# 802.11a versus HiperLAN/2 – A Comparison of Decentralized and Centralized MAC Protocols for Multihop Ad Hoc Radio Networks

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## ABSTRACT

In this paper a comparison of decentralized and centralized *Medium Access Control* (MAC) protocols for multihop ad hoc wirless networks is carried out. The *Carrier Sense Multiple Access* (CSMA) scheme of the IEEE 802.11 contention-mode has been selected as the most prominent example of a decentralized protocol. The European wireless LAN system HiperLAN/2 is an example of a centralized system, in which one station organizes the access to the radio interface of all other stations within a certain area.
It is shown how a centralized MAC protocol like the one of the HiperLAN/2 system can be enhanced to build a multihop wireless network. The advantages of such a system in terms of throughput due to a possible frequency re-use have to we weighted against the advantages of decentralized protocols in terms of spectrum efficiency and ease of network management.

**Keywords:** WLAN, ad hoc networks, 802.11, HiperLAN/2, MAC

## I. 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 re-use of infrastructure-oriented protocols and equipment.

It is the aim of this paper to evaluate and compare decentralized and centralized *Medium Access Control* (MAC) protocols. As an example of a decentralized protocol the IEEE 802.11 access scheme based on *Carrier Sense Multiple Access* (CSMA) is considered. A representative of a centralized MAC protocol is the HiperLAN/2 MAC, which is based on polling of terminals (after previous resource requests). In the standardization bodies and research community there are currently intensive discussions about the advantages and relative performance of the two systems in a single hop scenario [1, 2]. However, it should also be considered how these protocols perform in a multihop environment, which is a very probable scenario for next generation wireless systems. By comparing the two protocols some general conclusions can be drawn regarding the suitability of decentralized rsp. centralized MAC protocols for multihop radio networks.

In section II we introduce the IEEE 802.11 standards family and give a brief overview of the 802.11 MAC protocol. Section III deals with the system concept and the MAC protocol of the HiperLAN/2 system and its possible extension for multihop communication. We then compare the performance of the two protocols in section IV.

## II. IEEE 802.11 AD HOC NETWORK

The IEEE defined the supplement standard 802.11a for a new OFDM based physical layer for the 5GHz U-NII band. The same transmission scheme as in HiperLAN/2 is adopted for a high-speed physical layer, allowing a maximum throughput of up to 54 Mbit/s. See the next section for some details on the harmonized physical layer of HiperLAN/2 and 802.11a. In [3], an overview of both systems is given.

The CSMA based medium access protocol of 802.11, the *Distributed Coordination Function* (DCF), is still used in 802.11a systems of the 5GHz band. The DCF performs a fully decentralized CSMA with *Collision Avoidance* (CA), thus requiring all transmitted data frames to be acknowledged by the receiving stations. A new Enhanced DCF (EDCF) currently under discussion at Task Group E of the 802.11 standardization body will allow priorities within EDCF, based on different minimum sensing times and contention window sizes for individual traffic categories.

There is no centrally coordinating station as long as the *Optional Point Coordination Function* (PCF) or *Hybrid Coordination Function* (HCF) are not used, and thus all stations send their data frames after sensing the radio channel using the *Clear Channel Assessment* (CCA) and detecting that there is no other transmitting station. However, in case two 802.11a stations are sensing the radio channel and detect it as CCA idle at the same time, collisions between the data frames will happen and acknowledges will not be sent. In this case both stations retransmit data frames after random back-off. As long as there are not too many contending stations with high traffic load, this contention-based MAC scheme is sufficient for reliable data transmission.

To support QoS and to carry real-time services, priority schemes equivalent to the centralized HiperLAN/2 MAC frame have been introduced in the 802.11 standard, the centrally controlled PCF, and the more flexible HCF. Both are centrally controlled and work on top of the (E)DCF, where in case of PCF a contention-free period allows polling of stations by a central *Point Coordinator* (PC) and in case of HCF deterministic transmission opportunities are granted to stations by the *Hybrid Coordinator* (HC).

The hidden node provision is supported by the optional use of the so-called RTS/CTS. After a station detected the channel as free, it transmits the short *Ready-To-Send* (RTS) burst in contention, followed by the *Clear-To-Send* (CTS) answer from the addressed station in case the RTS did not collide. As RTS and CTS include the information of how long the following data frame plus the necessary acknowledge response actually needs for transmission, other stations close to the sender and the receiver will not start any transmissions (a timer called *Network Allocation Vector* (NAV) is set). This drastically reduces overhead due to collisions of long data frames.

## III. CLUSTERED NETWORK BASED ON HIPERLAN/2

In [4] the concept of a clustered multihop ad hoc network based on the HiperLAN/2 standard has been presented. The concept is an example of a general class of cluster-based ad hoc networks [5]. Before we describe the main concepts of the network we will first give a very brief overview of the HiperLAN/2 standard.

### A. HiperLAN/2

HiperLAN/2 (HL/2) is a wireless *Local Area Network* (LAN) standardized by the *European Telecommunications Standardisation Institute* (ETSI). It covers the radio interface, that is the *Physical Layer*, *Medium Access Control* (MAC) including *Automatic Repeat Request* (ARQ), as well as the *Radio Link Control* (RLC) protocol of a wireless communication system.

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. It can be depicted, that the higher the PHY-mode the more its performance is degraded by interference and noise.

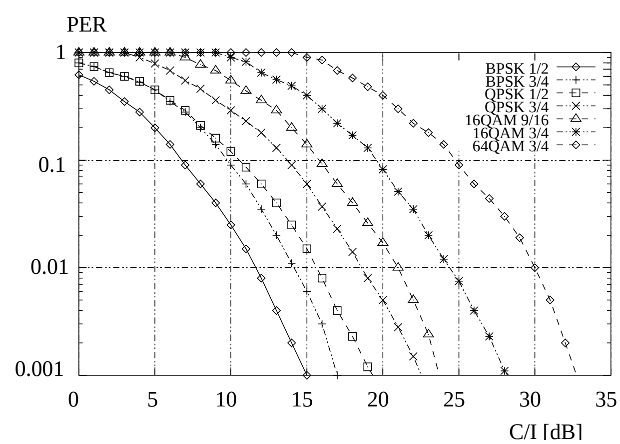


Fig. 1: PER versus $C/I$

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. The MAC protocol foresees that the AP or CC builds MAC frames, in which Time Division Multiple Access (TDMA) is employed. The AP/CC grants resources inside the MAC frame upon resource requests of the terminals.

In the base-station oriented mode each cell, respectively AP transceiver, operates on only one frequency. In ad hoc mode the same applies, but the network consists of only one cell (called a sub-net or cluster in the ad hoc case).

### B. Cluster-based 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 [4] 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. 2.

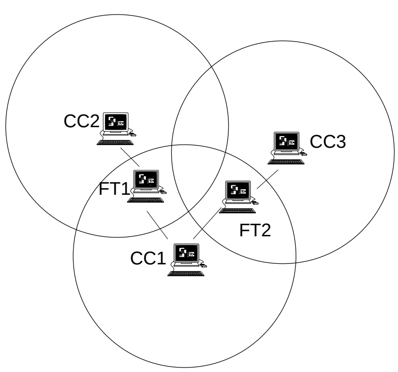


Fig. 2: Cluster-based networking concept

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. 3 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.

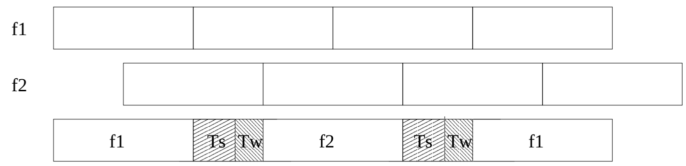


Fig. 3: Absence times of the Forwarding Terminal

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. 4 for the forwarding mechanism described above.

The throughput is plotted versus the number of MAC frames the FT stays in each of the two inter-connected 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 one cluster, which is equal to about 45 Mbit/s (see e. g. [6] for the determination of the maximum throughput of HL/2). However, if the switching cycles are very long, also the delay introduced by the FT becomes bigger (cf. Fig. 5).

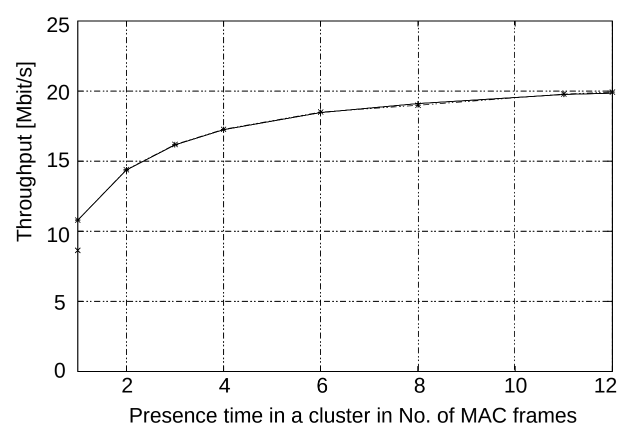


Fig. 4: Forwarding throughput

## IV. PERFORMANCE EVALUATION

### A. Simulation scenario

Our simulation scenario is an exhibition hall of the size $72\,\mathrm{m} \times 72\,\mathrm{m}$. Inside this area we place 81 devices equally distributed at fixed positions as illustrated in Fig. 6.

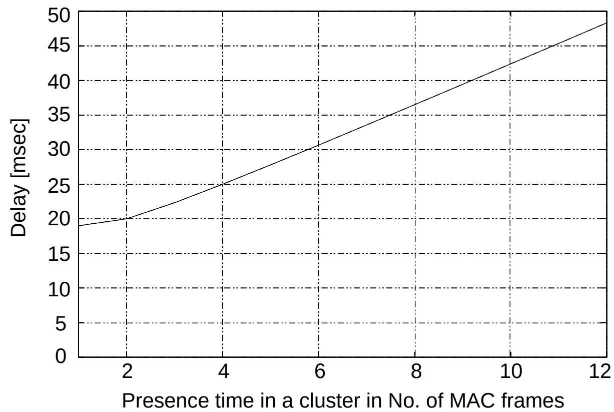


Fig. 5: Forwarding delay

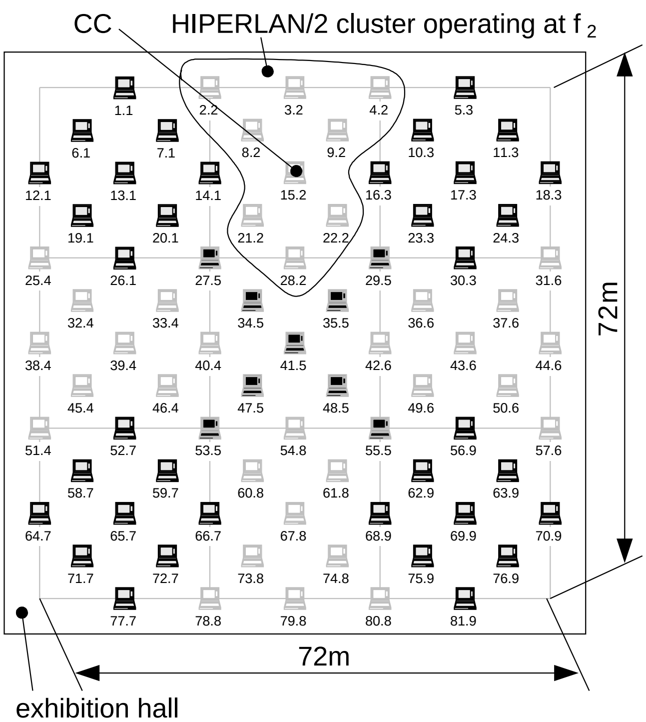


Fig. 6: Simulation scenario

A propagation law according to eq. 1 is assumed.

$$P_R = P_S \cdot (\frac{c_0}{4\pi f})^2 \cdot \frac{1}{d^\gamma} \quad (1)$$

$P_R$ is the received power and $d$ the distance between sender and receiver. The transmitter power $P_S$ of the devices is constant and set to 0.1 W. $c_0$ is the speed of light, $f$ the carrier frequency, which is set to 5.5 GHz. We have assumed a typical propagation exponent of $\gamma = 3.5$.

We do not consider the interference due to terminals outside the blocking range in the case of the 802.11 system, neither the interference due to frequency re-use in the HL/2 system (as each frequency is used only once in the considered scenario). If an infinite scenario had been considered, these effects would have to be taken into account. Nevertheless, it can be expected that the relative performance of the systems would not be altered very much, because the frequency re-use distance of HL/2 would be in the order of the blocking range of 802.11. The blocking range of the 802.11 system can be derived from the blocking threshold at the receiver, which we have set to -86 dBm. With eq. 1 it is found that the blocking range is 48 m. For the 802.11 system this means that stations situated at opposite borders of the scenario can transmit at the same time.

We presume a constant noise floor of -95 dBm (as it has been done e. g. in [7]).

To limit the complexity of the simulation we aim at the employment of a single PHY-mode for the transmission of user data. The highest PHY-mode (64QAM3/4) can be applied until a lower threshold of the $C/I$ of 30 dB, for a target PER of 1 % (cf. Fig. 1). Given the described propagation law and noise level, the $C/I$-boundary of 30 dB is reached at a distance between sender and receiver of appr. 12 m. This is exactly the distance between a station and its vertical and horizontal direct neighbours in the scenario in Fig. 6. Most of the stations (except the terminals near the borders of the exhibition hall) have therefore 8 direct neighbours, with which a 1-hop user-data connection can be maintained.

If we want to be able to apply the highest PHY-mode everywhere, the 30 dB threshold of the $C/I$ determines the cluster boundaries in the case of the HL/2 system, which are shown as rectangles in Fig. 6. The stations situated in the middle of the cluster boundaries act as Forwarding Terminals between the two respective, adjacent clusters. The station in the center of each rectangle is assumed to take over the Central Controller function.

Regarding the traffic distribution inside the network, we have modelled, that communication between all stations in the network is equally probable. For the HL/2 system this results in 1/9 of the traffic being in-cluster traffic. With 9 stations per cluster, 8 terminals have therefore active connections to terminals outside the own cluster. We have assumed that each of these 8 connections is directed to a different cluster, thereby creating an equal number of connections between all clusters. In each cluster, one terminal has only an in-cluster connection. Its communication partner has two connections: the in-cluster connection as well as a connection to a terminal in another cluster. We have assumed that in each cluster the CC is the terminal that has two connections. In total 45 permanent connections are simulated.

For each connection the traffic load is modelled as a Poisson arrival process of packets with a constant packet length. We have carried out simulations for two different packet lengths (namely 48, which is the payload of a HL/2 Long Channel, and 1514 bytes, which is the maximum size of an Ethernet packet with its protocol overhead excluding preamble and check-sum). 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.

The assignment of terminals to the clusters, that we have chosen for the HL/2 system, is illustrated in Fig. 6 by the second number after the Terminal ID. In the case of HL/2, a different frequency is employed in each cluster.

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. Routes within the 802.11 system are on average slightly shorter than the routes found for the HL/2 system.

We have implemented the complete MAC protocols of 802.11 and HiperLAN/2 in the *Specification and Description Language* (SDL). The protocols as well as their necessary enhancements for multihop networks are embedded in an event driven simulator, which also contains channel and traffic models.

Fig. 7-11 show the results of our simulation experiments. The throughput as a function of the offered traffic per connection (in one direction) is illustrated in Fig. 7 for the 802.11a and in Fig. 8 for the HL/2 system.

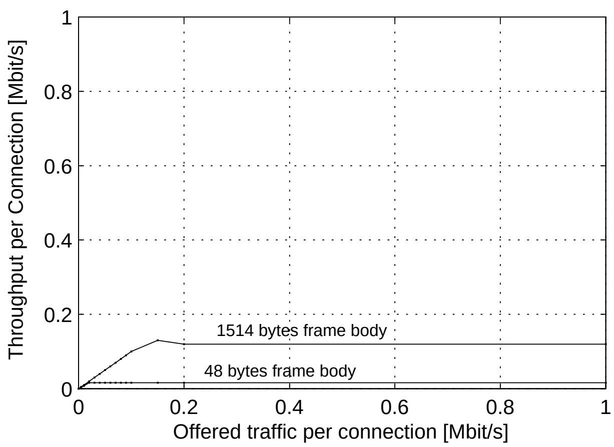


Fig. 7: Throughput of 802.11a

As expected, the throughput of the 802.11a CSMA protocol is very much dependent on the packet size. For small packets the throughput is extremely low, which is due to frequent collisions and the overhead of each access to the medium. For the maximum packet size of 1514 byte a maximum throughput slightly above 100 kbit/s per connection (and direction) is achieved.

From Fig. 8 it can be depicted that a much higher throughput can be achieved in the cluster-based network. The system begins to saturate at an offered traffic of about 800 kbit/s per connection (and direction). As the throughput of the HL/2 system is almost independent of the packet size, we have only included the results for a packet size of 48 byte. The throughput with a packet size of 1514 byte is only about 1 % lower, which is due to the segmentation of each long packet into a multiple of 48 byte packets.

The end-to-end system load that can be carried in the cluster-based network is about $0.8 \cdot 90 = 72\,\mathrm{Mbit/s}$, which is owing to the use of multiple frequency channels. Taking into account the average number of hops per connection which is approximately 4.5, the total load over all clusters is this factor higher than the end-to-end load.

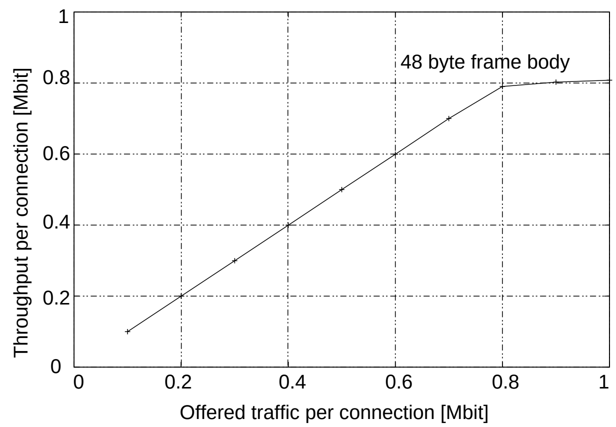


Fig. 8: Throughput of HiperLAN/2

The effect of using 9 frequency channels in the cluster-based network is reflected in the throughput figures. The reason that the throughput in the HL/2 system is not 9 times as high as the one in the 802.11a system, but only 8 times as high is due to parallel transmission of 802.11a terminals in opposite corners of the exhibition hall and due to a slightly more efficient routing in the decentralized network.

The mean packet delay for each of the 90 connections (both directions of the 45 connections) is shown in Fig. 9 and 10. We have selected for both systems the results of the most favourable scenario (1514 byte packet length for 802.11a and 48 byte packet length for HL/2) at a load slightly below the respective saturation load.

Fig. 9 illustrates that in the 802.11a system most of the connections experience a very high delay. For about half of the connections the mean packet delay is higher than 200 ms, which is not acceptable for real-time or interactive applications. The high delays are due to collisions and waiting times because of an occupied medium.

In the cluster-based network (cf. Fig. 10) the mean delay is much smaller than in the decentralized system and stays in most cases below 60 ms, which is acceptable for most types of applications. The packet delay of a specific connection does mainly depend on the number of radio hops, rsp. Forwarding Terminals involved.

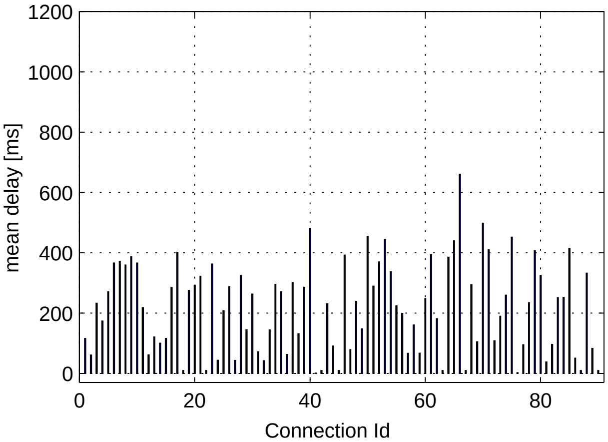


Fig. 9: Average packet delay per connection for 802.11a

To give more insight into the distribution of packet delays, we have included in Fig. 11 the *Complementary Distribution Function* (CDF) of the packet delay over all connections in the cluster-based system. It can be seen that the packet delay stays always below 100 ms and does not depend very much on the load (up to the saturation load of 0.8 Mbit/s).

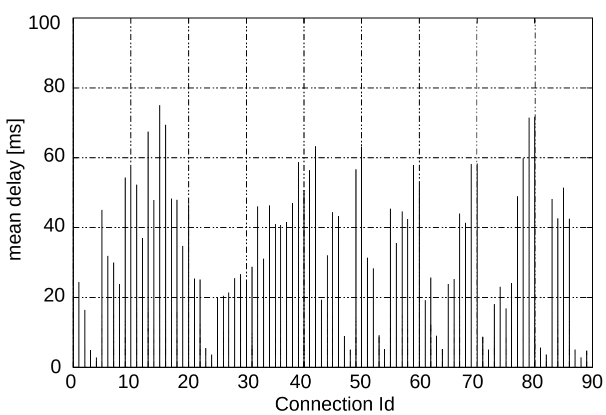


Fig. 10: Average packet delay per connection for HL/2

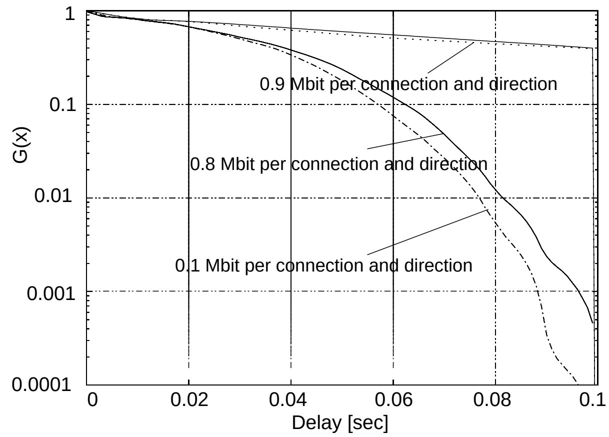


Fig. 11: CDF of packet delay for HL/2

## V. CONCLUSIONS

The concept of a cluster-based ad hoc network, in which the clusters are inter-connected by *Forwarding Terminals* can not only be applied to the HiperLAN/2 system but also to the PCF/HCF of 802.11 or any other centralized protocol. The findings of this paper can therefore be interpreted as a more general comparison of centralized and decentralized MAC protocols in the ad hoc environment rather than a pure evaluation of HiperLAN/2 and 802.11a.

It could be shown that for the existing channel definitions in the 5 GHz-band throughput and packet delay can be significantly improved by the use of multiple frequency channels. However, this does not imply that a centralized system is more spectrum efficient than a decentralized network, as the performance gain has been achieved by using a larger part of the spectrum.

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