Performance Evaluation of HiperLAN/2 Multihop Ad Hoc Networks

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ABSTRACT

We analyse the performance of the HiperLAN/2 protocol in a multihop environment. It is shown by computer simulation that the limited transmitter-window size of the Automatic Repeat Request (ARQ) protocol is one of the key parameters with respect to the maximum achievable throughput on a single hop as well as on an end-to-end basis. Our results indicate that the currently standardized window-size is in some cases an important bottleneck in the system performance.
First, the performance of the network is evaluated for different modulation and coding schemes in a scenario without transmission errors. Afterwards, the influence of the ARQ-protocol is studied in the case of an erroneous channel. Simulation results indicate that there is a trade-off between signalling overhead and limitations due to the transmitter-window.

1 INTRODUCTION

Wireless networks can be divided into infrastructure-based and self organising networks. Traditionally, radio networks have always been infrastructure-based. However, interest in self organising networks has recently grown owing to the possible ad hoc deployment of the systems.

Whereas ad hoc networks were mainly used by the military in the past, various other applications are foreseen today. Examples are *Personal Area Networks* (PAN) for short range communication of small user devices, *Wireless Local Area Networks* (WLAN) mostly for user and data communication and *In-house Digital Networks* (IHDN) for audio, video and data exchange. First communication standards with ad hoc capability have already been completed: Bluetooth (a wireless PAN), IEEE802.11a (a WLAN) and HiperLAN/2 (a WLAN and IHDN).

Two classes of ad hoc networks can be distinguished: *decentralized* and *centralized* (also called *clustered*) ad hoc networks.

In decentralized ad hoc networks the access scheme as well as the network management is completely decentralized. An example of such a network is the IEEE 802.11 system. Advantages of decentralized systems are their simplicity and their robustness against failures.

In centralized networks certain functions like the *Medium Access Control* (MAC) or the *Routing* are performed by one specific station per cluster, the so-called *Central Controller* (CC) or *Cluster Head*. The HiperLAN/2 Home Environment Extension (HEE) is organised in such a way. The advantage of centralized networks is the control of the quality of service and the possible reuse of infrastructure-oriented protocols and equipment.

It is the aim of this paper to evaluate the performance of a centralized ad hoc network based on the HiperLAN/2 standard. We have presented the concept of such a network in [1]. The concept is very similar to the one presented in [2]. So far this concept has only been analysed under the assumption of an error-free channel [1, 3, 4, 5]. However, the error control protocol can significantly influence the performance of the system.

We will first give a brief overview of the HiperLAN/2 standard and especially the error control protocol in section 2. In section 3 the performance of the protocol is analysed and simulation results are reported for a single cluster network. In section 4 the multi-cluster network concept is introduced. In this section we also study the influence of different propagation conditions in the clusters on the throughput and delay performance. The influence of the error control protocol on the performance of the multi-cluster network is treated in section 5. Finally, some conclusions are drawn in section 6 .

2 HIPERLAN/2 SINGLE-CLUSTER NETWORK

HiperLAN/2 (HL/2) is a wireless *Local Area Network* (LAN) standardized by the *European Telecommunications Standardisation Institute* (ETSI). In HL/2 two modes of operation are possible:

- In a base-station oriented mode the network is organized like a traditional cellular radio network, in which so-called *Access Points* (AP) act as base stations and access point to a wired core network.
- In the ad hoc mode no core network is present and the network is self-organising, i. e. one station is dynamically chosen to act as an AP, which is called *Central Controller* (CC) in the ad hoc mode. The advantage of this organisation is that the same centralized MAC protocol can be applied in both modes of operation.

2.1 Physical layer

On physical layer *Orthogonal Frequency Division Multiplexing* (OFDM) with 52 sub-carriers is used. Each sub-carrier can be modulated with four different modulation schemes (BPSK, QPSK, 16QAM and 64QAM). Forward error correction is achieved with a convolutional code with code rate 1/2 and constraint length 7. Different code rates (1/2, 9/16 and 3/4) can be achieved by the application of puncturing schemes. A combination of a modulation scheme and code rate is called a *PHY-mode*. With the highest PHY-mode (64QAM3/4) a data rate of 54 Mbit/s can be achieved.

In Fig. 1 the *Packet Error Ratio* (PER) versus the *Carrier to Interference Ratio* (C/I) is shown for the different PHY-modes. The curves have been derived by link level simulation [6]. It can be depicted, that the higher the PHY-mode the more its performance is degraded by interference and noise.

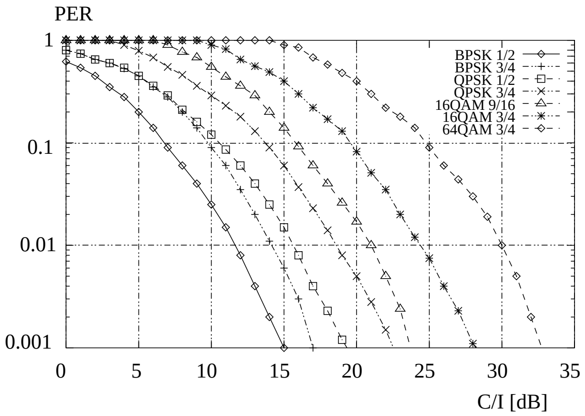

Figure 1: PER versus C/I

2.2 MAC protocol

The AP/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 access mechanism foresees that terminals request resources within so-called *Short Channels* (SCH) that are transmitted piggy-back to one or several data packets. Data are segmented and transmitted in packets of 48 byte length, that fit into so-called *Long Channels* (LCH). The AP/CC collects all *Resource Requests* (RR) received during a frame and allocates resources in the next MAC frame accordingly. The so-called *Resource Grants* of the CC are announced in a Broadcast Channel at the beginning of each MAC frame.

2.3 Error Control Protocol

Beside the FEC on physical layer, a *Selective Reject Automatic Repeat Request* (SR-ARQ) protocol is used on DLC layer. To signal erroneous packets to the sending terminal partial-bitmap acknowledgments are used, i.e. correct and erroneous packets are acknowledged in form of a bitmap. An acknowledgement, also called *ARQ-feedback PDU*, contains three *Bit Map Blocks* (BMB). Each BMB consists of 8 bits, whereby a 0 bit indicates an errored packet and a 1 bit a successful reception. Each packet is identified by a Sequence Number (SN) that is defined modulo 1024 (10 bit). The SNs to which the three BMBs refer are given by their *Bit Map Number* (BMN).

The transmitter (TX) and receiver (RX) windows of the SR-ARQ protocol have a size of 512 and their indices are defined modulo that number. A bigger size could result in ambiguities among transmitter and receiver due to the SN-space of 1024.

The transmitter can send packets until the TX window is full. Upon reception of an ARQ-feedback PDU (with the so-called *Cumulative Acknowledgement* bit set to 1) the bottom of the TX window is shifted to the SN of the first 0 in the first BMB. This opens the TX window again and consequently a number of new packets corresponding to the size of the window shift can be transmitted.

It is obvious that the probability of a closed TX window limits the maximum achievable throughput on DLC layer. We will analyse this effect in the following section.

If the lifetime of a packet has expired after several unsuccessful transmissions, the transmitter can discard it and inform the receiver about this with a DISCARD message. Upon acknowledgement of this message the TX window can be shifted.

3 PERFORMANCE EVALUATION OF THE ARQ-PROTOCOL

To get realistic throughput values we first consider the throughput of the Medium Access Control (MAC) protocol of HL/2 T_{MAC}. In [7] it has been shown that this throughput is given by

$$T_{MAC} = \left\lfloor \frac{L_{LCH}}{\left\lceil \frac{54}{BpS_{LCH}} \right\rceil} \right\rfloor \cdot \frac{48 \cdot 8}{2\,\mathrm{ms}}. \qquad (1)$$

In this equation L_{LCH} is the number of free *Long Channels* (LCH) in the MAC-frame which will be considered as a given number in the following. BpS_{LCH} is the number of bytes that are transmitted by one OFDM-symbol (depending on the PHY-mode).

To obtain the final throughput the SR-ARQ mechanism has to be taken into account. It is known that this scheme ideally results in the throughput (cf. [8]):

$$T_{DLC} = T_{MAC} \cdot (1 - PER) \qquad (2)$$

Inserting eq. 1 and the PER versus C/I relations of Fig. 1 into eq. 2 we obtain the final throughput versus C/I relations for the different PHY-modes illustrated in Fig. 2.

However, for a single connection the theoretical curves can only be reached with a sufficiently large TX/RX window size. For the given TX/RX window size of 512 and for a single connection, the theoretical throughput with QAM64-3/4 can not be reached which is due to the closing of the transmitter window.

Fig. 3 illustrates the sequence of data transmission and acknowledgement in case of a Direct Link (DiL) connection. It can be depicted that the window can only be shifted after 3 MAC-frames. The maximum throughput is therefore bounded by the size of the window:

$$T_{DLC} = \frac{512 \cdot 48 \cdot 8\,\mathrm{bit}}{3 \cdot 2\,\mathrm{ms}} = 32.76\,\mathrm{Mbit/s} \qquad (3)$$

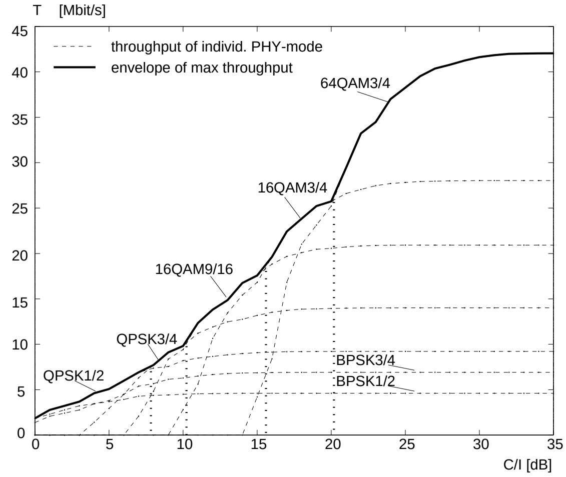

Figure 2: Throughput versus C/I

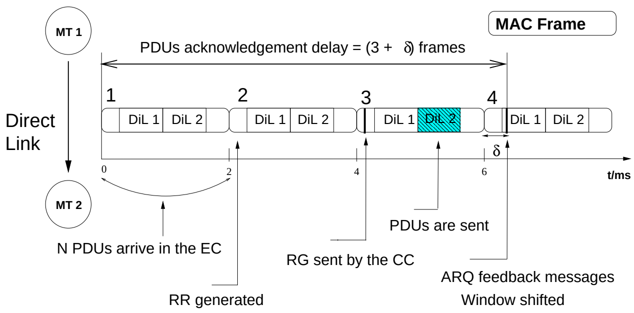

Figure 3: Frame sequence in DiL connection

Taking also transmission errors into account, the throughput gets even worse, because the window can not be shifted in case of an errored packet. Furthermore, the transmission can not only fail once but also retransmissions may be errored.

We have carried out simulation runs at the PHY-mode 64QAM-3/4 (cf. 4). The severe impact of the window-size on the maximum throughput of a single connection especially for high PER becomes obvious.

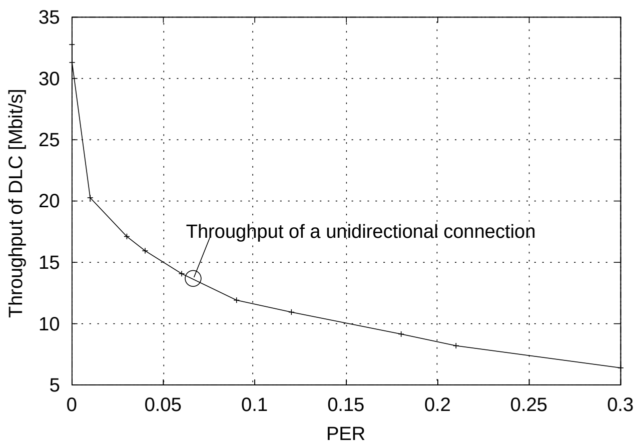

Figure 4: TX/RX-window bound on throughput

4 MULTI-CLUSTER AD HOC NETWORK

Because the one-cluster solution of the HL/2 standard restricts very much the coverage area of the ad hoc system, we have presented in [1] how the network could be extended to a multi-cluster system. Each of the clusters operates on a single and different frequency. The clusters are inter-connected on MAC level by so-called *Forwarding Terminals* (FT), that are located in the overlapping zones of the clusters and participate in the communication of several (usually two) clusters. In each cluster a CC grants access to the radio interace to all the terminals in its cluster. This network concept is illustrated in Fig. 5.

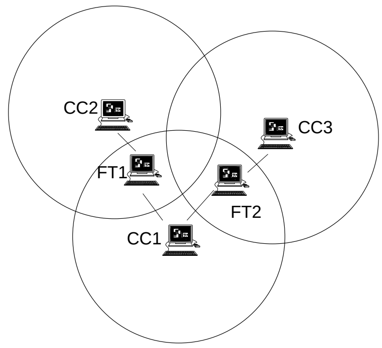

Figure 5: Cluster-based networking concept

Because each cluster operates on a different frequency the FTs have to switch from one frequency to another and can be present in only one cluster at a time. This mechanism is illustrated in Fig. 6 where the two upper rows of rectangles represent the MAC frame structure in two different clusters and the lowest row the presence times of the FT in cluster 1 and 2, respectively on frequency f1 and f2. It can be seen that the MAC frames in the two clusters are in general not synchronized. Consequently, the FT is not only absent during the frequency switching time T_S but loses also waiting time T_W until the beginning of the next MAC frame.

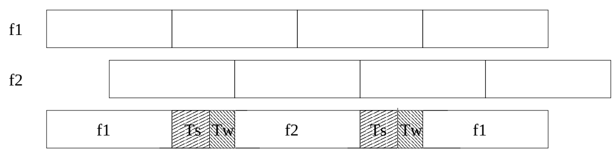

Figure 6: Absence times of the Forwarding Terminal

We have simulated and also analytically validated the throughput that can be achieved with this forwarding mechanism. The results of the simulations are shown in Fig. 7, 8 and 9 for one forwarded unidirectional connection and different PHY-modes in source and destination cluster. To study the influence of different propagation conditions in the two inter-connected clusters, in one cluster always the highest PHY-mode 64QAM-3/4 is employed, whereas it is varied in the other cluster. In terms of throughput it does not matter whether the lower PHY-mode is employed in the source or the destination cluster. However, as far as the delay is concerned a slightly higher delay is found if the lower PHY-mode is used in the destination cluster (cf. Fig. 9) than if it is used in the source cluster (cf. Fig. 8). This is due to the fact that a lower transmission rate in the destination cluster immediately results in a higher data delivery delay, whereas a lower transmission rate in the source cluster does not change the fixed point in time, when the FT switches to the other cluster. Therefore, a faster transmission in the source cluster has no influence on the delay as long as the throughput limit is not reached.

The throughput is plotted versus the number of MAC frames that the FT stays in each of the two interconnected clusters. It can be depicted that the switching and waiting times become negligible, when large cluster presence times are chosen. The throughput converges towards half of the maximum capacity in the cluster with the lower PHY-mode, which is different for each specific PHY-mode. This is because the FT is present for half of the time in one cluster and half of the time in the other cluster. However, if the switching cycles are very long, also the delay introduced by the FT becomes bigger (cf. Fig. 8 and 9).

In these simulations an error-free channel has been assumed and the ARQ-protocol was not employed.

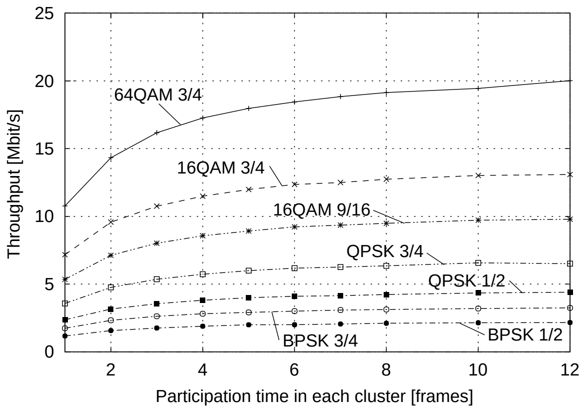

Figure 7: Maximum throughput for different PHY-Modes in source and destination cluster

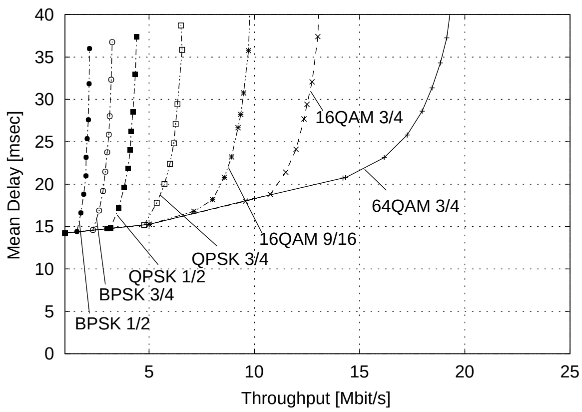

Figure 8: Throughput versus delay for various PHY-Modes in the source cluster

In order to take the worse propagation conditions in one of the two clusters into account, we propose asymmetric cluster presence times of the FT. The FT should stay exactly that factor longer in the cluster with the lower PHY-mode that corresponds to the relation between the

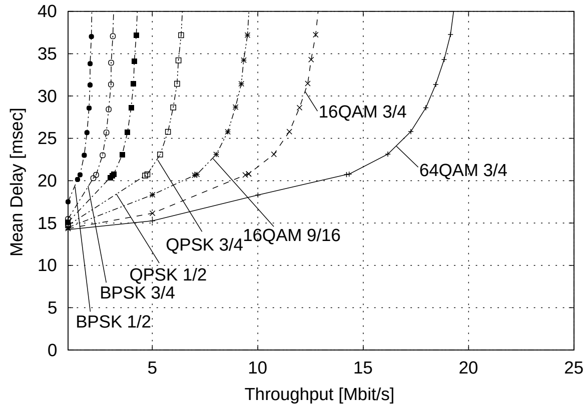

Figure 9: Throughput versus delay for various PHY-Modes in the destination cluster

achievable data rates in the two clusters. Fig. 10 illustrates the performance gain that can be achieved with the asymmetric presence times for the case of 64QAM-3/4 (with 54 Mbit/s) in one and 16QAM-9/16 (with 27 Mbit/s) in the other cluster.

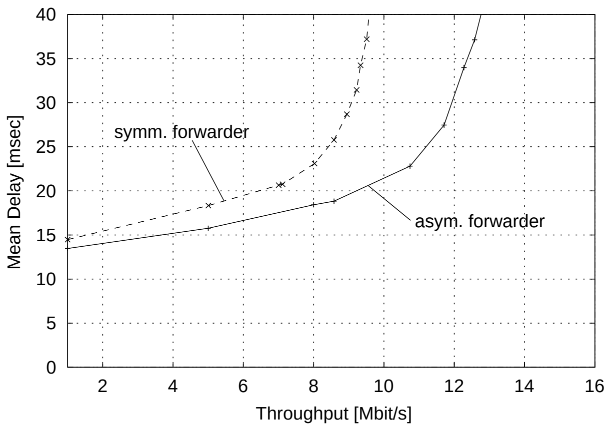

Figure 10: Gain of asymmetric forwarder

5 INFLUENCE OF TRANSMISSION ERRORS ON INTER-CLUSTER COMMUNICATION

In this section the performance of the HiperLAN/2 ARQ-protocol is studied in a multihop environment. This means that in contrast to the previous section the transmission is subject to errors and the ARQ protocol is employed (hop by hop).

5.1 Multi-cluster simulation scenario

A multi-cluster indoor simulation scenario is considered. The scenario consists of four rooms, in each of which one cluster is formed. In total 16 terminals are present at fixed positions inside the rooms as shown in Fig. 11. Four terminals are placed in each of the four door frames interconnecting the four rooms.

To limit the complexity of the simulation a single PHY-mode is applied, which is the highest PHY-mode (64QAM3/4). Depending on the size of the rooms, a certain C/I and thereby PER-value will be found.

Twelve terminals are associated exclusively to one of the four clusters. In each cluster, one of the three termi-

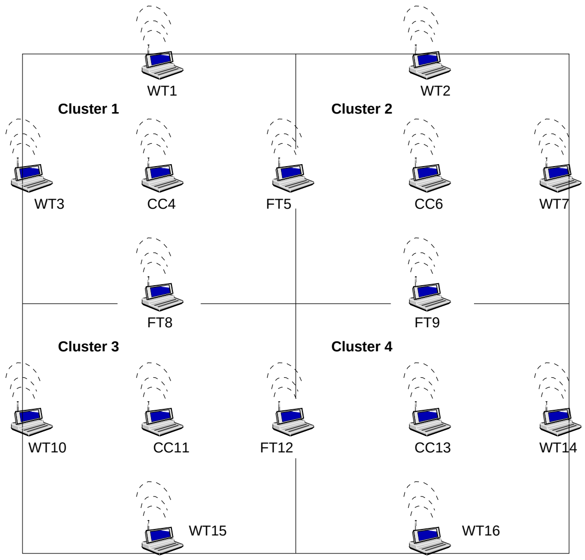

Figure 11: Multi-cluster simulation scenario

nals assumes the role of the Central Controller (CC) and the two other terminals are simple Wireless Termnials (WT). The four terminals in the door frames are associated to two clusters at the same time and serve as Forwarding Terminals (FT) in-between the clusters.

Regarding the traffic distribution inside the network, we have modelled, that communication between all stations in the network is equally probable. This results in 1/4 of the traffic being in-cluster traffic and 3/4 inter-cluster traffic. With 16 stations, 8 terminals consequently maintain an in-cluster connection, whereas 12 stations communicate with a station in one of the three other clusters. In total 16 permanent duplex connections are simulated.

For each connection the traffic load is modelled as a Poisson arrival process of packets with a constant packet length of 44 byte user data. The mean inter-arrival rate of the packets is varied to model different traffic load situations of the network. All connections are bi-directional and symmetric.

Regarding the routing, we have assumed routes in such a way that the number of hops in each route was minimised and that at the same time the traffic was spread as much as possible over the entire network.

5.2 Multi-cluster simulation results

We have carried out simulations for PERs of 6 % and 0 %. For the case without transmission errors (PER of 0 %) we have compared the performance of the system with ARQ-protocol and the performance without ARQ-protocol. Fig. 12 summarises the throughput achieved in all three types of scenarios (versus the offered load of a single connection).

It is interesting to note that for a PER of 0 % the maximum throughput with and without ARQ-protocol is almost identical (cf. Fig. 12). With ARQ-protocol the system goes into saturation only a little earlier. Obviously, there is almost no TX-window effect, which is owing to the fact that the capacity of a cluster is shared among several connections.

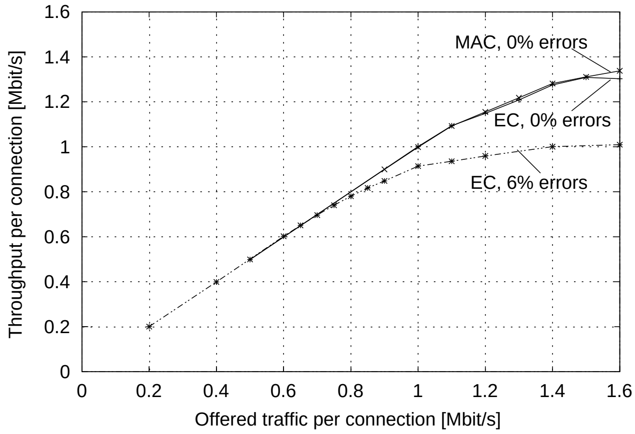

Figure 12: Throughput versus offered load

With a PER of 6 % the system saturates already at about half of the offered (end-to-end) load compared to the case without transmission errors. Here, the throughput limitation due to a closed TX-window is very noticeable. This result is in line with the results for the single-hop case (Fig. 4), where the throughput at a PER of 6 % was even less than half the maximum throughput. The reason why, in the considered scenario, the performance is better than in the single-hop/single-connection case, is again that the cluster-capacity is shared among several connections.

As far as the delay is concerned, we have plotted the Complementary Distribution Function (CDF) of the packet delay for each of the three scenarios in Fig. 13, 14 and 15.

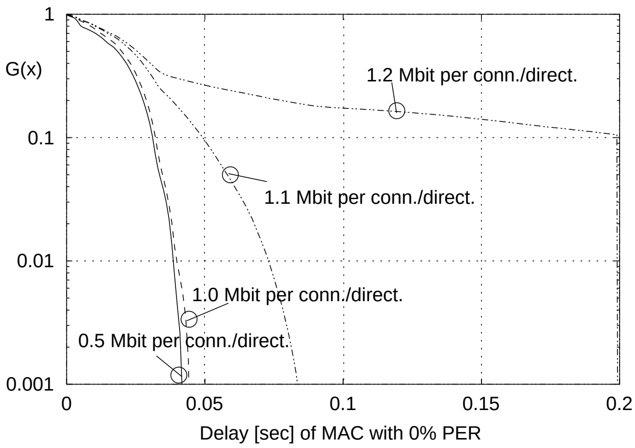

Figure 13: CDF of packet delay, PER 0 %, no ARQ

It can be depicted that up to an offered load of 1.1 Mbit/s per connection very low delays are achieved in the scenario without ARQ-protocol and without transmission errors (cf. Fig. 13). With ARQ-protocol this throughput bound is a little lower at about 1.0 Mbit/s (cf. Fig. 14) as already explained above. In the non-saturated state the CDF of both cases is almost identical as it would have been expected.

At a PER of 6 % the packet delay is significantly higher than in the scenario without transmission errors as it can be depicted from Fig. 15. In this figure the maximum

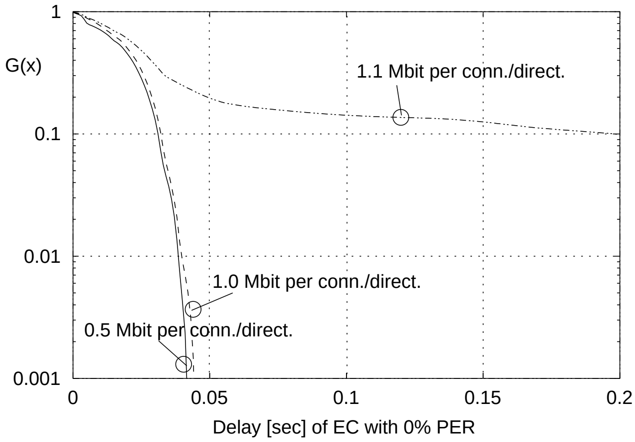

Figure 14: CDF of packet delay, PER 0 %, with ARQ

throughput of about 0.7 Mbit/s is also evident, because the system is in saturation for a load of 0.75 Mbit/s.

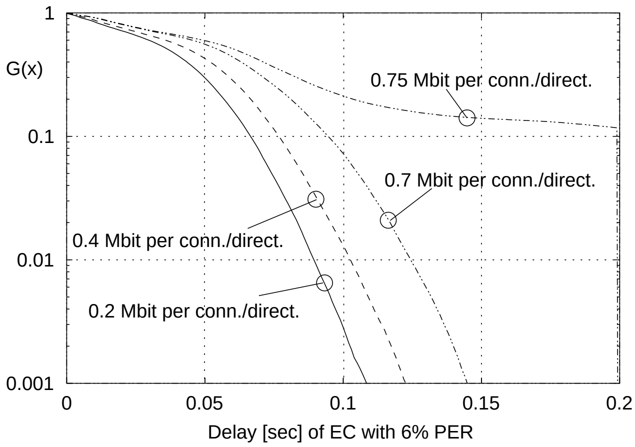

Figure 15: CDF of packet delay, PER 6 %, with ARQ

Finally in Fig. 16, 17 and 18, the average packet delay is shown for each connection and direction (16 bidirectional, rsp. 32 unidirectional connections). The main purpose of these figures is to identify connections, rsp. paths, which are more loaded than the other paths. It can be seen that e. g. connections 2, 3, 11, 21 and 22 are almost saturated whereas some other connections experience a very low packet delay. Obviously the delays do not only depend on the path-load but also on the length of a connection in number of hops. However, a slightly unequal load distribution can limit the maximum throughput of the whole network. This hold especially true, if several multihop connections pass one single cluster (MAC-limit) or path (TX-window-limit).

One conclusion of the simulations should be that there is a trade-off between signalling overhead and the TX-window limitation. The TX-window effect can be avoided as far as possible, if a new DLC-connection is established for each multihop-connection on a given hop. In our simulations, we had multiplexed all multihop-connections, that pass through the same hop, on a single DLC-connection. The reason was to save the signalling overhead that is associated with each DLC-connection.

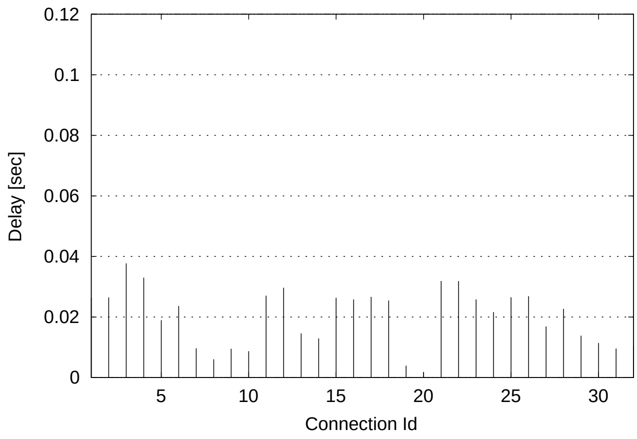

Figure 16: Mean delay per conn., PER 0 %, no ARQ

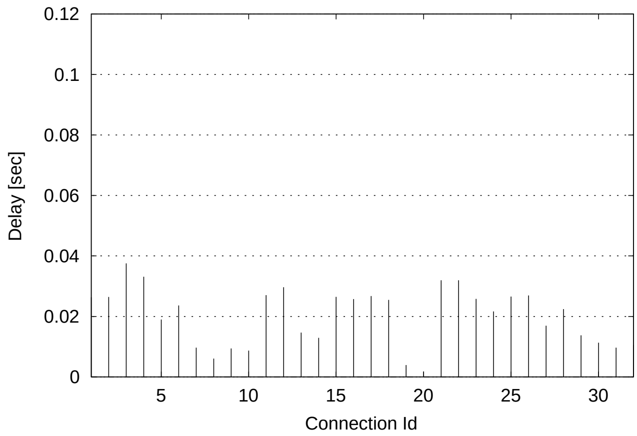

Figure 17: Mean delay per conn., PER 0 %, with ARQ

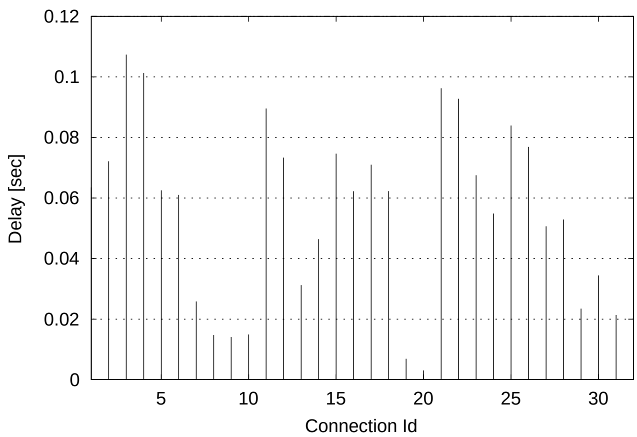

Figure 18: Mean delay per conn., PER 6 %, with ARQ

However, it turns out that in this case the TX-window effect becomes very noticeable, especially at high PERs.

We therefore propose to bundle multihop connections on a single DLC connection as long as the TX-window is not closed frequently. If this happens, an additional DLC-connection has to be opened in order to re-open the TX-window again.

6 CONCLUSIONS

It was our aim to assess the influence of the HIPERLAN/2 Error Control protocol on the performance of a single-hop and multihop ad hoc network. It was shown that with a sufficiently large TX/RX-window the protocol behaves like an ideal SR-ARQ (lowering the throughput by a factor of $(1 - PER)$). However, with the standardized window-size of 512, the maximum throughput is upper bounded by the ARQ-protocol.

Nevertheless it has to be noted, that the upper bound refers to the maximum throughput of a single connection. If the capacity of the system is split among several connections (which will normally be the case), the theoretical maximum throughput of an ideal SR-ARQ is nearly reached.

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