Hierarchical Coverage Extension in Self-organising Wireless Network Systems

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Abstract

Future self-organising ad hoc networks (MANETs) will provide Internet access for ubiquitous wireless computing. In combination with cellular systems, e.g., B3G and 4G networks, self-organising networks will increase the coverage of cellular systems. The advantage of the so-called coverage extension is that there is no demand for extension of cost-intensive infrastructure, yet it extends network access where no coverage is provided by network operators.

This paper extends studies of other related and ongoing work regarding the integration of ad hoc networks in cellular systems and coverage extension based on a complete network topology, which has been implemented for this research. A simulation study is presented in this paper with an evaluation of coverage extension methods in a free scalable hierarchical network environment and considers a trade-off discussion based on a scalable coverage area including various numbers of ad hoc nodes and base stations.

Keywords: *Hierarchical Mobile IP, ad hoc, coverage extension, scalability, multiple interfaces*.

1. Introduction

The motivation of the presented work is to increase the coverage area of cellular networks based on self-organising multihop ad hoc networks in such environments where there is no or not sufficient coverage of a cellular network available [1]. Today, mobile multimedia applications need high bandwidth, which is not currently provided by the mobile operators, as it has been presented in [2]. With a combination of wireless ad hoc networks and cellular systems the demand for high bandwidth and higher capacity can be achieved, e.g., by sharing data flows via multiple interfaces [3]. Moreover, coverage extension has the advantage, that there is no need to extend the cellular infrastructure by increasing the number of base stations. The coverage extension is based on intermediate ad hoc nodes which act as mobile routers to provide access via multihop routes. However, some of the mobile ad hoc nodes have to act as mobile gateways to the cellular infrastructure and thus become the bottlenecks for the remaining ad hoc nodes, which are attached to such gateway nodes.

In this study, the extension scenario of wireless base stations in combination with multihop ad hoc networks is examined. The system architecture consists of a free scalable hierarchical topology that is more efficient for high frequent handovers between the base stations and high velocities of the mobile users. Hierarchical Mobile IP is an appropriate candidate for micro-mobility and it has been applied for the coverage network architecture in this study.

There are several multihop ad hoc routing protocols currently under development, and each of them has been developed to cover a specific routing problem or movement scenario. The Ad hoc On-Demand Distance Vector Routing protocol (AODV) is a suitable candidate for scenarios with a high number of mobile users and moderate velocity. It provides efficient mobility support including low routing overhead for dynamic ad hoc networks. Moreover, the reactive behaviour of this routing protocol matches to the reactive character of Mobile IP [4] and allows an efficient coverage extension.

This study contains an overview on related work that is outlined in section 2. The system architecture of cellular coverage extension and the integration of ad hoc networks in combination with hierarchical Mobile IP are described in section 3. In section 4, details for the examination of hierarchical coverage extension are described and two coverage extension methods are presented. The simulation setup of the free scalable hierarchical network topology is presented in section 5 and section 6 contains the simulation results. Section 7 concludes this study summarising the benefits and outlines the future work.

2. Related work

Recently, there are several projects which examine the coverage extension in cellular networks. This paper outlines some of them which look sufficient for an integration of cellular and ad hoc networks.

A hierarchical integration of cellular and ad hoc is described in [3], [13] as a logical consequence. It leads to a system architecture which is called hierarchical multihop cellular network (HMCN). The hierarchy consists of different wireless technologies and introduces multihop capable nodes (MHNs) which can be installed stationary or even mobile [3]. The cellular network coordinates the multihop cells in order to reach an efficient load balance in the entire network. However, these two studies do not describe the hierarchical approach to provide efficient micro-mobility for seamless handovers.

Another approach is presented in [14] and contains a proxy based system architecture for coverage extension. It allows an increased download performance of the cellular system that can be improved by 40 kbps whereas the signal strength can be increased by 20 dBm [14]. Increasing the signal strength allows that more mobile users may have access to the cellular network providing a decreased blocking rate. Due to the fact that the entire cost of the path is not considered in this algorithm, an efficient route cannot be chosen, which is needed for an optimal route decision in ad hoc networks.

In the future, specific ad hoc nodes will be integrated in cellular networks to act as multihop ad hoc pico cells. Such nodes will play the role of an integrated ad hoc backbone system with higher bandwidth, supervisory and AAA functions. This is related to the iCAR approach in [15] where specific ad hoc nodes act as relays for coverage extension and load balancing in cellular networks.

3. System architecture

Coverage extension in this study has been integrated within a scalable hierarchical topology by using WLAN and multihop ad hoc protocols. The integration of cellular and WLAN is typically specified by the way of using coupling mechanisms, namely loose coupling, tight coupling and very tight coupling, which have been discussed in the study, presented in [5]. For the hierarchical integration the base stations consist of a wired interface connected to the cellular core network and a wireless interface to integrate wireless ad hoc networks as defined as the very tight coupling mechanism in [5]. The base station includes an extended network stack to interact with the hierarchical infrastructure and the wireless ad hoc nodes simultaneously. The network stack of the base station contains the hierarchical Mobile IP protocol (HMIP) and the multihop ad hoc routing protocol (AODV) which are briefly described in the following.

3.1. Hierarchical Mobile IP (HMIP)

Hierarchical Mobile IP provides mobility support in IP-based networks where frequent handovers between access networks are necessary, especially between adjacent access networks. The micro-mobility which is supported by HMIP reduces signaling overhead and handover delays [6]. The micro-mobility support is based on an extended network topology which consists of the mobile node (MN), home agent (HA), foreign agent (FA), and further mobility agents (MA), namely the gateway foreign agent (GFA) and regional foreign agents (RFA). These two entities, the GFA and the RFA, support the micro-mobility by managing local movements and handovers between sub networks. This reduces handover latencies, because the GFA/RFA is aware of the local registration of the MN. Global mobility is handled by the HA using so-called binding updates (BU) during regular intervals.

3.2. Ad hoc on-demand distance vector (AODV) protocol

The implementation of ad hoc coverage extension in hierarchical cellular networks needs an appropriate routing protocol. There are several ad hoc protocols available, table-driven and on-demand routing protocols, e.g., AODV [7], TBRPF [8], OLSR [9], and DSR [10]. Moreover, there are hybrid routing candidates being discussed which are more suitable in combination with cellular networks. These routing protocols use routing information which is managed by a central unit (base station). This reduces route discovery and signaling overhead within the ad hoc domain [11]. However, such routing protocols are not currently standardised.

However, standardised ad hoc routing protocols will be implemented in the near future in mobile devices, such as cell phones, PDAs, and notebooks. An appropriate candidate suite are on-demand routing protocols, especially the AODV protocol. The route discovery of AODV is efficient and uses less signaling overhead that is important for high density wireless ad hoc networks as it has been shown in [7]. AODV starts the route discovery only when a new route is needed. Moreover, AODV supports route maintenance by sending route errors and hello messages to locate stale routes.

3.3. Interworking between HMIP and AODV

The integration of AODV within the HMIP infrastructure requires an extension of the network stack. Especially the base station has to act as a foreign agent (FA) to provide MIP services inside the ad hoc domain. The base station is

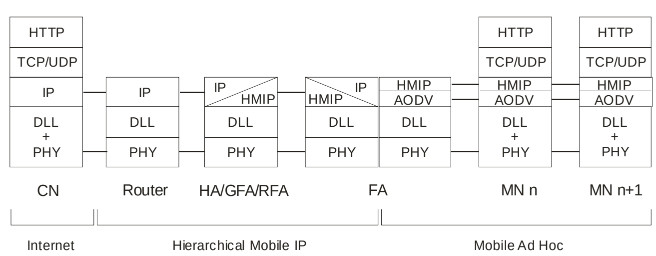

Figure 1: Protocol stack of the HMIP and AODV integration for hierarchical coverage extension

connected to the wired HMIP infrastructure, the HA/GFA and the RFA (see Fig. 1). The base station consists of the FA stack to send and receive registration messages (registration request and replies) from/to the mobile nodes.

Fig. 1 shows the interworking of HMIP and AODV where the base station works as a gateway between HMIP infrastructure and the ad hoc network. Furthermore, the ad hoc nodes contain the AODV and HMIP stack to provide ad hoc access. Further details concerning the integration of HMIP and AODV can be found in a former study, presented in [12].

4. Coverage extension

The alignment of the base stations defines the radius of the coverage extension of the entire cellular network. The base stations only have a limited coverage radius (e.g, 250m) that can be extended by ad hoc nodes which are in coverage of those base stations. Such ad hoc nodes can act as intermediate nodes to attach nodes which are not in the coverage area of the base stations.

The system topology for coverage extension in cellular networks is presented in Fig. 2. It shows the hierarchy and the alignment of the base stations. Each base station is connected via regional foreign agents and gateway foreign agents. One RFA maintains a defined number of base stations for local handovers. Handovers between RFAs are maintained by the GFA. This reduces the handover latency and the signaling overhead.

Fig. 3 describes the hierarchical topology of 3-3-1 alignment (3 RFAs, 3 BS per RFA, and 1 GFA). For this study a free scalable network environment has been implemented to study various numbers of hierarchical topologies, e.g., increasing/decreasing number of base stations, changing the coverage radius of the base stations and extension of communication gray/dead zones.

Based on a proactive coverage extension base stations provide frequent agent advertisements which can be

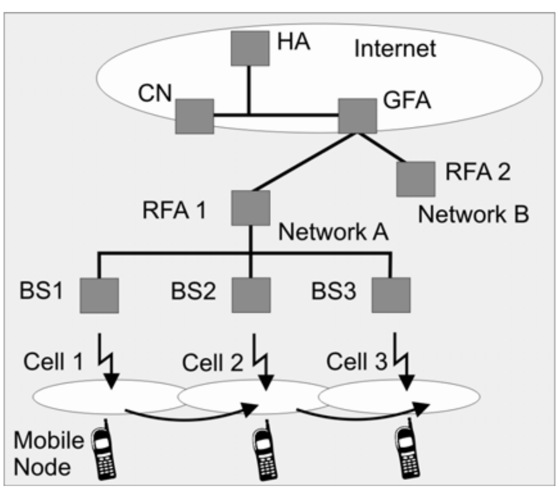

Figure 2: Network architecture of multihop ad hoc cellular networks based on hierarchical Mobile IP

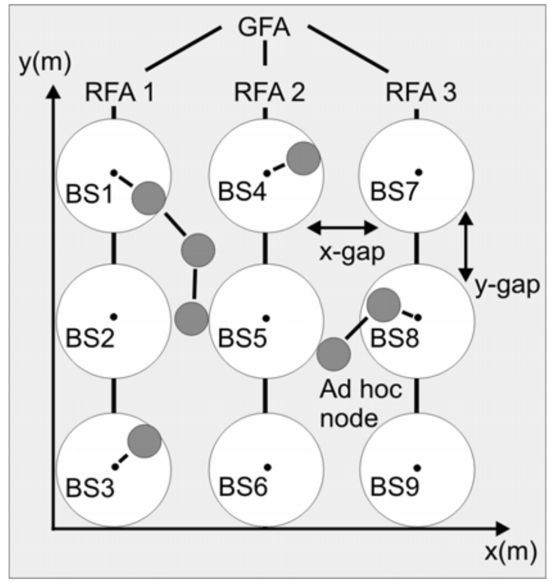

Figure 3: Network topology of the 3-3-1 alignment of cellular base stations

detected by the MN. Sending agent advertisements has the advantage that the MN is aware of any movement by receiving unknown agent advertisements from a foreign network. However the agent advertisements flood the entire ad hoc domain that increases the signaling traffic.

To calculate how many advertisements are sent based on the proactive coverage extension, the equation in (1) can be used where 1/*a(i)* [1/s] is the interval of sending agent advertisements, *t(i)* [s] is the duration of sending agent advertisements, i.e. simulation time, and *n* is the number of the base station.

$$adv_{basestation} = \sum_{i=1}^{n} \frac{1}{a(i)} \cdot t(i) \qquad (1)$$

The parameter *a* and *t* are related to each separate base station *B*(*i*). This allows an exact calculation of the number of agent advertisements of each separate base station in the entire network.

The retransmission of agent advertisements within an ad hoc network can be calculated based on the number of ad hoc nodes as defined in equation (2). This equation considers ad hoc nodes *k(i)* which are inside the coverage area of base station *B(i)*. Only these nodes will retransmit the agent advertisements of *B(i)*. An endless bouncing of advertisements can be avoided by using sequence numbers of the broadcast messages, which was also part of the integration for this study.

$$adv_{multihop} = \sum_{i=1}^{n} k(i) \cdot \frac{1}{a(i)} \cdot t(i) \qquad (2)$$

In Fig. 4 the relation between the period of sending agent advertisements and the number of signaling packets is shown for the proactive coverage extension.

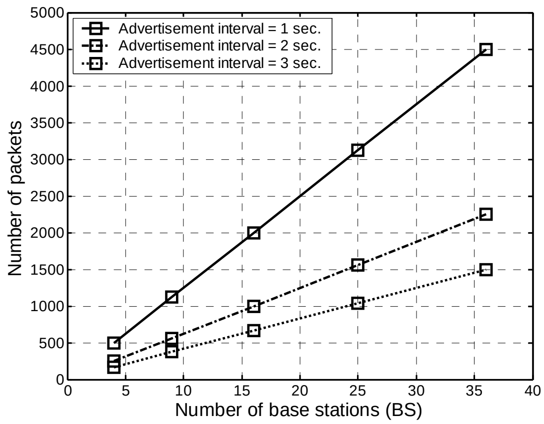

Figure 4: Number of signaling packets during proactive coverage extension (number of BS= 4, 9, 16, 25, and 36)

It can be observed that the number of packets increases by an increasing number of base stations. Thus, a trade-off discussion is needed to find an optimized relation between the number of base stations and sending rate of agent advertisements.

Fig. 4 also shows that in the case where the sending rate of broadcasting agent advertisements increases, more signaling traffic can be observed. Thus, an examination is needed, to show the impact of the coverage extension in a scalable hierarchical network environment. There are studies which show that the reactive method is suitable for the interworking between wired networks and multihop ad hoc [16], [17]. However, these studies are mainly based on a specific network section, e.g., the access point environment [16] or the gateway environment [17].

5. Simulation setup

The simulation environment is based on the network simulator ns-2 and its extension for hierarchical mobility support which has been described in [12]. The interworking of HMIP and AODV requires also the implementation of the extended protocol stack which has also been outlined in [12]. The network topology is based on a 3-2-1 topology. Each base station is linked to the RFA which again is linked to one GFA. The topology consists of max. 30 ad hoc nodes which contain the HMIP and AODV stack.

The simulation examines the impact of the movement and the number of mobile nodes of the network scenario. The number of nodes increases from 10 to 30 nodes and the different velocities are 0, 2, 5, and 10m/s. All base stations and mobile nodes use the Lucent WaveLAN IEEE 802.11b interface with a transmission range of 250m. The simulation time is 125 seconds and the results are based on 100 iterations with different movement patterns (random walk) and traffic patterns (RTP/CBR traffic with constant 10 active CBR nodes, packet size 512 bytes, and sending interval 0.2). The number of 100 iterations is a trade-off between the reduction of the simulation error and a reduced simulation time. All scenarios were simulated with a gap (distance between the coverage areas of adjacent base stations) of 200m up to a max. of 300m to change the coverage area.

6. Simulation results

The results of the coverage extension are presented in Fig. 5-10. In Fig. 5 and 6 the results of Mobile IP registration requests are presented for both coverage extension methods. Registration requests are sent from the mobile node when a new foreign network is detected receiving agent advertisements at the MN. Both figures show that the coverage extension detects the same maximum number of registration request (900 requests) for the highest velocity (10m/s). This leads in sending registration replies from the base stations, which can be observed in Fig. 7 and Fig. 8. Both figures present that for the reactive coverage extension more registration requests are sent. This leads to more reliable connection links between the MN and the hierarchical network, which can be studied in Fig. 9 and 10. It shows the packet delivery ratio as network throughput comparing the different coverage extension methods. The network throughput is calculated as the ratio between received packets at the destination and packets sent by the source. For the reactive approach an increasing throughput can be observed within the entire network.

To compare the total number of routing packets both methods are presented in Fig. 11. It shows an increased number of routing packets for the proactive approach. It can be observed that the reactive coverage extension is more suitable for cellular networks. This is due to the fact that the reactive approach avoids network flooding of agent advertisements.

To study the trade-off of the reactive coverage extension and the alignment of the base stations, the gap was increased from 200m to 300m. The result can be observed in Fig. 12 and shows that the network throughput based on the reactive coverage extension is reduced while the gap was increased. For an increasing number of mobile nodes the coverage extension behaviour can be observed for 250m and 300m.

An increasing number of ad hoc nodes act as mobile routers between the base stations and increases the coverage extension that is shown by the increasing throughput between 15 and 20 ad hoc nodes. A higher number of ad hoc nodes lead to an increased retransmission and link disruption during the movements. Hence, an optimal trade-off between the number of ad hoc nodes and the gain of coverage extension can be observed for this specific mobility scenario between 15 and 20 ad hoc nodes.

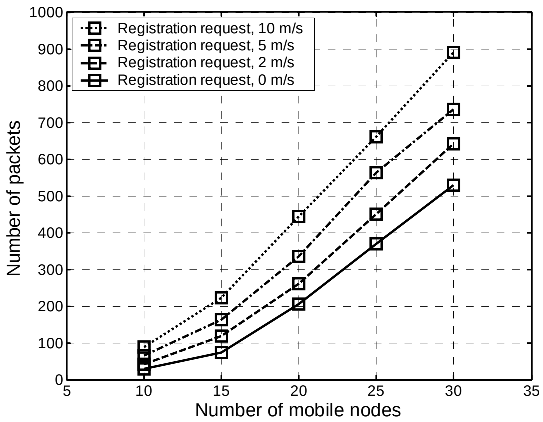

Figure 5: Registration request, proactive, 3-2-1, gap=200m

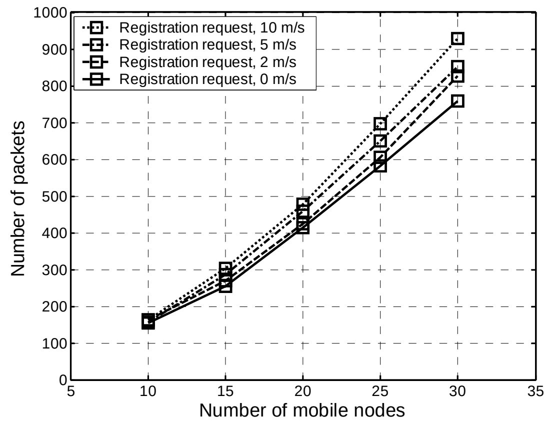

Figure 6: Registration request, reactive, 3-2-1, gap=200m

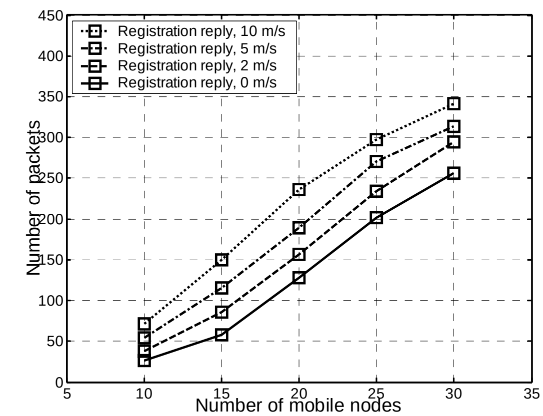

Figure 7: Registration reply, proactive, 3-2-1, gap=200m

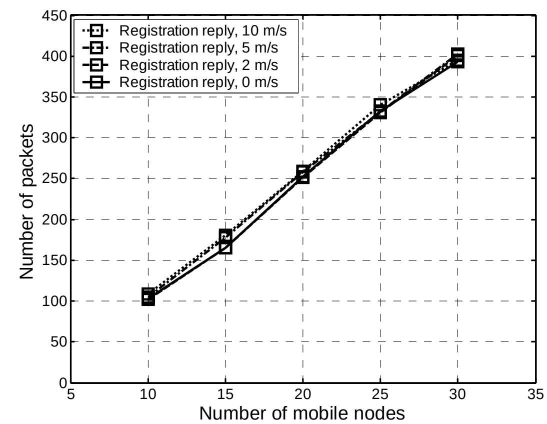

Figure 8: Registration reply, reactive, 3-2-1, gap=200m

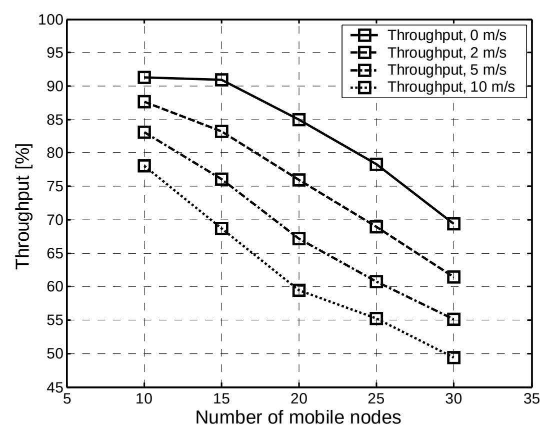

Figure 9: Throughput, proactive, 3-2-1, gap=200m

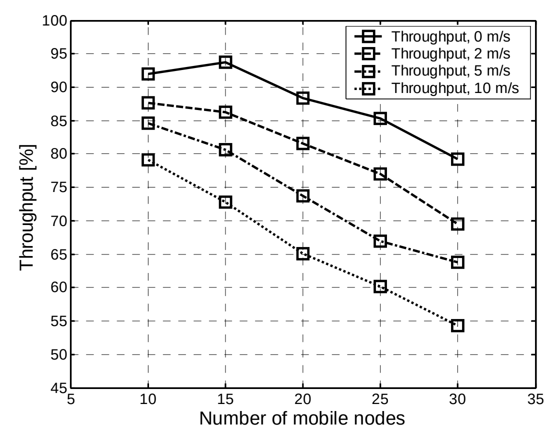

Figure 10: Throughput, reactive, 3-2-1, gap=200m

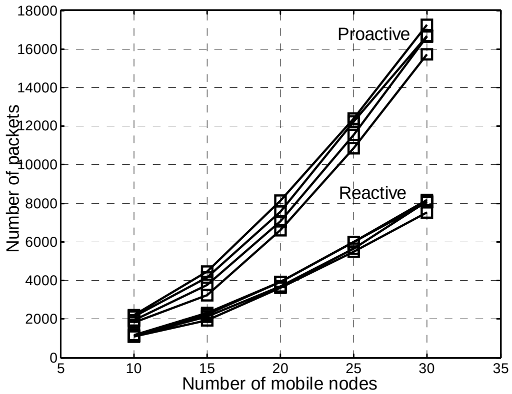

Figure 11: Comparison of proactive and reactive coverage extension (routing overhead)

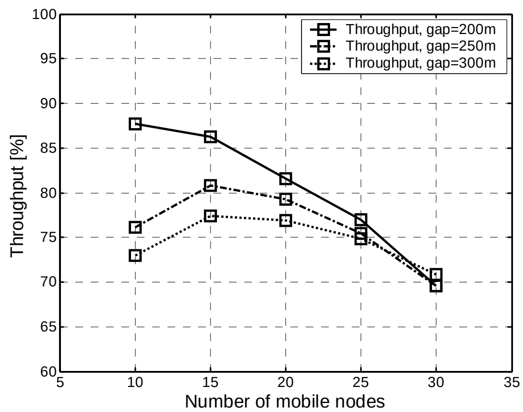

Figure 12: Trade-off examination (throughput) with different gap (200m, 250m, and 300m)

7. Conclusions and future work

This study presented a free scalable network environment for hierarchical coverage extension in self-organising wireless networks. The system architecture was introduced as a combination of hierarchical Mobile IP (HMIP) and the ad hoc routing protocol AODV. It allows the extension of network coverage in cellular networks and reduces signaling overhead. This study has shown that a reactive coverage extension is suitable for cellular networks. Finally, the study has shown a trade-off between the number of ad hoc nodes and the gain of coverage extension.

Future work will be based on the integration of multiple interfaces, which is needed for handover between ad hoc networks and cellular systems. Moreover, multiple interfaces provide simultaneous data flows so that an increasing throughput can be assumed.

Acknowledgment

This research was performed under research contract “Cognitive Wireless technology” for the Ministry of Internal Affairs and Communications.

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