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Outline of a centralised multihop ad hoc wireless network

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Abstract

A concept of a multihop ad hoc network and associated algorithms for adaptive clustering in wireless ad hoc networks are presented in this paper. The algorithms take into account the connectivity of the stations as well as the quality of service requirements. The concept of a centralised ad hoc network is adopted, in which a cluster is defined by a Central Controller granting access to the radio interface to all terminals in its cluster. By these means the CC contributes to provide quality of service guarantees to the users. This concept is also used in the HiperLAN/2 (HL/2) Home Environment Extension (HEE), an ad hoc wireless LAN standardised by the European Telecommunications Standardisation Institute (ETSI). The HEE is restricted to one single cluster. It is shown in this article how the network can be extended over several clusters by the introduction of so-called "forwarding" stations. These forwarders interconnect the clusters and enable multihop connections of users roaming in different clusters. A solution is presented to ensure, as far as possible, an interconnection of clusters by means of the clustering algorithm.

Keywords: Ad hoc networks; Clustering; Forwarding; Routing; HIPERLAN/2; Mobility management; Handover

1. Introduction

Traditional wireless networks are infrastructure-based. The traffic over the radio interface is organised by base stations that serve at the same time as access points to the fixed core networks like the Internet or the public switched telephone networks (PSTN).

In contrast to these traditional networks, ad hoc networks are self-organising. Every station may serve as an access point to the fixed networks. These self-organising systems are characterised by being ad hoc deployable. Consequently, classic application scenarios for such systems are battlefield communications, disaster recovery as well as search and rescue. Recent applications for the systems are personal communications networks (PCN) especially in the home or office. This is owing to the possible plug-and-play deployment and installation of the system.

The size of the area covered by the systems is in general much bigger than the transmission range of the stations. Communication between two stations therefore involves several other stations that have to forward the data. This means that ad hoc communication results in multihop networks whereas infrastructure-based communication uses only one hop (uplink or downlink).

Two different types of ad hoc networks can be distinguished: decentralised and centralised ad hoc networks.

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In decentralised ad hoc networks the access scheme as well as the routing and mobility management are completely decentralised. An example of such a network is the IEEE 802.11 system. Advantages of decentralised systems are their fairness with respect to power consumption and processing requirements of the terminals as well as their robustness against failures.

In centralised networks certain functions like the medium access control (MAC) are performed by one specific station per cluster, the so-called central controller (CC) or cluster head. These functions do not necessarily have to be carried by the same station all the time, i.e., they can be handed over to another station in the same cluster able to carry them. The HiperLAN/2 (HL/2) Home Environment Extension (HEE) is organised in such a way. One advantage of centralised networks is that control on quality of service is eased. Furthermore, infrastructure-oriented protocols can be re-used.

In this paper, a concept for a centralised multihop ad hoc network is developed. It is based on the HEE, which can be considered as a first step in this direction.

For this reason a brief overview of HL/2 and its HEE is given in Section 2.

In Section 3, the cluster concept of the HEE is extended to a multi-cluster, multihop network where the problems related to cluster interconnection, dynamic clustering and routing are addressed.

Simulations of the effects of the developed clustering schemes have been carried out and are presented in Section 4.

Finally, conclusions are drawn in Section 5.

2. HiperLAN/2 ad hoc network

2.1. Introduction to HiperLAN/2

HL/2 is part of the ETSI project broadband radio access networks (BRAN) and defines the radio interface of a wireless LAN. For this LAN, interworking with existing core networks like ATM, IP, UMTS and IEEE1394 is provided via so-called convergence layers (CLs). An overview of the HL/2 system is given in [1].

At the physical layer HL/2 provides a data rate of up to 54 Mbit/s resulting in a user data rate of up to 45 Mbit/s. Orthogonal Frequency Division Multiplexing (OFDM) is used with 52 sub-carriers, out of which 48 are used for data transmission. Adaptive modulation and adaptive coding can be applied to cope with varying propagation conditions and QoS requirements. For this purpose different PHY-Modes are defined. A PHY-Mode consists of a combination of a modulation and coding scheme. Possible modulation schemes are BPSK, QPSK, 16 QAM and 64 QAM. For the encoding, a punctured convolutional code is used which can produce code rates of 3/4 or 9/16. The system operates in the 5 GHz band and has a transmission range of up to 200 m depending on the applied PHY-Mode and propagation conditions.

At the data link control (DLC) layer the system is connection oriented. DLC connections are set up by radio link control (RLC) procedures. Other functions of the RLC protocol are authentication, encryption, automatic frequency selection, radio and network handover, etc. Thus, terminal mobility is supported. QoS is provided based on a set of parameters that are assigned to each connection.

The medium access control (MAC) is organised by the CC. In the HEE the CC functionality is taken over by one of the stations of a cluster.

The CC is responsible for building MAC frames with a constant length of 2 ms, i.e., 500 OFDM symbols. Inside a frame a dynamic time division multiple access (TDMA) structure with time division duplex (TDD) is applied. The beginning of a MAC frame is marked by the occurrence of the broadcast channel (BCH). The BCH carries a logical channel, called broadcast control channel (BCCH) which contains control information about the cell and the frame structure. In Fig. 1 the structure of a HiperLAN/2 MAC frame is shown.

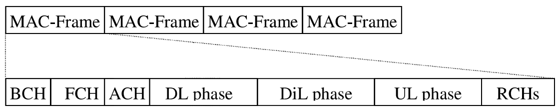

Fig. 1. Structure of the HiperLAN/2 MAC frame.

The frame channel (FCH) carries the frame control channel (FCCH), which provides the information about the allocation of slots in the downlink (DL), direct link (DiL) and uplink (UL) phases. Two types of slots exist: short slots, which are 9 bytes long and can carry 52 bits of (signalling) payload, and long slots, which are 54 bytes long and carry 48 bytes of payload. Short slots are mainly used for the transmission of the resource requests of wireless terminals (WTs in the following) as well as for ARQ feedback messages. Long slots are mainly used for data transfer as well as for some signalling messages.

There are two different modes of data communication: centralised mode (CM) and direct mode (DM). In the latter mode, which is used in the HEE, data is transmitted from one WT to another on direct links (DiLs). In the HEE, UL and DL communication is only used for some signalling messages.

There also exists a possibility for random access to the medium in so-called random channels (RCHs). These are mainly used by WTs that want to get into contact with a CC for the first time. The responses of the CC to access attempts, made in the RCHs of the previous frame, are contained in the association feedback channel (ACH).

For data transfer an ARQ protocol may be applied which uses partial bitmaps and selective repeat with discarding.

2.2. Hiperlan/2 home environment

In the HEE another error control scheme for real-time data has been specified as an optional choice. This scheme uses no ARQ but an additional Reed Solomon – forward error correcting coding with interleaving. To further improve the support of real-time applications a fixed slot allocation (FSA) can be applied in the HEE for specific connections. An FSA connection always occupies the same part of each MAC frame for the entire lifetime of the connection. With FSA, no resource requesting and resource granting is necessary.

Further features of the HEE are a dynamic Direct Link Power Control scheme and a Link Quality Calibration mechanism. The Link Quality Calibration enables the CC to build a complete topology map of the subnet [2].

The ad hoc networking concept of the HEE is realised by two functions: CC Selection and CC Handover.

The CC Selection algorithm ensures that only one CC per cluster is established. When powered on, each CC-capable station autonomously executes the CC Selection process.

The idea underlying the algorithm is that every CC-capable terminal withdraws from the selection process if it detects another CC-capable device. Consequently, there will be only one station left that takes over the CC function.

After an initial network configuration has been set up, handing over the CC function from one station to another will be a frequent task. All information on WTs and DiL connections has to be transferred during such a CC Handover. The CC Handover therefore consists of two main parts: associated signalling and data transfer.

The CC Handover is initiated by the current CC, which chooses a CC-candidate based on the clustering rule and sends a CC Handover request to this device.

After successful transmission of the RLC data, the old CC indicates to the CC-candidate a frame when to take over BCCH and FCCH transmission. This guarantees a seamless presence of the MAC frame.

Note that even though the RLC is stopped during CC Handover, the data transfer goes on as usual for all *existing* connections.

In [3] the CC Handover has been presented and analysed in detail.

3. Multihop networking concept

The HEE is designed for one single cluster. The system is extended in this section to a multi-cluster and multihop network. The concept is very similar to the one presented in [5].

In such a network, interconnection of the different clusters is a key issue and will be treated in Section 3.1.

Whereas in the HEE a CC Handover is mainly carried out if the current CC is switched off or runs out of power, re-clustering (enabled by the CC Handover procedure) will be a frequent task in multi-cluster networks. We will deal with it in Section 3.2.

Last but not least routing schemes are necessary in a multihop network. The routing scheme adopted in this paper is presented in Section 3.3. For further information on routing in ad hoc networks the reader is directed to [6] and [7] and the references therein.

3.1. Interconnection by means of "forwarders"

Terminals of two different clusters can only communicate via terminals that are able to participate in both networks. A terminal can only participate in different clusters at the same time, if it is in the transmission range of the CCs in the respective clusters. Such a scenario is illustrated in Fig. 2 for the two leftmost clusters.

The traffic can then be forwarded from one cluster to another by the terminal in the middle, which will therefore be called "forwarder".

Due to the CC selection process carried out at network set-up and due to the dynamic frequency selection (DFS) of HL/2, two neighbouring clusters will operate on two different frequencies. Forwarding in the frequency domain is therefore necessary. If we assume, that each terminal is equipped with only one transceiver, the forwarder has to switch from one frequency to the other

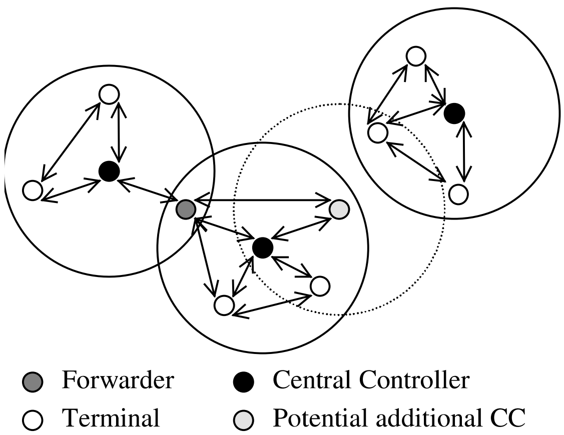

Fig. 2. Forwarding scenario.

consecutively. The frequency switching time is projected to be up to 1 ms in HL/2. Switching to the other frequency and back again will therefore cause an absence time of the forwarder of 2 ms during which the forwarder will not be able to participate in any communication. This absence time corresponds to one HL/2 MAC frame.

The MAC frames in two different clusters are not synchronised. Consequently, the forwarder is not only absent during the frequency switching T_S but he also loses waiting time T_W until the beginning of the next MAC frame. Such a situation is shown in Fig. 3.

It is assumed in this case that the forwarder participates in one cluster for exactly one MAC frame. Based on considerations elaborated from Fig. 3, the traffic a forwarder is able to carry under this assumption, amounts to only a quarter of the available capacity on one frequency channel.

In the other extreme case that the forwarder participates in each of the two networks for a very long time, the absence times become negligible. The forwarding capacity results to be half the capacity of one frequency channel.

In any chosen solution, the maximum user data throughput that can be achieved for forwarded connections lies in between 1/4 and 1/2 of the maximum system throughput on a single hop. For HL/2 the maximum 1-hop user data throughput amounts to 45 Mbit/s [4]. The throughput of the forwarded connections depending on the number of frames the forwarder stays in each cluster is shown in Fig. 4.

A trade-off between high throughput and low delay can be observed, because the transmission delay increases with the number of MAC frames

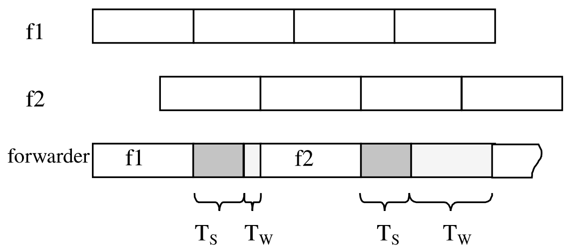

Fig. 3. Absence times of the forwarder.

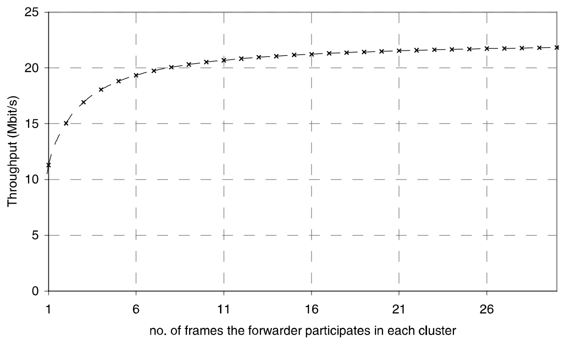

Fig. 4. Throughput versus number of frames in a cluster.

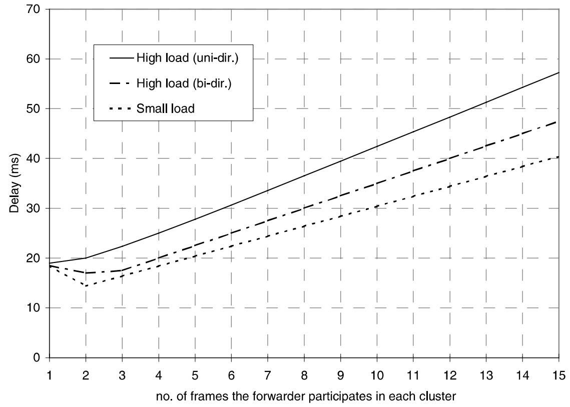

Fig. 5. Delay versus number of frames in a cluster.

the forwarder stays in each cluster (cf. Fig. 5). In Fig. 5 "high load" condition refers to a situation in which the forwarder uses the whole frame for its communication when present in a cluster. "Small load" condition means that the forwarder has only a few packets to forward. The difference in the delay times can be explained by the fact, that in the high load situation a part of the forwarding data has to be delayed until the beginning of the next switching cycle, whereas in the small load situation all data can be transmitted in the same switching cycle.

In general, a forwarder could inter-connect more than two clusters, even though this is not recommended due to the involved frequency switching and waiting times. If possible, several forwarders could be used two connect the same two clusters.

For the installation of a forwarder either a specific set-up procedure or existing HL/2 RLC procedures like "MT-ABSENCE" can be used.

No forwarding is possible, if no terminal exists that is able to participate in both networks. A clustering algorithm has been designed which resolves insofar as possible such situations.

3.2. Dynamic clustering

Reasons for re-clustering of the network may be:

- switch-off of a current CC,
- power constraints of a CC,
- poor connectivity of one or multiple terminals,
- capacity constraints in one or several clusters,
- new or ending connections,
- movement of the terminals.

The clustering has to serve different concurrent objectives:

- minimum number of cluster changes,
- minimum number of clusters,
- optimum capacity allocation,
- minimum number of discontinued connections,
- minimum number of terminal handovers,
- optimum routing,
- guaranteed interconnection of clusters.

Most known clustering algorithms form clusters based on clustering criteria that normally do not take into account the QoS requirements inside a cluster. In this analysis it is considered that the number and location of clusters depends not only on the topology of the network, but also on the maximum allowed load per cluster, assumed to be 20 Mbit/s in our simulations. To cope with these requirements, two matrices are introduced: a distance matrix and a traffic matrix.

An element of the distance matrix equals the distance between a pair of WTs. The matrix can be built based on the Calibration procedure defined in the HL/2 HEE. This calibration process foresees that each WT is frequently polled by the CC to report about received signal strength (RSS2) values of all other WTs. By this means the CC can build a RSS2 matrix of its subnet. Fig. 6 gives an example of the structure of an RSS2 matrix.

As all RSS2 measurements of the WTs are carried out at maximum transmit power of the

	MAC-ID1	*MAC-ID2*	*MAC-ID3*	...	*MAC-IDn*
MAC-ID1		RSS2 1 ← 2	RSS2 1 ← 3	...	RSS2 1 ← n
MAC-ID2	RSS2 2 ← 1		RSS2 2 ← 3	...	RSS2 2 ← n
MAC-ID3	RSS2 3 ← 1	RSS2 3 ← 2		...	RSS2 3 ← n
...	...	...	...	...	...
MAC-IDn	RSS2 n ← 1	RSS2 n ← 2	RSS2 n ← 3	...	

Fig. 6. RSS2 matrix of the network.

sender, the distance matrix can be easily derived from the RSS2 matrix. It is proposed here (see Section 3.3) to exchange RSS2 matrices between CCs, to obtain a global topology map of the network.

The traffic matrix has a similar outlook to the RSS2 matrix in Fig. 6. An element of the traffic matrix contains the mean data rate in one direction of a connection between a pair of WTs. It might also contain other QoS parameters like maximum delay, delay jitter or packet loss of the connection. The matrix can be built inside the CC by considering resource requests of WTs over a certain time interval.

3.2.1. Basic algorithms

New algorithms have been developed which make use of the two matrices discussed above. These algorithms are compared against the well-known *Lowest ID (LID)* algorithm. With the latter, the device with the lowest ID always becomes CC. The algorithm does not take into account any capacity constraints. Nevertheless the algorithm is considered in the following to serve as a reference as far as the (minimum) number of clusters as well as of CC Handovers is concerned.

Two clustering algorithms are introduced to account for capacity restrictions of the clusters:

3.2.1.1. Lowest distance value (LDV). Each terminal computes the sum of all distances to its direct (1-hop) neighbours divided by the number of the 1-hop neighbours. The terminal for which this sum is lowest becomes the first CC. All 1-hop neighbours join this cluster starting with the nearest ones (as long as capacity is available). Instead of the distance the Received Signal Strength (RSS2) could be used, in which case the terminal with the highest average RSS2 of all its 1-hop neighbours becomes CC.

3.2.1.2. Highest in-cluster traffic (ICT). The idea is to build clusters based on the traffic of each terminal with its direct neighbours, to minimise the forwarding traffic. Every terminal knows its 1-hop neighbours and can calculate its total traffic with them. The terminal with the highest direct neighbour traffic is selected as CC. All 1-hop neighbours of this terminal join the cluster (as long as capacity is available).

3.2.2. Enhancements

3.2.2.1. Check changes (ChCh). Aiming at a minimisation of re-clustering events, a useful enhancement to the previous algorithms has been developed, called the “check changes” algorithm. At first, the algorithm tests if the old cluster configuration can be kept further on. Only if the old configuration is not possible, the normal clustering algorithm is called. The check changes algorithm can be combined with any of the above clustering rules.

3.2.2.2. Guarantee forwarding. As mentioned before, the clustering may lead to situations, in which two clusters are not interconnected by a forwarder. The “guarantee forwarding” algorithm has been conceived to resolve such a situation.

Every terminal frequently scans for terminals on other frequencies. Note that procedures for this purpose already exist in the HL/2 standard. If a terminal has detected another cluster, it asks the CC if a forwarding possibility to this cluster exists. If this is not the case (i.e. there are two terminals that can hear each other but that are not connected), one of the two terminals becomes a CC. By these means the “gap” between the two existing clusters is filled by a new cluster (see Fig. 2). Forwarding nodes can then be easily installed.

3.3. Applied routing scheme

We have developed a routing algorithm called hierarchical time-vector-routing (HTVR), which is based on routing tables that are stored at the CCs and periodically updated by message exchanges of the CCs.

Each routing table contains one field per terminal in the network as well as the time t_{up} at which the table was last updated. Each of the terminal fields has five entries: the identifier of the forwarder to which the data of the respective terminal has to be directed, the path length, the maximum transmission rate of the path, a so-called field generation time t_{gen} and a field registration time T_{reg}. If the terminal is roaming in the cluster of a CC, the forwarder entry of the terminal field at the routing table of this CC is empty.

The entry t_{gen} indicates, when the terminal has changed the cluster for the last time and the entry t_{reg} stores, when the field has been updated for the last time by the CC that stores the respective routing table. The updating procedure foresees that a CC periodically sends its t_{up} to all its neighbouring CCs and asks for all their terminal fields which have a generation time $t_{gen} > t_{up}$. The fields received are then updated in the routing table of the updating CC, if certain update criteria are met.

The HTVR algorithm is described in detail in [8].

4. Performance evaluation

4.1. Simulation scenario

We simulate the different clustering algorithms by placing 15 devices in a 50×50 m area. Results are given in the following for a Brownian movement of the terminals. This is a very simple model of a random terminal mobility. Each terminal has a fixed velocity and a uniformly distributed direction interval $(0, 2\pi)$.

The traffic per sender WT is uniformly distributed from 0 to 6 Mbit/s. The overall traffic load is fixed to 40 Mbit/s.

It is assumed that every device is CC-capable and has a unique ID. Within the clusters, Direct Link connections are used for the communication of two WTs. The cluster size is controlled through the radio power. In the simulations the transmission power is fixed for all WTs/CCs. We assume that two terminals can hear each other if their distance is in the transmission range, which is set to 30 m.

4.2. Results

In Fig. 7 the resulting average number of CC Handovers per time unit is shown depending on the velocity of the terminals.

As expected the LID algorithm gives the most stable configurations, but it has to be considered, that the LID does not take into account any capacity restrictions and that the load inside the clusters may exceed the capacity of 20 Mbit/s. The LID therefore only serves as a lower bound for the number of CC Handovers per time unit. As it is shown in Fig. 7, the LDV and the ICT result in a comparable number of CC Handovers per time unit with the ICT being slightly superior in terms of stability. The check changes algorithm improves the performance of the algorithms by about 15%, which is shown for the case of ICT but which is true for LDV as well.

Regarding the number of terminal handovers per time unit (cf. Fig. 8) ICT and LDV produce almost identical results. The LID algorithm leads also in this category to the best results, which is

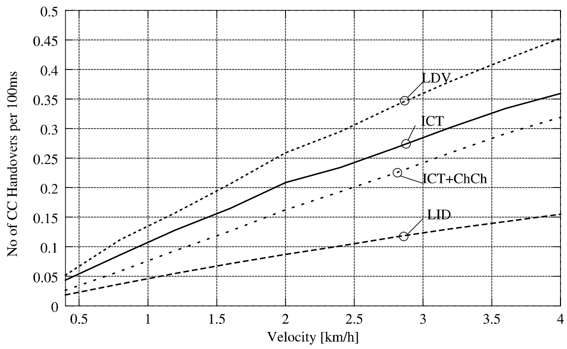

Fig. 7. Number of CC Handovers versus velocity.

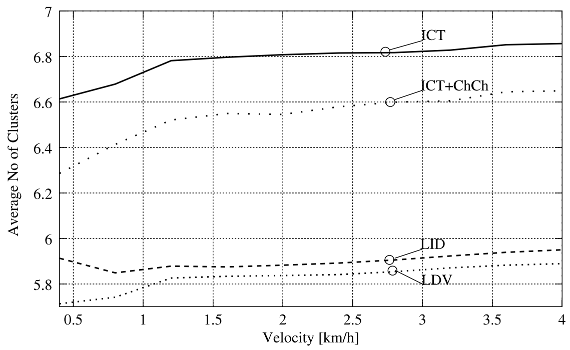

Fig. 8. Number of terminal handovers versus velocity.

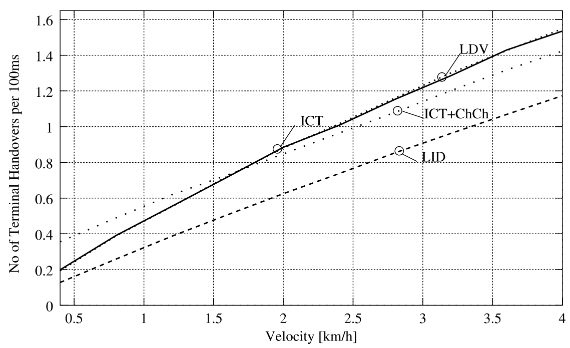

Fig. 9. Average number of clusters.

due, again, to the fact that capacity restrictions are not considered.

Finally, the average number of clusters is illustrated in Fig. 9, where LDV appears to be even superior to the LID. This is not surprising as the LDV optimises the clustering considering the physical topology of the network. The application of ICT or ICT + ChCh results in one additional cluster compared to LID and LDV, independently of the velocity of the terminals.

Simulation results have illustrated that a trade-off has to be made between a low number of CC Handovers on the one hand and a low number of clusters on the other hand. Weighting the importance of the two criteria, a low number of CC Handovers has certainly to be preferred considering the traffic overhead that a CC Handover induces to the network.

In this perspective, the "highest in-cluster traffic" algorithm in combination with the check changes algorithm is the preferred solution also considering that the algorithm minimises the forwarding traffic, which is not reflected in the figures.

5. Conclusions

A concept of a wireless centralised multihop ad hoc network has been presented. The proposed concept is based on the HL/2 HEE, which is the first standardised ad hoc network able to provide quality of service guarantees to the users [4].

The HL/2 HEE foresees only one single cluster which restricts the coverage area of the system to 30–100 m. Multi-cluster, multihop networks will probably be the subject matter of the second standardisation phase of the HEE.

Three major fields of research have been identified in this analysis: the forwarding problem, dynamic clustering of the network, and finally routing. A solution has been proposed to achieve inter-connection of neighbouring clusters by forwarding in the frequency domain.

Furthermore, different clustering schemes have been developed which take into account the topology and the capacity restrictions in the network. Simulations have proven the stability and applicability of these algorithms. A solution has been conceived to cluster in such a way that overlapping of clusters is guaranteed as far as possible to enable forwarding in between clusters.

In the simulations instantaneous updating of information has been assumed and signalling traffic for information request and updating procedures disregarded. We are currently evaluating the signalling overhead associated with the developed procedures but do not expect that the applicability of the algorithms is endangered. Most of the signalling procedures needed are already available in the HL/2 system.

By applying the presented concepts the network can extend over a large area enabling multihop connections of mobile users roaming in different clusters. The compatibility with the HL/2 standard, which would be upgraded in the way presented, ensures the practical relevance of the concept.

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Martin Nadler received his diploma degree in electrical engineering from Aachen University of Technology in Germany in 2000. A part of the work presented was carried out in the framework of his diploma thesis on “development of algorithms for dynamic clustering of mobile users in wireless ad hoc networks”. Further research interests of Mr. Nadler have been QoS provision in wireless IP and routing strategies for wireless ad hoc networks. In August 2000, Mr. Nadler joined Deutsche Bank AG, where he is currently working on call center technologies.