MULTIHOP COMMUNICATIONS IN FUTURE MOBILE RADIO NETWORKS

H. Li, M. Lott, M. Weckerle, W. Zirwas, E. Schulz

Siemens AG, Information and Communication Mobile, 81730 Munich, Germany, Hui.Li@icn.siemens.de

Abstract - Cellular networks and wireless local area networks (WLAN) are being widely deployed for mobile radio communications. Taking into account the advantageous and drawbacks of both network architectures, it becomes obvious that a combination of them is the logical consequence for future mobile radio networks. The scope of this paper is to introduce a future radio network architecture called hierarchical multihop cellular network (HMCN), which includes several multihop cells. The overlaying cellular network coordinates multihop cells in order to reach an optimal load balance in the whole network. The next evolutionary step towards a HMCN structure is to introduce multihop capable nodes (MHNs), which can be fixed or even mobile. The paper shows the challenges and benefits of multihop with fixed nodes, especially the placement of fixed MHNs and reduction of radio protocol overhead in order to provide high performance. When MHNs are normal mobile nodes, multihop routing becomes a key point in the HMCN concept. The paper proposes a cellular based routing scheme and compares it with the ad hoc routing algorithms being developed by IETF.

Keywords - Cellular networks, multihop cells, WLAN, future radio networks

I. INTRODUCTION

Recently, two types of mobile communication systems have been realized: Cellular systems like GSM, GPRS and UMTS and so called wireless local area networks (WLAN), e.g. IEEE802.11 or HIPERLAN/2 [3]. The latter systems provide an infrastructure mode to provide high-speed access to the Internet, and additionally a so-called ad hoc mode without the need of an infrastructure for spontaneous communication between devices. Unlike systems providing an ad hoc mode, cellular systems rely on an infrastructure of base stations (BS) and require network-planning and operation in licensed radio spectrums with narrow frequency bands to provide full coverage and the required grade of service (GoS). The traditional application in cellular systems like GSM is speech communication. For mobile data communications with data rates up to 2Mbit/s a new generation of cellular systems, called UMTS, is being developed. This cumulative data rate is still not enough for hot spot areas where the number of mobile nodes (MNs) per area is higher than that of network specifications. To increase the individual data rate of users, WLAN systems are introduced, which can provide transmission rates of about 20 Mbit/s [3]. Because these systems use unlicensed radio spectrum and less expensive access points, generally they offer mobile data communications with very low cost. On the one side transmission power in such kind of communication systems is limited that possible many systems can fairly co-exist in the same area without significant interference between them. However, the interference between such systems is difficult to predict and to control, resulting in instability of radio transmission quality. On the other side, coverage and mobility in this type of radio communication systems is limited. Taking into account the advantageous and drawbacks of cellular network and WLAN architectures, it becomes obvious that a combination of them is the logical consequence for next-generation network concepts [1][12].

The scope of the paper is to introduce a new radio network architecture, called hierarchical multihop cellular network, which integrates multihop cells as sub-cells into cellular networks and is described in section 2. The multihop cell can be established through fixed nodes or mobile nodes. In section 3 we shall show the challenges and benefits of multihop with fixed nodes, especially the localization of fixed nodes and the reduction of radio protocol overhead. In section 4 multihop with mobile nodes will be discussed with the focus on the comparison of different routing protocols. Section 5 concludes the paper summarizing the benefits and potentials of the new proposed architecture.

II. MULTIHOP CELLULAR NETWORK

A. Architecture

An evolutionary approach towards the architecture of a hierarchical multihop cellular network (HMCN) can be seen in Fig. 1. An overlaying cellular mobile radio system, e.g. a 3G system, forms the basis of the proposed network architecture. The possible connection of each MN to a BS guarantees full coverage and this connection can always be taken as a fall back solution in the case that a MN looses connection to any other kind of networks it might be connected to. This requires interoperability of existing networks and future networks and the support of vertical handover, i.e. handover between different wireless access networks. The BS provides Internet access and due to the centralized network structure an efficient centrally controlled resource management can be realized. In order to satisfy the increasing demand of higher data rates in hot spot areas WLAN systems allow a broadband radio access to the Internet provided by access points (APs).

The next evolutionary step towards a HMCN structure is to introduce multihop capable nodes (MHNs), which can be fixed or even mobile, see Fig. 1. In this architecture we define a sub-cell, which is called multihop cell. The range of the multihop cell is the whole coverage of one AP and several MHNs. In the case that MNs can become MHNs, the range of the multihop cell can be dynamically changed, so that communication between MNs and AP and between MNs in the multihop cell can be performed through one hop or relays of MHNs.

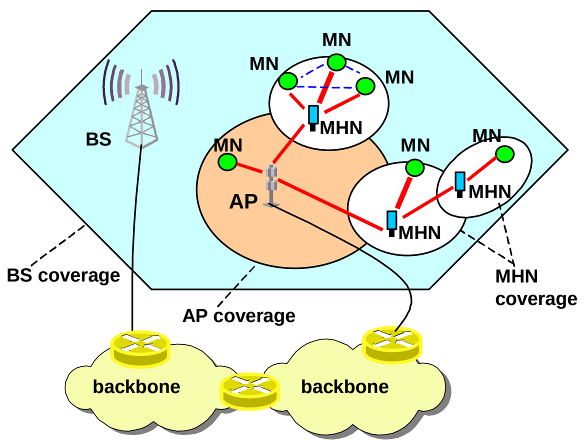

Fig. 1. Cellular Multihop Architecture

B. Benefits of the proposed architecture

Several benefits and advantageous over existing network architecture, which can be made up with the novel proposed HMCN architecture, are listed in the following.

AP coverage extension: Owing to the introduction of fixed/mobile MHN an extended AP coverage is provided. Especially with fixed MHN it becomes possible to overcome shadowing areas by appropriate placement, e.g. behind buildings. Moreover, MNs at the AP coverage border do not longer suffer from bad link quality and low data rates, since MHNs provide the required QoS.

Transmit power reduction: In the multihop cell the required transmit power can be considerable reduced, since several low-power links are established to connect arbitrary end-user-nodes with each other over several MHNs [2]. At the same time interference is reduced and the stand-by time is increased. Nevertheless, it is worth mentioning that relaying requires power consumption and introduces additional delays. However, with fixed MHN connected to power supplies the power consumption is less critical.

Capacity gain: Consequently, with the aforementioned benefits of decreased interference and deployment of adaptive antennas, an increase of capacity can be expected. With intelligent scheduling and resource allocation in AP and MHNs the frequency re-use distance can be decreased (see Section 3). Moreover, the spectral efficiency of the system can be enhanced when reusing the same frequency in different MHN coverage areas, and the available transmission rate can be increased if using different frequencies. Due to HMCN architecture a cellular based routing in multihop cell can be used which results in low signaling overhead and excellent scalability (see Section 4).

Low costs: The HMCN architecture allows the self-organization /-configuration of multihop cells and load balancing between BS and less expensive APs and MHNs. Consequently, a cost-effective, rapid and easy installation of infrastructure can be realized.

Optimized resource control: With the centralized and hierarchical resource control by the BS, APs and MHNs, an optimal resource management can be provided. E.g., the location database and topology information located at the BS can be accessed by the MNs, which implies advantages for routing, e.g. path selection with space diversity [12]. Furthermore, it can be guaranteed that an access to the backbone is available and by incorporating connection admission control, the QoS of existing and new communication sessions can be controlled.

The key point in the HMCN architecture is the realization of multihop cells, which can be established with fixed or mobile nodes. In the following sections we shall show the challenges and benefits of multihop with fixed extension points mobile MHNs.

III. MULTIHOP WITH FIXED EXTENSION POINTS

As described above, we see certain evolutionary steps for HMCNs. Here we concentrate on fixed MHNs, also called EPs (Extension Points). A typical scenario is shown in Fig. 2. The APs have direct connection to the IP core network, while the MHNs are situated at planned locations according to the actual environment. This might be on traffic lights for power supply. We assume mainly traffic of MNs into/from the core network - similar to the situation of e.g. a GSM network. In case of traffic between MNs in the range of an MHN this could be handled by direct links nonetheless. In the BMBF funded project COVERAGE we investigate the broadband wireless Internet access, i.e. up to an aggregate data rate of 54 Mbit/s in public hot spot scenarios on the basis of the ETSI BRAN standard HiperLAN/2 (H/2) [3]. We are interested in high performance systems, which may be run by an operator and which provide a high level of GoS, high spectral efficiency, maximum coverage, etc. One advantage of H/2 is the central control of the scheduling by the APs. Centrally controlled scheduling is less complex than distributed schemes and increases the system capacity significantly. In a high performance multihop network a central controller is even more important to organize and synchronize the transmission on the different radio links of the multihop network [7]. Additionally, H/2 adapts very fast to varying traffic conditions as typical for data transmission. We want to maintain these features for our multihop networks. Not shown in Fig. 2 is the cellular overlay network, but it is an underlying assumption. At least in the beginning full coverage is not possible with MHNs and hence cellular systems can be used to fill the gaps. For fixed MHNs the cellular overlay network can be exploited for security issues (SIM card by GSM) for authentication, etc. and for system diversity. System diversity means the connection to two different radio systems concurrently. Details are beyond the scope of this paper.

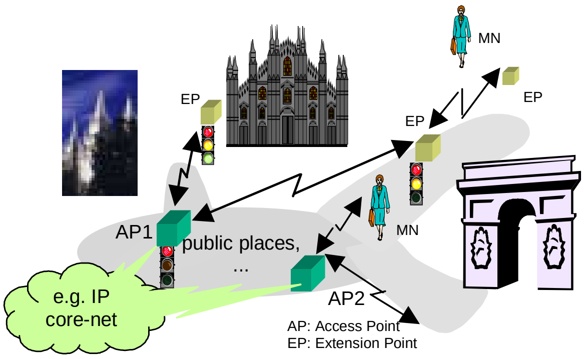

Fig. 2: Typical hot spot scenario for public places with fixed MHNs (EP)

The following list contains some main requirements for a high performance HMCN and describes the benefits of fixed and planned MHNs:

a) We assume MNs that are standard conform, i.e. in our case conform to H/2. The MN should not see any difference whether connected to an AP or MHN. This allows users to roam between office, home- and public environments. For the MHN it means it has to support AP functionality plus additional multihop functions. The MHN is not a simple direct repeater but has additional intelligence such as full scheduling capability and processes the forwarding data in the base band.

b) The AP-MHN link should be proprietary to optimize the overall performance of the HMCN. As we have shown in [5] the protocol overhead will become otherwise extensive. Just 7 MHNs may consume all available capacity for protocol overhead. Our proprietary solution supports more than 20 MHNs with substantial data rates and for high number of MTs. We achieved this e.g. by exploiting the trunking gain on the AP-MHN links and suitable frequency reuse [5].

c) The planned and fixed locations of the MHNs guarantee full coverage within the area of the multihop cell. In contrast mobile MHNs might be switched off or the owner of the MHN might despise relaying data for other users, e.g. because his battery will be emptied. Security is weakened for mobile MHNs, although man-in-the-middle attacks are possible for single hop systems as well.

d) In [4] it has been shown that the theoretical End-to-End throughput in open space and with omni-directional antennas for multihop networks is typically smaller than for one single direct link. The reason for that is the capacity loss due to relaying, because data have to be transmitted from/to AP to/from MHN and also from/to MHN to/from MN. This requires two resources, i.e. two time slots, frequencies or codes. A countermeasure in case of planned MHNs is the use of directional antennas like sector antennas at the AP as well as at the MHNs. As we see later in case of shadowing, which is the typical situation, e.g. for inner cities, MHNs have an additional advantage.

e) A further advantage of planned MHNs is the extremely simple routing, as the AP knows which MHNs are at which locations. So routing becomes a special type of scheduling. We have elaborated the so called BEACON concept for scheduling, which is essentially a frame wise switching between AP and MHNs [5] in time domain.

f) Planning guarantees that the MHNs are situated at locations, where they yield the highest benefit. In Fig. 3 we see, e.g., the gain in net data rate by the use of MHNs for the inner city of Munich. The location of EP2 has been chosen, so that it transmits its power mainly into side streets with good effect [5]. The simulation has been conducted with the help of the ray-tracing tool WINPROP. The SFN concept (Single Frequency Network) mentioned is beyond the scope of this paper (see [5]).

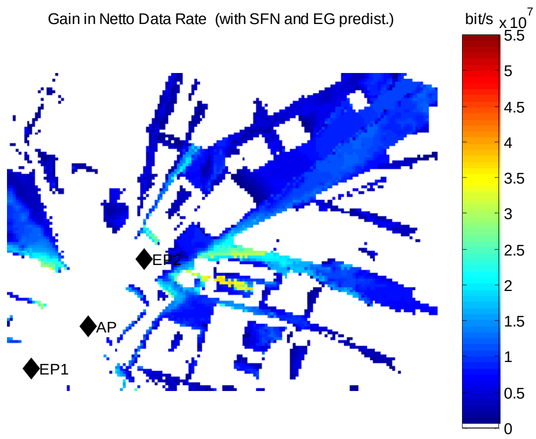

Fig. 3. Gains of forwarding and SFN compared with a single AP. The colors give the additional data rate

We have started to investigate the capacity and interference of planned HMCNs [6]. As one result see for example in

Fig. 4 the frequency reuse pattern in case of a Manhattan grid. Due to the strong shadowing effects between different streets, the whole area can be supported with only two frequencies. A quite different scenario would be open space, where a frequency reuse of >12 is required to avoid interference in order to reach the similar system capacity as in Figure 4. In reality we have something in between those both extreme scenarios. Actually a trial system is developed within the project COVERAGE, which will allow, e.g., measurements for real HMCNs.

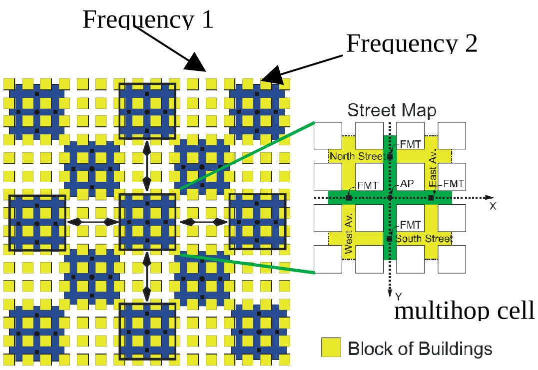

Fig. 4: Location of HMCNs with fixed MHNs (here called FMT) for a Manhatten grid and a frequency reuse factor of 2

IV. MULTIHOP WITH MOBILE NODES

Routing mechanism will become one of the important topics for HMCNs, when MHNs are normal mobile nodes. In the BMBF funded project IPonAir [9], we are working on multihop routing and radio resource management in HMCNs with mobile MHNs. For our investigations the following assumptions are considered. Future radio network will have the similar structure as one depicted in Fig. 1. Most MNs are equipped at least with two sets of radio transceivers operating in separate frequency bands. One for the cellular transmission between MNs and BSs, e.g. using UMTS, and the other for the radio transmission between MNs and between MNs and APs, e.g. using IEEE802.11 WLAN. Each MN can support the multihop function. There is a location controller in the cellular network where the information of locality and neighborhood of each MN is stored. The providers of APs are registered in a service controller in the cellular network. To access the Internet through APs, MNs have to perform two tasks, AP discovery (service discovery) and route discovery.

In the MANET group of IETF, several multihop routing algorithms such as DSDV, AODV and DSR [8] have been investigated. An assumption of the MANET group is that no infrastructure exists in multihop cells, hence the network management, radio resource management and routing algorithm are performed among mobile nodes in a self-organized and distributed way. Earlier study of those algorithms has shown high overhead of radio transmission protocols and low efficiency in network throughput. As studied by Perkins [9], in a medium size, moderate loaded ad hoc mobile network, generally more than 80% of the transmission capacity is used for routing, medium access and radio link control protocol packets.

Based on the observation above, we are studying a hybrid routing scheme, which is similar to the ad hoc routing algorithms, but it needs the support of cellular networks. The cellular based routing algorithm works in the following way. Before sending a data packet, the source MN first checks its routing table. If routes to the destination are known, the source MN inserts one of the routes together with the route ID into the header of data packet. Otherwise, it starts the route discovery through unicasting a route request (RREQ) packet to BS. In the RREQ packet, the source and destination addresses are included. Upon receiving a RREQ packet, the BS checks the node table. If the destination MN is available, BS computes several suitable routes from the nodes topology information and unicasts a route reply (RREP) packet containing the routes information and corresponding route IDs to the source MN. Otherwise, the BS unicasts a route error (RERR) packet back to the source MN. Upon receiving a RREP packet, the source MN registers the routes to the destination in its routing table. Each MN periodically broadcasts HELLO packet to enable its neighbor MNs update topology information. Periodically, the node also reports the information about its neighboring nodes back to the BS. Upon receiving a data packet, the node compares its address with the destination address. If both addresses are not identical, the node unicasts the data packet to next node along the source route specified in the data packet. If the packet failed to be delivered, the node unicasts the RERR packet to BS reporting error occurred. BS then broadcast this RERR packet over the whole network. Upon seeing RERR packet, each node marks that route ID as invalid for a certain time, and simply drops any packet carrying this route ID.

We have compared the cellular based routing algorithm with ad hoc routing algorithms DSR, AODV and DSDV in a simple multihop cellular network topology, where all MNs are uniformly distributed inside the cell, and each one has the same distance to its six neighboring nodes. Hence the nodes form a central symmetric hexagon as illustrated in Fig. 5. We assume that half of the nodes on the border have data packets destined for its central symmetric counterparts. The distance between two neighbor nodes is r, where r is set up in such a way that a node can communicate with its direct neighbors, but not further neighbors. The radius of the coverage of a base station is $R=N*r$. In order to introduce dynamics in the topology, we assume that every t seconds the route can be broken with a probability p, which invokes a route repair process. In Fig. 6., we give the analytical results of average number of routing packets per route per second produced by the four routing algorithms. We assume there is no collision during radio transmissions. The AODV algorithm can always find the best route. The DSR algorithm can find several routes, which have the least number of hops. The curves in Fig. 6 shows that the cellular based routing (MCN) consumes the lowest routing overhead and shows excellent scalability in dynamic multihop networks, if the number of hops is larger than 4. The detail analysis and explanation of the results can be found in [11]. Based on this topology model we shall continue throughput analysis including the radio link layer. In addition, we shall consider some open issues like power control and reuse of radio resource.

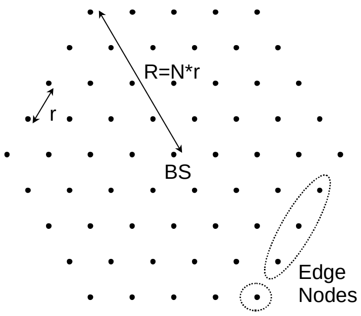

Fig. 5: A simple MCN topology

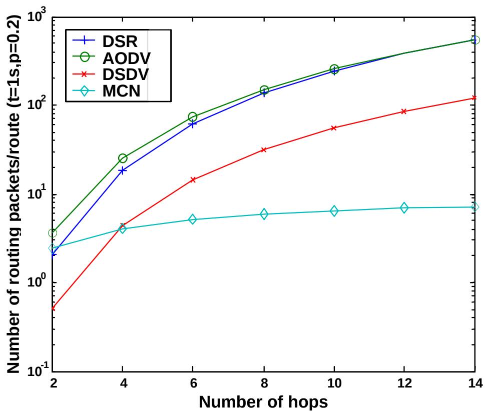

Fig. 6. Comparison of routing protocol overhead

V. CONCLUSION

This paper describes a hierarchical multihop cellular network (HMCN) architecture that is suitable for future mobile radio communications. The concept combines existing cellular network and WLAN and introduces four network components, i.e. base station (BS), access point (AP), multihop capable node (MHN) and mobile node (MN). Using the proposed architecture the traffic load in the whole network can be dynamically distributed between the network components. This results in efficient regulation of transmission power and low installation costs for infrastructure. The evaluation step towards a HMCN structure is to develop and manage multihop capable nodes that can be fixed or even mobile. For HMCN with fixed MHNs the paper shows that high performance can be reached through optimal placement of MHNs and reduction of radio protocol overhead. Multihop routing in HMCN with fixed MHN nodes is quite simple, while in HMCN with mobile MHNs it becomes the key issue. The paper compares a cellular based routing scheme with three ad hoc routing algorithms DSR, AODV and DSDV. The results show that the cellular based routing protocol has low overhead and excellent scalability in dynamic HMCNs. In future works we will consider some open issues like power control and reuse of radio resource in the HMCN architecture.

AKNOWLEDGEMENTS

The projects *Coverage* and *IPonAir* are partly funded by the German Ministry of Education and Research (BMBF). We would like to thank all partners of the projects for their ideas and input.

REFERENCES

[1] Y.-D. Lin, et. al, " Multihop Cellular: A New Architecture for Wireless Communications", in IEEE INFOCOM, 2000.

[2] O.C. Mantel, et. al, "Radio Aspects of Hybrid Wireless Ad-Hoc Networks," in Proc. of VTC´01 Spring, Rhodes, Greece, 2001.

[3] ETSI/BRAN: Technical Report 101 683 V1.1.1, Broadband Radio Access Networks; HIPERLAN Type 2; System Overview.

[4] W. Zirwas, et. al, Broadband Multihop Networks for Public Hot Spots, 3rd WWRF Meeting Stockholm, September 2001

[5] W. Zirwas, et. al, Broadband Multihop Networks with reduced Protocol Overhead, European Wireless 2002 Florence, February 2002

[6] N. Esseling, et. al, A Multi Hop Concept for HiperLAN/2: Capacity and Interference, *European Wireless* 2002 Florence, February 2002

[7] J. Li, et. al, Capacity of Ad Hoc Wireless Networks

[8] www.ietf.org

[9] www.iponair.de

[10] C.E. Perkins, et. al, "Performance comparison of two on-demand routing protocols for ad hoc networks", *IEEE Personal Communications*, Feb. 2001,pp16-28

[11] H. Li, et. al, "Performance comparison of ad-hoc and cellular based routing algorithms in multihop cellular networks", the *5th international symposium on wireless personal multimedia communications (WPMC)*, 2002

[12] R. Ananthapadmanabha, et. al, "Multi-hop Cellular Networks: The Architecture and Routing Protocols", Proc. PIMRC, 2001.