A Comparison of New Single- and Multiple-Transceiver Data Forwarding Mechanisms for Multihop Ad Hoc Wireless Networks

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A cluster-based multihop ad hoc network is considered, in which different clusters are inter-connected by Forwarding Terminals (FTs). Because the clusters operate on different frequencies, a FT has to switch the frequency to forward data from one cluster to another. Due to switching, waiting and absence times of the FT, data forwarding represents a bottleneck of the network in terms of throughput and delay. Therefore, efficient data forwarding mechanisms are needed on Medium Access Layer to optimize the performance of the network.
In this paper two different solutions for efficient forwarding of data in-between sub-nets are presented. The first one foresees FTs that are equipped with only one transceiver. Efficient capacity allocation, respectively scheduling, mechanisms are developed in order to minimize the propagation delay. As an alternative solution it is proposed to equip the FTs with multiple (usually 2) transceivers. By these means, switching and absence times could be eliminated. Simulations are carried out to assess if the additional hardware complexity could be justified by a considerable gain in throughput or delay performance.

Keywords: ad hoc network, forwarding, MAC, HIPERLAN/2, dual-transceiver

1 INTRODUCTION

Ad hoc networks, that are sometimes also called self-organizing networks, do not contain any wired core or backbone network and are thereby 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. The latter is owing to the convenience of a possible plug-and-play installation of the system.

The size of the area covered by an ad hoc network 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 links comprise several radio hops, whereas infrastructure-based communication uses only one radio hop from the so-called Base Station to the terminal (downlink) or vice-versa (uplink).
Beside classic decentralized ad hoc networks, like the IEEE 802.11 system (in the so-called contention mode), there is another class of ad hoc networks based on clusters of terminals [1, 2].
In each cluster, the Medium Access Control (MAC) and/or routing are performed by one specific station, called the Cluster Head or Central Controller (CC). The HiperLAN/2 Home Environment Extension (HEE) standardized by the European Telecommunications Institute (ETSI) is an example of a cluster-based ad hoc network, even though the current standard foresees only a single cluster. In such a network, Quality of Service (QoS) provision is eased owing to the central capacity allocation and it is possible to re-use protocols of infrastructure-based systems thereby enabling interoperability of the infrastructure-based system and the ad hoc network.
In Figure 1 the cluster-based ad hoc networking topology is illustrated.
It has been shown in [2] that in such a cluster-based network three main problems arise:

- Clustering of stations,
- Interconnection of clusters, respectively forwarding of data and
- Routing of data packets.

We have presented solutions to the clustering problem in [2], [3] and [4]. Other clustering algorithms are e.g. described in [5] and [6].

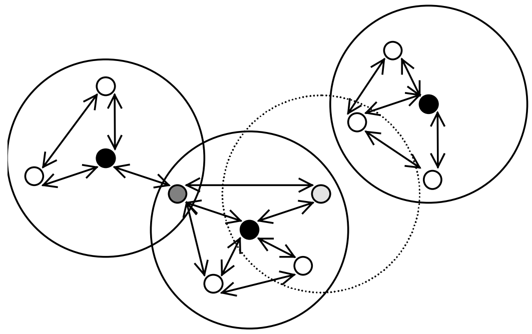

Figure 1 Cluster-based network architecture

Regarding routing in ad hoc networks several schemes have been proposed. „Dynamic Source Routing“ (DSR) [7], „Zone Routing“ [8], and „Ad hoc On-Demand Distance Vector Routing“ (AODV) [9] are only some of the available routing schemes for this type of network. In our case, due to the clustered network structure, a hierarchical routing scheme may be appropriate. The advantages of hierarchical routing schemes are e.g. described in [10] and [11]. We have presented a new routing scheme, which is specifically adapted to the clustered network structure, in [12].

The inter-connection of clusters will be addressed in the present paper. For the analysis we assume a Time Division Multiple Access (TDMA) MAC scheme like the one of the HIPERLAN/2 system. For such a MAC scheme efficient mechanisms for the forwarding of data between the clusters are presented. Two different solutions are proposed which solve the problem of unacceptable forwarding delay and throughput. Before the problem of the forwarding delay is described, a brief overview of the HIPERLAN/2 system is given in the next section. The remainder of the paper describes the two new data forwarding schemes, possible improvements and associated performance evaluation results.

2 HIPERLAN/2 AD HOC NETWORK

2.1 Introduction to HiperLAN/2

The harmonized physical layer of HiperLAN/2 (HL/2) and 802.11a for the 5 GHz-band provides a data rate of up to 54 Mbit/s resulting in a maximum user data rate of 43 Mbit/s in the case of HL/2.

On MAC layer 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).

A so-called Frame Channel (FCH) carries the information about the allocation of slots in the Downlink (DL), Direct Link (DiL) and Uplink (UL) phases of the frame. Two types of slots exist: short slots, which are 9 bytes long and can carry 52 bits of (signaling) payload, and long slots, which are 54 bytes long and carry 48 bytes of payload.

Resource allocation is based on a resource requesting – resource granting mechanism: The terminals send resource requests (RR) to the CC, which answers with appropriate resource grants in the next or one of the following MAC frames.

2.2 Hiperlan/2 Home Environment

To improve the support of real-time applications either a so-called Fixed Capacity Agreement (FCA) or a Fixed Slot Allocation (FSA) can be applied. Both FCA and FSA do not use any resource requests, but instead a fixed capacity is allocated to a FCA or FSA connection for the entire duration of the connection. The difference between the two schemes is, that for FCA connections the start-point of the allocated slots is signaled in each MAC frame in the FCH, whereas an FSA connection always occupies the same part of every MAC frame. This means that with FSA, neither resource requesting nor resource granting is necessary.

The ad hoc networking concept of the HEE is realized 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 station autonomously executes the underlying algorithm.

During operation, the CC function can be handed over from one station to another by means of the CC Handover procedure. In [3] the CC Handover has been presented and analyzed in more detail.

The current standard foresees only one single cluster of terminals. It will be described in the following how the network could be extended over several clusters by introducing mechanisms for the inter-connection of several clusters on MAC layer.

3 FORWARDING MECHANISM AND ASSOCIATED TROUGHPUT RESRICTIONS

Terminals of two different clusters can only communicate via terminals that are able to participate in both networks. A terminal can only participate in two clusters at the same time, if it is in the transmission range of both Central Controllers (CCs) in the respective clusters. Such a scenario is illustrated in Figure 1 for the two leftmost clusters. In this figure the gray terminal in the overlapping zone forwards data from the leftmost cluster to the cluster in the middle and vice-versa.

In HL/2, two neighboring 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 FT has to switch from one frequency to the other consecutively. The frequency switching time can amount up to 1 ms. Switching to the other frequency and back again will therefore cause an absence time of the FT of up to 2 ms during which the FT will not be able to participate in any communication. This absence time corresponds to one HL/2 MAC frame.
If the MAC frames in two different clusters are not synchronized, the FT is not only absent during the frequency switching T_S but it also loses waiting time T_W until the beginning of the next MAC frame. Such a situation is shown in Figure 2 [2].
It is assumed in this figure that the FT participates in one cluster only for one MAC frame. It can be depicted from Figure 2, that in this case the traffic, a FT is able to carry, amounts to only a quarter of the available capacity on one frequency.

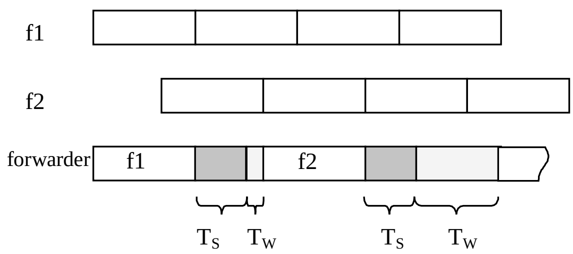

Figure 2 Absence times of the FT

In the other extreme case that the FT 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 available capacity for forwarded connections lies in between ¼ and ½ of the maximum user data rate (~43 Mbit/s), as can be depicted from Figure 3. Three scenarios are illustrated. It can be seen that the throughput for a FT with symmetric presence times is independent of the symmetry of the load (identical curves). It is furthermore illustrated that a symmetric FT performs better in terms of throughput than a FT with asymmetric presence times (one frame more in destination cluster), even in case of asymmetric (i.e. unidirectional) load.

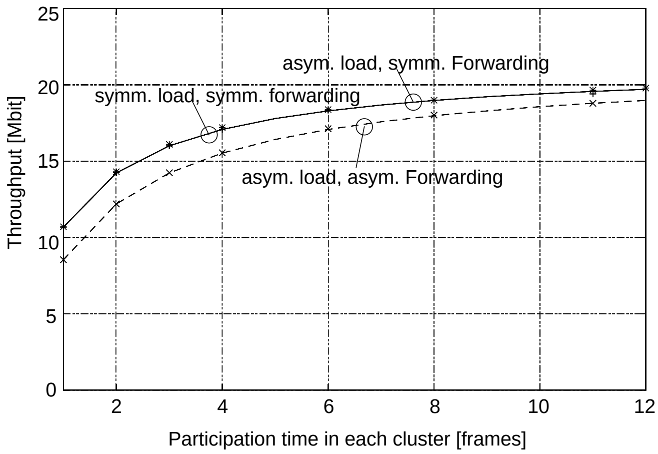

Figure 3 Throughput depending on presence time per cluster

4 NEW DATA FORWARDING SCHEMES

In this section two alternative solutions are presented how the data forwarding process can be optimized and a throughput and delay bottleneck prevented.

4.1 FT set-up and prioritization

This first solution foresees that the FT is equipped with only one transceiver. The following solutions are proposed to minimize the forwarding delay:

1. The FT is installed by the CCs of the involved sub-nets by means of a “FT set-up” procedure.
2. In this set-up procedure it is negotiated how long (rsp. for how many frames) the FT stays in one cluster and in which cluster the FT is present at a specific start time. The advantage of this solution is that the presence of the FT in a cluster can be predicted by the CC and that the CC can therefore take this into account during the scheduling process.
3. A “FT modify” procedure can be used to change the number of frames a FT stays in one cluster, if this becomes necessary or appropriate during the “life-time” of the FT. Very similar to the “FT set-up” procedure, the “FT modify” procedure is a message exchange to re-negotiate the parameters of the forwarding process between the involved clusters.
4. Because the FT is a bottleneck in the throughput and delay performance of the network, it is proposed that forwarding traffic be always prioritized with respect to in-cluster traffic. However, service specific priorities should be kept and respected. We have therefore foreseen, that the service specific priority of a connection is increased by n levels ($n \in 1,2\ldots$), in case of an inter-cluster-connection.

5. To minimize the delay of the forwarded data, a fixed capacity rsp. channel based allocation scheme is proposed for the forwarded connections that are the most delay-sensitive. In HL/2 one of the two schemes “Fixed Capacity Agreement” (FCA) or “Fixed Slot Allocation” (FSA) should be used for these inter-cluster-connections. The advantage of this solution is that no resource requesting (and in case of FSA even Resource Granting) is necessary which would induce further delays in combination with the frequency switching of the FT.
6. If fixed capacity allocation is used, the amount of frames the FT stays in the source and destination cluster shall be identical (symmetric).
7. The number of frames, the FT stays in one cluster, shall be chosen according to delay and throughput restrictions. A trade-off between these two performance characteristics has to be made.
8. If no fixed capacity allocation is used, the FT shall stay at least two frames in the destination cluster. The reason is that in the first frame the FT can only transmit a resource request and that only in the second frame the data can be transmitted after a resource grant by the CC of the destination cluster. Asymmetric presence of the FT in the involved clusters may be appropriate in case of streaming (rsp. unidirectional) data.
9. We propose that a sliding synchronization should be performed in such a way that the frames of two inter-connected clusters are shifted by exactly half a MAC frame. In section 5 we will show that the accuracy of the synchronization can be relaxed if the switching time of the FT is smaller than 1 ms. With synchronization of the clusters, the duration of the switching cycle of a FT can be reduced by one MAC frame, which gives a gain in the average delay performance of about 1 ms.
   The sliding synchronization is achieved by lengthening or shortening the MAC frames in one of the two clusters. The FT, which is aware of the time shift between the MAC frames in the two clusters, requests one of the two CCs to carry out the necessary time shift. This CC then selects during how many MAC frames it will complete the time shift. If a time shift of 1 ms (extreme case) was necessary and a duration of the sliding synchronization of e.g. 250 MAC-frames (5 s) selected, each of the 250 frames would only have to be lengthened or shortened by 4µs (equal to one ODFM symbol in HL/2). A periodic update of the synchronization by means of a FT request to one of the two CCs might be needed in order to maintain synchronization. Figure 4 illustrates the sliding synchronization for the example of lengthening the MAC frames. In this figure the upper MAC frames are lengthened to a length T_l, whereas the MAC frames in the lower cluster have the normal length T_n. Once the synchronization is achieved the MAC frames in the upper cluster again have the normal length T_n.
10. In the last frame of the presence time of the FT in a cluster, the CC shall allocate the resources for the FT at the beginning of the data transmission phase. The FT then switches to the other cluster directly after its own transmission and reception, because its presence is not required any more during the respective MAC frame. This technique has the same positive effect than a decrease of the switching time, which will be described in section 5. If the two clusters are synchronized (without the 1ms shift), a complete elimination of waiting times might be achievable.

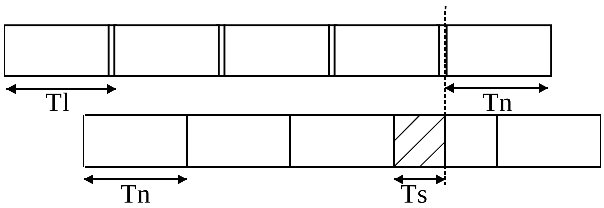

Figure 4 Sliding Synchronization

4.2 Multiple-transceiver solution

Another solution to circumvent the delay and throughput bottleneck is to equip the FT with multiple transceivers. In the following two transceivers are assumed for simplicity.

In this case the FT can operate in two networks at the same time. No switching of the frequencies is necessary. Therefore no switching and absence times occur.

The main issue for this type of device is the simultaneous transmission and reception at the same time and in the same place. The transmitter (TX) and receiver (RX) frequencies have to be kept well separated and the antennas physically far apart. Two antennas, one for each transceiver (or each transmitter and receiver pair), are required.

At the present time (within the constraints of the current specification) Dynamic Frequency Selection (DFS) is based on a random channel selection and so there is very little control over the separation of the TX and RX frequencies. This will result in a minimum, not negligible distance between TX and RX antenna.

Since each transceiver is arbitrarily spaced in frequency from the other, they cannot share the same local oscillator. So at this point one could come to the conclusion that two complete, well-separated transceivers are needed. However there might be some scope for sharing of the transceiver elements.

The first thing to note is that when one transmitter is transmitting its associated receiver is not doing anything. The problem here is that the exact MAC phases (BCH, DL, DiL etc) for each of the two radio connections will be slightly different. Therefore simultaneous transmission (or reception) in both clusters might occur. Consequently, two TX and RX per FT are required. However, it might be worthwhile to consider how the TX and RX phases of the FT during the MAC frames in two clusters could be coordinated in order to avoid parallel transmission (or reception) in both clusters. If this had been made possible, long guard periods at the point of TX to RX turn-around could be used to switch the frequency of the TX rsp. RX.

Another point that arises here is exactly what happens to the data between the RX and the TX. If the data is decoded by the RX and sent to the MAC before being sent to the TX, then there will be some latency. Unfortunately a decoding seems to be unavoidable, as new packet trains will probably be formed on the next hop.

If the requirements dictate that the forwarding device has to be free to transmit (or receive) on both connections at any instant during the MAC frame then most of two complete transceivers per forwarding terminal are needed. Again there must be two separate antennas, in this case one antenna feeds two receivers, the other feeds two transmitters. Some components can however be shared or saved. Firstly the TX/RX switches are no longer needed. Secondly one TX power amplifier can be shared and used simultaneously. It will need to be a bigger device but this is probably less costly than two standard devices. Two local oscillators are still needed to deal with the DFS situation but there is now no need for fast frequency switching, the standard HL/2 synthesizer can be employed. The rest of the TX needs to be doubled if the system is to be capable of transmitting on both connections simultaneously.

The same requirements apply to the RX. The front-end filter and maybe the low noise amplifier can be shared, but after this everything needs to be doubled up. There will be basically two complete transceivers except the shared RF front-end devices. The power consumption of the two transceivers will obviously be more than one but not twice since they are individually transmitting on average 50% of the time.

5 PERFORMANCE ANALYSIS

5.1 Delay of different FT types

This analysis assumes that the FT will participate synchronously in both of its clusters for a certain number of MAC frames *n*. In every switching cycle two MAC frames are lost due to the switching and waiting time constraints as described above.

This leads to an overall switching cycle *c* equal to $2*n + 2$ MAC frames. The terminology *n/c forwarder* refers to a FT that stays n MAC frames in each of its clusters within a cycle period of *c* MAC frames.

As suggested in section 4.1, a special FT set-up is assumed that makes the cyclic, regular participation and absence times of the FT known to the CCs of both clusters.

This dedicated FT set-up increases performance and reduces delay by avoiding unnecessary RLC signaling in every switching cycle.

Because the CC knows the times during which the FT is present in its cluster, it withholds resource grants corresponding to previously received RRs until the FT switches back to the cluster.

Assuming enough transmission capacity to transmit all requested user data within one switching cycle, the following reflections should be done to minimize the packet delay, which is an important QoS characteristic.

Mainly two effects have to be taken into account.

On the one hand the switching cycle should obviously be kept as short as possible, which would lead to the 1/4 forwarder concept.

On the other hand the first MAC frame in the destination cluster is needed in order to transmit the FTs RR. Only the second MAC frame can be used to transmit user data from the FT to the destination. Due to this effect a 2/6 forwarder concept is to be preferred over a 1/4 concept and all other forwarder concepts with longer cycle times.

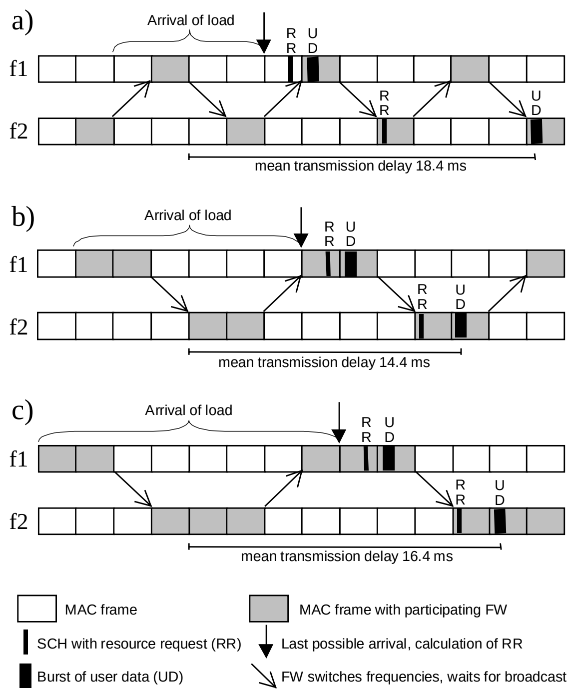

Figure 5 Forwarding examples

Figure 5 shows a communication example for the three basic concepts a) 1/4 forwarder, b) 2/6 forwarder and c) 3/8 forwarder. In this basic analysis it is assumed to have only little load.
It is assumed that for the depicted transmission cycle the user load arrives within the shown period according to a uniform distribution. This causes an initial average delay of half of the transmission cycle. At the beginning of the next frame the RR from the source terminal is calculated and transmitted. Later arriving user load can not be considered in this FT switching cycle. In the subsequent MAC frame the user data is transmitted from the source terminal to the FT (assuming a Direct Link connection between them). Then the FT switches to the other frequency (rsp. cluster). The maximum switching time in HL/2 of 1 ms and the mean broadcast waiting time of another 1 ms (half MAC frame) coincidentally lead to the depicted synchronous clusters as the scenario of the mean delay case. In its first active frame in the destination cluster the FT transmits its RR to the respective CC. In the subsequent active frame the FT can send its user data load to the destination terminal.
Figure 5 shows the different mean transmission delays caused in one switching cycle of each of the three forwarding concepts.
It can be seen that although the 1/4 forwarder has the shortest switching cycle, the 2/6 forwarder performs with the minimum delay, because the 1/4 forwarder has to wait for a whole switching cycle before it can make use of its previously transmitted RR.
Also the 3/8 forwarder performs worse than the 2/6 forwarder in terms of delay because of its longer transmission cycle and thus its longer mean waiting time before traffic can be taken into account by the calculation of the RR in the source cluster.
In terms of delay the 2/6 forwarder performs best.
For the average packet delay Figure 6 shows analytically derived curves as well as simulation results which are represented as points on the analytical lines.
We have implemented the developed procedures and algorithms in our WILMA (Wireless LAN Multihop Ad hoc) simulator. In this simulator all protocols are formally specified in the Specification and Description Language (SDL) and afterwards translated into C++ code by a code generator called SDL2SPEETCL, where SPEETCL stands for “SDL Performance Evaluation Tool Class Library”. All algorithms are directly implemented in C++.
In Figure 6 highest load corresponds to the maximum throughput of the respective *n/c* forwarder (cf. Figure 3). Small load refers to a load of 1 Mbit/s.

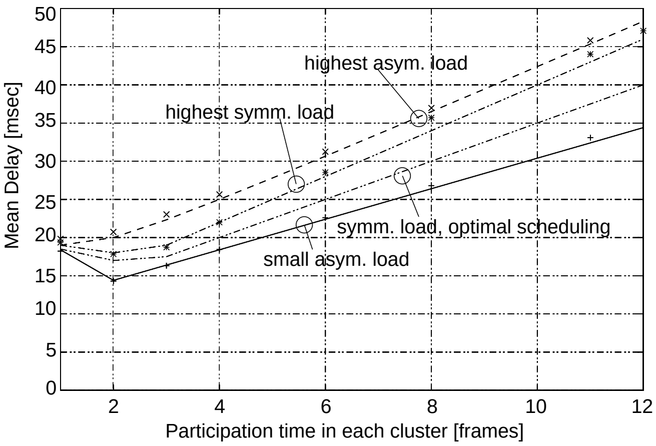

Figure 6 Forwarding delays

5.2 Impact of improvements

Asynchronous forwarding

Assuming equally good link quality in the source and destination cluster, a major source of additional delay, especially in high load conditions with unidirectional data flow, is that the first MAC frame of the destination cluster has to be used for the RR of the FT. This forces the FT to delay its remaining load until the first active frame in the next switching cycle. The probability for this event can be reduced if the FT stays one MAC frame longer in the destination cluster than in the source cluster, which leads to a slightly asynchronous forwarding approach. As can be seen in Figure 7 this has a considerable effect especially for small presence times.
Asynchronous forwarding should also be used in case of big differences in the link quality in the two clusters. The FT should stay more MAC frames in the cluster with the slower connection in order to avoid congestion and buffer overload and thus strong increase of the delay times. During the lifetime of the FT, its participation times in each cluster can be adapted to the requirements of the traffic situation by the suggested FT modify procedure.

Fixed capacity agreement, FCA

Because of the regular cyclic participation in each cluster of the FT set-up approach, fixed capacity agreement can be used and thus delay is reduced significantly due to the omitted waiting times caused by the resource request mechanism.
This has a major effect especially for the 1/4 forwarder as depicted in Figure 7.
Nevertheless, the use of FCA requires as well that the employed scheduler is able to withhold the resource grants until the FT comes back to the cluster.

Two transmitters

If two transmitters can be employed in the FT, the transmission delay remains constant and is equal to the delay of two independent DiL transmissions. As shown by Figure 7, a two-transmitter solution gives major advantages in terms of delay especially for high performance requirements. The delay stays almost constant.

Analytical and simulative results how the proposed improvements impact the delay performance are depicted in Figure 7. To facilitate the evaluation of the performance gains, also the graph of the synchronous scheduling with high unidirectional traffic load is shown as reference line.

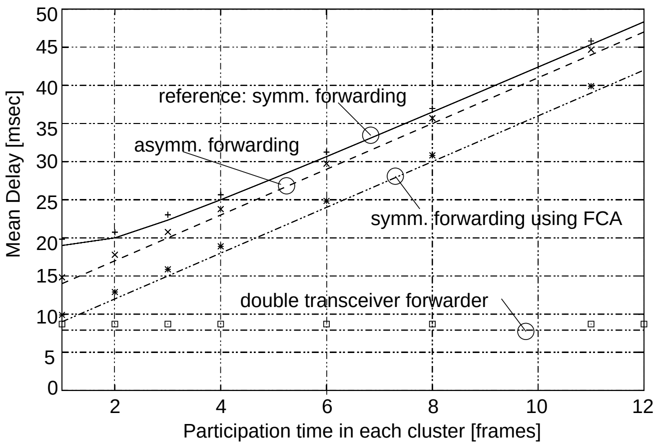

Figure 7 Impact of improvements

The curve for the asymmetric forwarding in Figure 7 has to be interpreted in such a way that the FT stays in the source cluster for the number of frames given on the x-axis while it stays one frame longer in the destination cluster.

Figure 8 illustrates the trade-off to be made between maximum throughput and mean delay for the different forwarding mechanisms. While asymmetric forwarding improves the mean delay only for small throughput requirements, FCA reduces significantly the delay for a given throughput. The double-transceiver solution shows again the best performance, especially for high throughput requirements.

In Figure 9 the effect of prioritization is shown. We have considered a scenario of two clusters with 1 inter-cluster-connection with an offered traffic of 9 Mbit/s and priority class 2 as well as in each cluster 3 in-cluster-connections of 9 Mbit/s each and priority classes 1 (lowest), 2 and 3 respectively. This leads to an average load of 36 Mbit/s in each cluster. It can be seen that the delay performance of the forwarded connection strongly depends on its additional scheduling priority. If the forwarded connection is not considered with extra priority, the FT does not get sufficient capacity during its presence in each cluster, while there would be enough free capacity in other frames when the FT is not present.

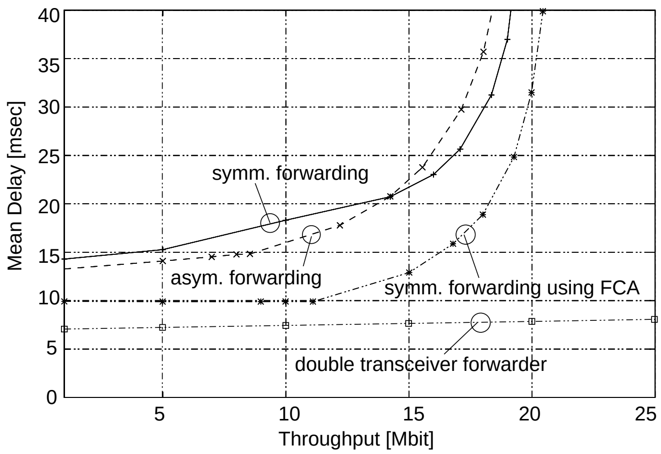

Figure 8 Throughput versus delay

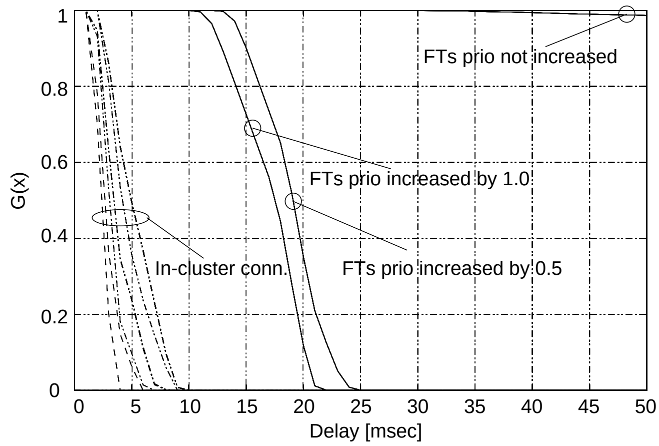

Figure 9 Effect of prioritization on CDF of packet delay

Figure 10 illustrates the mean delay of one unidirectional connection as a function of the time shift that the MAC frame in the destination cluster starts later than the one in the source cluster. First the delay increases linearly with the time shift between the clusters, because of the waiting time after switching. When the time shift becomes bigger than the switching time the delay is reduced abruptly by 3 ms. This is due to two effects. First, the FT can now synchronize almost directly after switching to the destination cluster while for a smaller time shift it had to wait for almost an entire MAC frame (2 ms). Secondly, within a time shift bigger than the switching time and smaller than 2 ms minus the switching time, the switching cycle can be reduced by one frame. This leads to a decrease of the average waiting time of 1 ms.

In case that the FT could switch fast enough to switch within the remaining part of its last present MAC frame (e.g. in the so-called RCH channel of HL/2) the mean delay could be reduced by another 1ms because of a further reduction of the switching cycle of 1 MAC frame. Another very important effect is that by reducing the switching cycle also the maximum throughput of the FT is significantly increased.

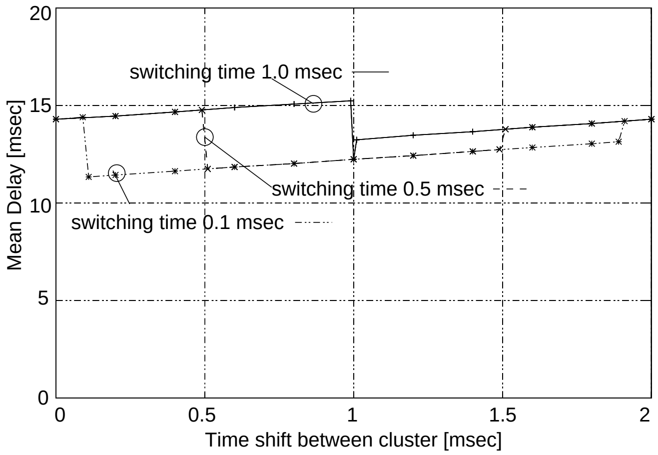

Figure 10 Effect of sliding synchronization

6 CONCLUSION

In this paper a new method for the interconnection of TDMA based sub-nets operating on different frequencies has been presented. The data forwarding mechanisms are used to build a multihop ad hoc wireless network.

The data forwarding requires that a FT equipped with only one transceiver has to switch frequencies during operation. The resulting throughput and delay have been analyzed in detail. Procedures have been developed to minimize the transmission delay. It has been foreseen, that a FT-set-up procedure has to be carried out, in order to guarantee to the CCs of the respective clusters predictable absence times of the FT. It has been shown that instead of a medium access scheme with resource requests and resource grants a fixed capacity allocation scheme should be used for multihop connections.

It has been analyzed how throughput and delay could be improved by equipping every FT with two transceivers. Analytical and simulation results indicate that the multiple transceiver solution provides a significantly better performance in terms of transmission delay and throughput compared to the single-transceiver-mechanism (especially in high load scenarios). The additional cost of a second transceiver has to be weighted against the cost of the big buffer space needed in a frequency-switching FT.

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