireless Mobile Broadband Networks

Although maximizing radio coverage through the use of relays, concepts like the Wireless Media System (WMS) presented in section 2 may still provide non-contiguous radio coverage in some areas.

The discontinuous radio coverage available from the WMS can be hidden to a maximum degree to the users by an Intelligent Service Control (ISC) so that the subscribers are provided with the contents they need within given time limits. The ISC simulates a virtual continuous radio network connectivity to applications of the wireless terminals. For further reference, see [3].

5.3.1 Service Architecture

The core network of the Wireless Media System (WMS) applies an Intelligent Service Control (ISC) to ensure that data communicated over the various radio access networks is continuously made available to a Mobile Terminal (MT) even if the radio connectivity to the WMS is interrupted time-wise owing to the discontinuous radio coverage available from the WMS. The ISC simulates to user applications a continuous connectivity of the MT to the WMS by making extensive use of caching at MTs and MPs or their nearby controllers. Spontaneous access via the WMS to contents data is typically executed with a situation-specific delay, since the respective MT must wait until it has reached an area with WMS radio supply – optionally the service might be provided from the mobile radio system, immediately.

An MT associated to the WMS, when reaching an MP served area refers to the session already established earlier with its remote application, receives the data it had requested earlier at a very high data rate from the cache of the respective MP controller and caches it locally for later use. The quantity of data transmitted should be large enough to accommodate the expected duration of the local processing while a terminal might not be connected to the system, e.g., mailbox content, MP3 music file or other large data file. An MT transmits all data waiting for transmission to the MP as soon as it reaches its coverage area.

MTs can use all services known from traditional cellular networks and the Internet, i.e., voice, data transmission, reception of broadcast transmissions, etc. and may operate interactive multimedia connections. The ISC can use the mobility management and localization function of an advanced 3G radio system and dynamically tunnels data across fixed networks. Handover between adjacent cells served by MPs is replaced by fast re-association to the next MP.

The ISC supervises and controls all of the sessions of any mobile terminal in the combined systems of cellular mobile radio and the WMS. Its purpose is to control in an optimal way how to provide communication services related data to mobile terminals. The ISC is a logical unit that co-ordinates and comprises the following functions:

- mobility management of all of the terminals,
- localization of the terminals in both, the mobile network and WMS,
- Subscriber Identity Module (SIM) common with cellular radio network,
- dynamic tunneling of data through core networks involved to serve a mobile terminal,
- authentication, authorization, accounting and encryption,
- caching of data for mobile users,
- self-learning algorithms to understand the behavior of a user and to take advantage of knowledge on the type of MT and applications running on it,
- Quality of Service (QoS) support depending on the used network.

The ISC may be a centralized or decentralized unit. It simulates a continuous broadband access service to mobile terminals although the radio network coverage of the WMS is discontinuous only.

6 Conclusions

The almost ubiquitous provision of the very high data rates envisioned for future wireless networks necessitates fundamental upgrades in the wireless network architecture. It is expected that the multihop capability in third and fourth generation cellular networks, in WLANs and in broadband fixed wireless networks will facilitate the much sought high data rate coverage in an efficient manner. Towards that end, the interest in multihop-augmented infrastructure-based networks is growing rapidly.

This White Paper presents a concept for a Mobile Broadband system based on fixed wireless routers (relays). Examples for different forwarding techniques/strategies as well as a pattern for the wide area urban coverage using clusters of access points and forwarders are proposed. It is shown for different applications that multi-hop solutions can provide substantial increases in link capacity when applied in areas with heavy shadowing (reduced connectivity). The benefit for a broadband radio system is that the very high coverage which can be expected from this type of system can be traded for radio range which would otherwise be limited due to high shadowing at high radio frequencies. This allows to meet the expected capacity needs per area unit without the danger of overprovisioning.

The other important concept presented in this White Paper is the use of Mobile Relays in Cellular Networks, which can serve to increase network capacity and radio range.

Summarizing the most important research tasks in this thematic area:

- Medium Access / Radio Resource Management Protocols for Multi-Hop networks, aiming at:
    - Maximizing Frequency Reuse
    - Allowing efficient exploitation / fair sharing of the available spectrum, esp. in unlicensed case
    - Guaranteeing QoS, since delay can be expected to be a crucial issue in Multi-Hop networks.
    - Minimizing Multiple-Access Interference (MAI), probably making use of advanced coordination across base stations in the system and of cooperation between base stations of different access technologies.
    - Providing seamless mobility in heterogeneous networks consisting of different radio access technologies.
    - Allowing the sequential coupling of different air interfaces to allow for heterogeneous tandem-links. This can be important either in the context of wireless connection of Base Stations / Media Points to the core network or in the case of relaying in unlicensed frequency bands.
- Determination of the best-suited air-interface for Multi-Hop radio system (Candidates might be SC/MC-CDMA, pure OFDM or SC-FDE in combination with either TD/FD/ODMA etc.

- Routing Protocols to determine the optimal path respectively the optimal relay node for a multi-hop connection.
- Service architectures which make optimal use of the special characteristics of multi-hop networks, probably also involving other technologies like broadcast.

Since Multi-hop / relaying is also an important enabler for pure Ad Hoc networks, It seems advisable to search close cooperation with research groups active in Protocol design for Ad Hoc networks in order to align research efforts and avoid parallel developments.

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8 Document History

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20/06/2003	Chair of Communication Networks – Ralf Pabst	Initial Version – to be discussed at WWRF9 in Zurich