Network Capacity Optimisation, Part II: Multihop Ad Hoc Radio Networks

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Abstract — **In this paper the network capacity of a cluster-based, wireless multihop ad hoc network is derived. Such a network consists of clusters, in which one station, called the *Central Controller* (CC) organises the access to the radio interface of all other terminals inside the cluster. The clusters are inter-connected by so-called *Forwarding Terminals*.**

It is shown that the network throughput is maximised, if all forwarding data are transmitted via the *Central Controller* instead of using Direct Mode Communication of the *Forwarding Terminals*.

The maximum throughput and delay of an average connection is derived analytically by calculating the average number of *Forwarding Terminals* involved in a connection. Taking into account the capacity of the clusters and the network topology it is finally determined how the total network performance can be optimised by appropriate selection of the cluster size.

Numerical results are included for a clustered ad hoc network based on the HIPERLAN/2 standard.

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. In this paper we will deal with the HIPERLAN/2 system, even though the presented approach can be applied to a general class of ad hoc networks.

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.

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

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

In centralised 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*. These functions do not necessarily have to be carried by the same station all the time. The functions can of course be handed over to another station in the same cluster being able to carry them. The HiperLAN/2 Home Environment Extension (HEE) is organised in such a way. The big advantage of centralised networks is the easy quality of service provision and possible re-use of infrastructure-oriented protocols and equipment.

The term *cluster* designates in infrastructure-based wireless networks a number of cells that share all available frequency channels. However, in the ad hoc research community, the term *cluster* is used to designate a group of terminals that share certain network functions. This double meaning is certainly unfortunate. We will use the second meaning of a *cluster* in the following, which is a group of terminals controlled by a *Central Controller*.

It is the aim of this paper to evaluate and optimise the network capacity, measured as average throughput, of a clustered ad hoc system. In section II we introduce the system concept and give a brief overview of HIPERLAN/2. Section III deals with the very important question whether all data should be exchanged via the *Central Controller* on *Uplink* (UL) and *Downlink* (DL) or whether terminals should communicate directly on *Direct Links* (DiL). This decision is crucial for the capacity of the system. The results of this first analysis are the basis to calculate in the following chapter the average throughput and transmission delay of the system and to analyse how throughput and delay can be optimised. The paper concludes with a summary and an outlook on future work.

II. Concept of a cluster-based ad hoc network

In [1] 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 [2]. 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) standardised by the *European Telecommunications*

Standardisation Institute (ETSI) and has been completed in the years 2000 and 2001. 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. Several so-called *Convergence Layers* (CL) provide interworking with existing standards like Ethernet, ATM, IEEE1394 and UMTS.

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 HL/2 two modes of operation are possible:

In a base-station oriented mode the network is organised 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 centralised 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 [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. 1.

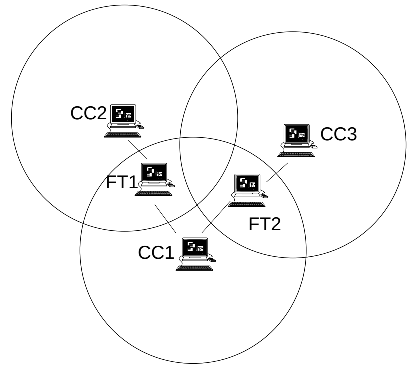

Fig. 1: Cluster-based networking concept

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. 2 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 synchronised. 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.

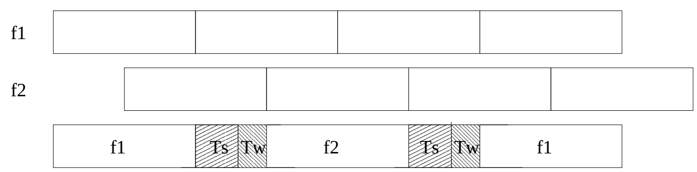

Fig. 2: Absence times of the Forwarding Terminal

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. 3 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. [3] 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. 4).

In these simulations application of the highest PHY-mode 64QAM3/4 has been assumed. On the other hand we have assumed the highest possible load situation as worst case approximation. At lower load the delay will be lower.

III. Analysis of direct terminal communication

We distinguish two cases in the following. In the first scenario, clusters influence each other by causing interference to neighbouring clusters that operate on the same frequency. Such an assumption is realistic for an outdoor system. However, in indoor scenarios, signals are heavily attenuated by walls and floors, especially at high frequencies as it is the case for HIPERLAN/2 (5-6 GHz). Clusters will therefore mainly be restricted to single rooms and interference among the clusters can be neglected. Such a scenario is treated in section III.B.

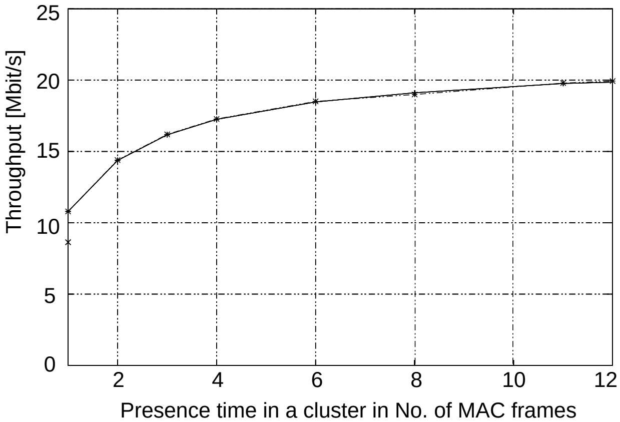

Fig. 3: Forwarding throughput

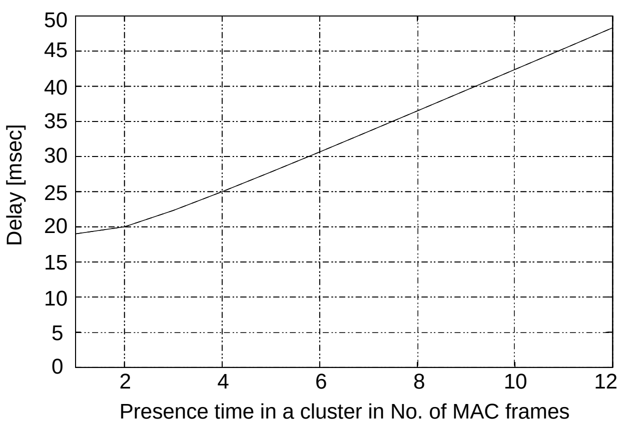

Fig. 4: Forwarding delay

A. Outdoor scenario

In a theoretical analysis of system capacity radio cells are traditionally represented as hexagons [4, 5, 6]. However, other forms of representation are possible or suitable, especially in the case of a clustered ad hoc network. In Fig. 5 triangular, square and hexagonal cell representation are compared.

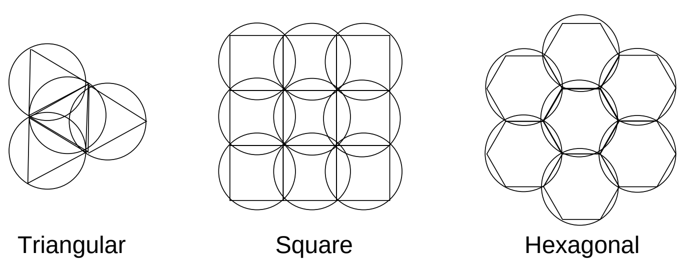

Fig. 5: Forms of Cell Representation

It can be depicted from Fig. 5 that the forms of cell rsp. cluster (in the case of an ad hoc network) representation differ regarding the degree of overlap of the clusters as well as the number of neighbouring clusters, i. e. the cluster connectivity. As a certain degree of cluster overlap is needed for the type of ad hoc network presented in section II, a triangular or square representation of clusters seems appropriate. We will consider a square representation in the following. However our calculations can also be carried out for other choices of cluster connectivity, rsp. overlap.

We model the FTs being situated in the middle of the overlapping zones of the clusters, i. e. on the borders of the squares, as well as each CC in the middle of its cluster (see Fig. 6). In Fig. 6 the three possible forwarding constellations, that can be chosen inside a cluster, are shown. In constellation 1 FTs do not communicate with each other directly but over the CC on an *Uplink* (UL) and a consecutive *Downlink* (DL). In constellation 2 the same applies to the FTs that are horizontally or vertically opposite to each other. However, in this scenario FTs that are diagonal neighbours communicate with each other directly on a *Direct Link* (DiL). Constellation 3 foresees that all FTs communicate with each other on DiLs.

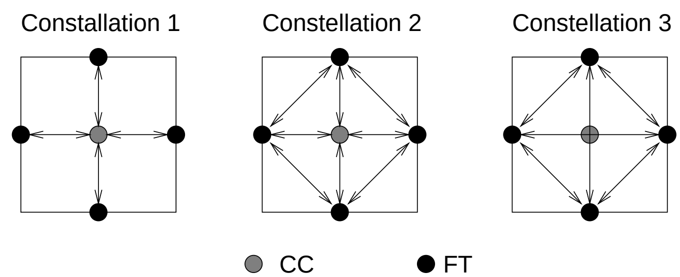

Fig. 6: Forwarding constellations inside a cluster

We will compare the three possible forwarding constellations in terms of throughput that can be achieved for forwarded connections. Taking the example of the HIPERLAN/2 system the achievable throughput does mainly depend on the *Carrier to Interference Ratio* (C/I) as illustrated in Fig. 7. The throughput relations for the different PHY-modes have been derived taking into account the data rate on physical layer, the overhead of the MAC protocol as well as retransmissions of the ARQ protocol [7].

To determine the average throughput that can be achieved by a CC as well as by a FT we have calculated the C/I at the cell center as well as at a distance of $1/\sqrt{2}R$ from the cell center, where R designates the radius of the cell. The received power level of the carrier as well as the interference are calculated by the following propagation law:

$$P_R = \begin{cases} P_S \cdot \left(\frac{c_0}{4\pi f}\right)^2 \cdot \frac{1}{l^\gamma} = \frac{K_2}{l^\gamma} & \text{for } l > \frac{c_0}{4\pi f} \\ P_S & \text{else} \end{cases} \quad (1)$$

where P_S is the power of the sender and P_R the received power, c_0 the speed of light, l the distance between sender and receiver and γ a propagation coefficient between 2 and 5. We have assumed a γ of 4 in the following.

For the calculation of the interference level we have to take into account the eight nearest clusters, which use the same frequency than the considered cluster (see Fig. 8 for the example

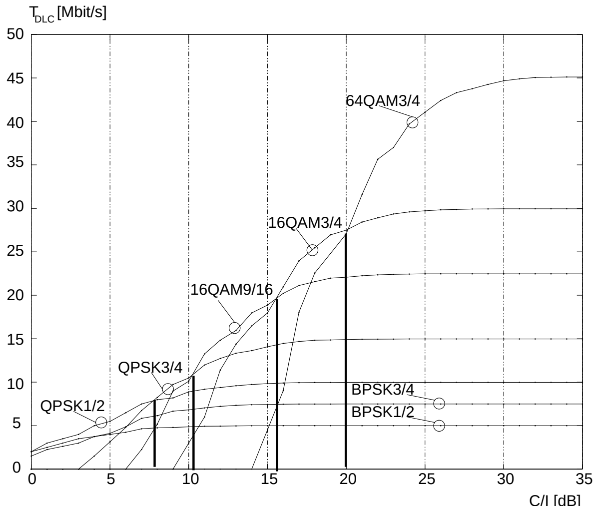

Fig. 7: Throughput versus C/I

of 4 frequencies available). In the HIPERLAN/2 system one frequency is used per cluster.

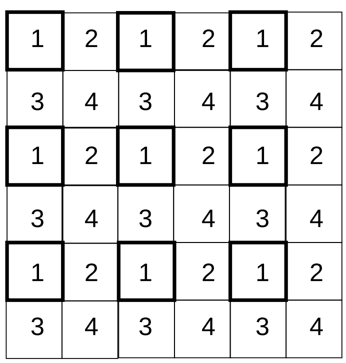

Fig. 8: Interference situation for 4 frequencies

In each of the interfering clusters we have modelled four FTs on the four borders as well as a CC in the middle of each cluster. We have assumed that in an interfering cluster one interferer is always active. In constellation 1 this interferer is the CC for 50 % of the time and each of the four FTs for 12.5 % of the time. For constellation 2 we have exemplarily assumed that 20 % of the forwarded connections are transmitted on DiLs and 80 % via the CC in the interfering cells. Consequently, 40 % of the interference is caused by the CC and 20 % by each of the four FTs. In constellation 3 no interference is caused by the CC at all and 25 % by each of the four FTs.

In [6] we have analytically proven that the error we make, when the position of the interferers is not modelled correctly, is in the order of 1 % for 9 and 16 frequencies available and 5 % for 4 available frequencies.

It should be noted that the C/I levels at the FTs and at the CC inside a cluster are independent of the cluster radius R, because carrier reception level C as well as interference I depend on R in the same way. This means that the dependence on R can be cancelled down in the C/I ratio (cf. e. g. [6]). The C/I is only depending on the *relative* position of a terminal inside a cluster.

By numerical evaluation we have obtained the throughput T that can be achieved by FTs and CC in each of the three possible constellations. In Table 1 results are displayed for the cases that 4, 9 or 16 frequencies are available.

Throughput [Mbit/s] for no. of freq.	4	9	16
Constellation 1:			
T_{FT} (UL)	11.27	19.74	22.13
T_{CC} (DL)	9.45	19.02	22.07
Constellation 2:			
T_{FT} (UL)	11.10	19.68	22.12
T_{CC} (DL)	9.37	18.94	22.06
$T_{diagonal}$ (DiL)	9.55	24.55	36.57
Constellation 3:			
$T_{diagonal}$ (DiL)	8.62	24.19	36.47
$T_{opposite}$ (DiL)	3.60	13.45	22.75

Table 1: Achievable throughput of FTs and CC

The results in Table 1 show that the achievable throughput is always a little higher in the center of a cluster (for the CC), than at the borders of the cluster (for the FTs). This is due to the slightly higher interference in an outer part of a cluster. The most important result is that the highest throughput can be achieved with constellation 2, owing to the possibility to transmit a fraction of the forwarded traffic on DiLs. Constellation 3 results in a lower throughput, even though all data are forwarded on DiLs. This is due to the big relative distance between opposite FTs, which can therefore only employ very inefficient PHY-modes.

It should be noted that we have taken for the UL and DL connections in Table 1 half of the actual achievable throughput on a single UL or DL, because it has to be accounted for the fact that two connections (one UL and one DL) are needed to forward data from one FT to another.

Constellations 2 and 3 differ from constellation 1 in a very important requirement: For DiL communication between FTs it is required that all four FTs are present in the cluster at the same time. This requires complete synchronisation of the frequency switching times of all FTs in the network. In contrast, with constellation 1 asychronous switching cycles and cluster presence times of the FTs are allowed and even recommendable in terms of throughput. If one considers, that the FTs are at least half of the time absent from a cluster, it can be concluded that unsynchronised FTs use the available bandwidth at least double as efficient as synchronised FTs, because the forwarding load is spread over all MAC-frames. Taking this into account means that the throughput figures for constellation 2 and 3 in Table 1 have to be divided by at least 2. Consequently, the highest throughput can be achieved by far with constellation 1. This solution has also the advantage that FTs need not be synchronised and that all the routing tasks can be taken over by the CC.

This is a very important result, because it means that all forwarding traffic should be transmitted via the CC on UL and DL. We will base our calculation of the complete system throughput in section IV on this result.

B. Indoor scenario

In the final version of this paper, we will analyse in this section the throughput of FTs in the case of an indoor scenario, in which we will assume a constant background interference that is independent on the relative position of a terminal inside a cluster.

IV. Analysis and optimisation of network capacity

It is our aim to determine the average system throughput and delay inside the network. The average number of FTs involved in a connection N_F influences the average system load and transmission delay. We therefore calculate this number N_F, which can be derived from the number of clusters in the network. Assuming square cluster representation the number of clusters N_C needed to cover a given area A is

$$N_C = \frac{A}{(\sqrt{2}R)^2}. \tag{2}$$

R is the cluster radius, which is equal to half the diagonal of a cluster square (cf. Fig. 5).

The complete network topology is represented in Fig. 9. The total number of clusters N_C is equal to n^2, where n is the number of clusters in the direction of x and y co-ordinates.

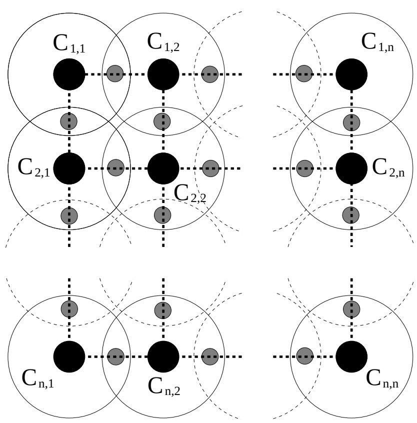

Fig. 9: Network Topology

The indices i and j give the position of the center of a cluster in the network. The number of FTs involved in connections between two clusters with indices i, j and k, l respectively is equal to:

$$d_{i,j,k,l} = |i-k| + |j-l| \tag{3}$$

To obtain the average number of FTs involved in a connection N_{FT} we have to sum $d_{i,j,k,l}$ for i,j,k,l<n and divide it by the number of possible cluster connections $n^2(n^2-1)$.

$$N_{FT} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} d_{i,j,k,l}}{n^2(n^2-1)} \tag{4}$$

This can be simplified to the following function:

$$N_{FT} = \frac{2}{3}n = \frac{2}{3}\frac{\sqrt{A}}{\sqrt{2}R} = \frac{\sqrt{2}}{3}\frac{\sqrt{A}}{R} \tag{5}$$

We begin with a throughput consideration. For this purpose we distinguish between in-cluster traffic I and forwarded connections, rsp. forwarding traffic F. We have to make certain assumptions regarding the percentage of in-cluster connections respectively forwarded connections: We assume that the terminals are equally distributed in the given area and that connections between all terminals are equally probable. In this case the fractions of in-cluster connections p_I and forwarded connections p_F are given by

$$p_I = \frac{1}{N_C} = \frac{(\sqrt{2}R)^2}{A} \tag{6}$$

$$p_F = \frac{N_C - 1}{N_C} = 1 - \frac{(\sqrt{2}R)^2}{A} \tag{7}$$

For the calculation of the mean throughput within one cluster for the given traffic mix (p_I, p_F) the different relative transmission durations for the two types of traffic with their different specific throughput have to be taken into account by eq. 8

$$T_{cluster} = \frac{1}{\frac{p_I}{T_I} + \frac{p_F}{T_F}} \tag{8}$$

All averaging of throughput was done analoguously to this equation.

The average in-cluster throughput was obtained by assuming DiL connections and averaging numerically over all possible constellations of sender and receiver inside the square cluster.

The average forwarding throughput was calculated by averaging the UL and DL traffic for the Constellation 1 in Table 1.

The resulting throughputs are shown in Table 2.

Throughput [Mbit/s] for no. of freq.	4	9	16
Constellation 1:			
T_I (DiL)	11.42	26.04	35.90
T_F (UL/DL)	10.29	19.37	22.10

Table 2: Av. throughput of in-cluster and forwarding traffic

The amount of load L_{system} that the system has to carry to provide the service of a certain end to end throughput $T_{end-to-end}$ increases with the average number of hops. For the Constellation 1 we can assume 2 hops for every forwarder that is involved in a connection leading to

$$L_{system} = 2N_F \cdot T_{end-to-end} = \frac{4}{3}n \cdot T_{end-to-end} \tag{9}$$

On the other hand the load the system can carry is determined by the average cluster throughput and the number of clusters in the system by

$$L_{system} = N_C \cdot T_{cluster} = n^2 \cdot T_{cluster} \tag{10}$$

By equating 9 and 10 we finally obtain the end to end system throughput:

$$T_{end-end} = \frac{3}{4} \cdot T_{cluster} \cdot \frac{n^2}{n} = \frac{3}{4} \cdot \frac{1}{\frac{1}{T_I}\frac{1}{n^2} + \frac{1}{T_F}\frac{n^2-1}{n^2}} \cdot n \quad (11)$$

Fig. 10 shows the resulting system throughput that can be carried inside a given area A depending on the number of clusters N_C that are built to cover this area.

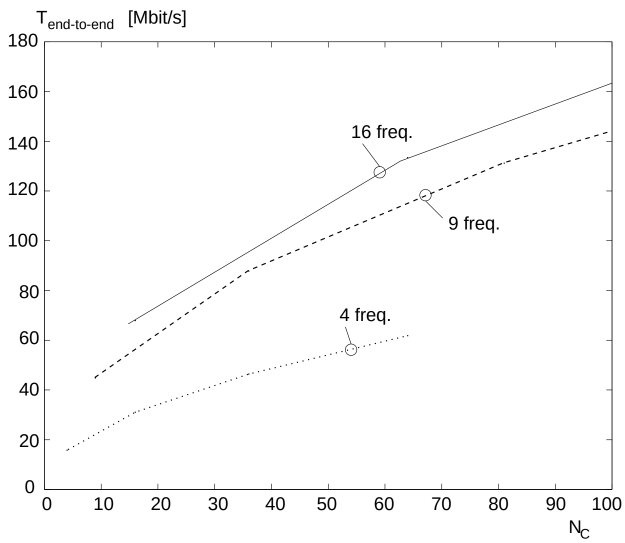

Fig. 10: Possible end to end system throughput

A very important result is illustrated in Fig. 10: In terms of throughput it is recommendable to maximise the number of clusters per given area, that is to minimise the cluster size.

For the delay consideration we assume that each FT involved in a connection adds a certain additional delay to the in-cluster delay distribution of HIPERLAN/2. Independently of the delay distribution for one FT in the intervall $[0, D_{max}]$ (where D_{max} is the maximum forwarding delay) the sum of all FT delays tends towards a Gaussian distribution for a large number of FTs. The average delay introduced by a chain of forwarders is simply given by $N_{FT} \cdot D_{FT}$ where D_{FT} designates the average delay of a single FT. The average delay over of all connections is finally given by:

$$D_{av} = p_I D_I + p_F(D_I + N_{FT} D_{FT}) = D_I + p_F N_{FT} D_{FT} \quad (12)$$

For many clusters N_C the delay is mainly caused by the forwarding delay that grows in the order of $sqrt(N_C)$. Thus, in terms of delay it is recommandable to limit the number of clusters.

V. Conclusions

We have derived analytical formula for the average end-to-end throughput and delay in a cluster-based multihop ad hoc network. For this purpose we have first proven that all forwarded data should be transmitted via the CC on an Uplink and a consecutive Downlink connection. In a next step the average number of hops and the average number of FTs involved in a connection have been determined. Taking into account the maximum throughput of a cluster, we have finally calculated the average throughput and transmission delay depending on the number of clusters needed to cover a given area. This number of clusters does only depend on the size of the clusters.

By adjusting the size of the clusters one can therefore control the average throughput and delay in the network. To maximise the throughput, the cluster-size should be minimsed but on the other hand to minimise the average delay, clusters should be made as large as possible. Our formula make it possible to choose an optimum cluster-size for a certain combination of throughput and delay requirements.

VI. References

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