KUNGL TEKNISKA HÖGSKOLAN
Royal Institute of Technology

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# Abstract

Higher profit and better quality of the communication systems, these are the requirements for a telecom company of today. This master thesis has investigated the possibility to construct cheaper wireless cellular networks while maintaining satisfactory performance. It is possible to make every part of a communication system more efficient and consequently more profitable. This thesis has studied a multihop technique which extends coverage as its primary benefit. Multihopping is, as the word implies, the use of other mobile devices, e.g. cellular telephones and laptops, as relays in order to transport a message between an access point and a mobile device. To implement this system, the mobile devices must be smarter and must have more functionality, e.g. routing. The multihop technique affects system performance in other ways, rather than just increasing coverage. This master thesis has studied two of those affected performances, delay and power consumption. Delay is important for realtime applications and the power consumption is important for the battery duration. The behaviour, i.e. the gradient, of the curves was studied and hypothetical formulas were suggested. The first performance measure used was the average delay per packet between a mobile station and the access point it is connected to. This measure was proposed to be proportional to the mobile station density and proportional to the reciprocal of the access point density raised to 1.5. With respect to the access point density, this was found out to be an upper bound of the delay. The second performance measure used was the average used transmitted power per packet and two hypothetical boundary equations were proposed. Simulations were performed and showed similarities and deviations compared to the hypothetical formulas. Despite certain deviations, the results and the discussion around them are valuable for network designers in the sense of deeper understanding of the principles behind these performance measures.

# Acknowledgements

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# Contents

# List of Abbreviations

| | |
|---|---|
| AP | Access Point |
| FIFO | First In First Out |
| GSM | Global System for Mobile Communications |
| LAN | Local Area Network |
| LoS | Line of Sight |
| MHA | Minimum Hop Algorithm |
| MS | Mobile Station |
| PRN | Packet Radio Network |
| QoS | Quality of Service |
| SINR | Signal to Interference and Noise Ratio |
| SIR | Signal to Interference Ratio |
| SMS | Short Message Service |
| STDMA | Spatial Reuse Time Division Multiple Access |
| TDMA | Time Division Multiple Access |
| WAN | Wide Areal Network |

# Chapter 1

# Introduction

This thesis has investigated performance measures in a cellular *packet radio network* (PRN) using a multihop technique. Multihopping is a technique where a packet can be relayed by *mobile stations* (MSs), for example a cellular telephone or a laptop, in order to reach its destination. Figure 1.1 illustrates the use of multihopping in a cellular system. One of the first experiments that used PRN was ALOHANET[1] on Hawaii. A similar strategy with intelligent relaying has been successfully implemented in the Internet, but there most of the links are wired.

## 1.1 Background and Usability

The cost of a commercial communication system, e.g. GSM, contains many factors. Nowadays, marketing, billing and administration constitute a very high cost for a wireless operator, while equipment costs tend to be a smaller part. The rent for places where the *Access Points* (APs), i.e. base stations, are positioned is a cost that could be reduced with a multihop technique due to extended coverage. The economic situation for the telecom companies makes it important for them to investigate where they can cut down the infrastructure costs in new networks at a relative low loss in performance. A network with multihopping is one possibility to increase the coverage from an AP but this would of course also decrease the *Quality of Service* (QoS) of the system. QoS in a PRN includes maximum throughput, delay and power consumption, or combinations of them[1]. A potential increase in coverage due to relaying could be cost efficient for rural areas where the amount of users is lower and thereby also the income of the operators. The multihop technique is not only suited for commercial purposes. If the network is also *adhoc*[2], the network could, for example, be well suited for the military and for rescue actions. An adoc solution for these scenarios is attractive because of the fast and simple installation and management of such networks. This is of course also valid for all other communication systems, especially private wireless *local area networks* (LANs). A general vision of the future commercial wireless communication systems is that there will be several different wireless systems, connected together via the wired backbone. Differ-

[1]Example: Throughput per used power as in [2].

[2]An adhoc network is selfmanaging and selfconfiguring.

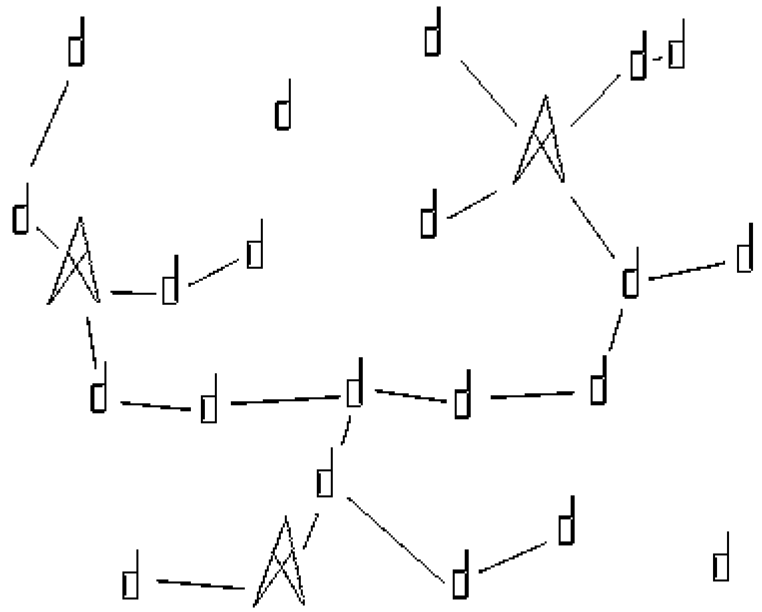

Figure 1.1: Example of a multihop system

ent communication systems have different advantages and disadvantages and a reason why wireless networks are increasingly common is the possibility of user mobility. Wired networks on the other hand are and will always be superior in data rates. Coverage against capacity and data rates is a design problem in wireless networks. A possible and economic solution would therefore be to use satellite communication in rural areas and cellular networks in urban areas. Extra capacity in for example airports and shopping malls, i.e. hot spots, could be covered with *wireless LANs* (WLANs). For areas where the need for data rates is higher than rural areas and lower than urban areas a multihop technique could with advantage be used. The leading motive for all these systems is after all an economical aspect. All these wireless networks together could then extend the Internet to (almost) the whole earth. A possibility is then that a MS could have more than one interface and then connect to the most appropriate network dependent on the service which is used. With such a device, travel could be possible between different areas without problems. An interesting point is also that if the placement of APs in a multihop network is close enough, it will be the same system as a non-multihop network. If the multihop system is adhoc, a network with low density of APs could first be built and new APs could easily be placed where the need for capacity tends to be higher.

## 1.2 Previous Research

The concept of multihopping has been discussed for a long time. However, very few implementations have actually used the technique. T.J. Harrold and A.R. Nix in [3] investigated this concept and had power reduction[3] and coverage extension as benefits of this. Harrold and Nix in [4] continued their work by investigating the capacity enhancement as a function of the number of relaying users and found an enhancement if compared to a usual architecture without multihopping. H-Y. Hsieh and R. Sivakumar in [2] obtained some interesting results after comparing the decrease in throughput in a multihop cellular network in relation to a non-multihop cellular network. This is due to the bottleneck at the AP. However when they compared the throughput with respect to the used power, the multihop technique appeared to be much more efficient. All these studies above compared the benefits and shortcomings between systems that either use or do not use multihopping.
With the introduction of multihopping, new features have to be added to the network. Routing and scheduling are two features that are added or changed in such a network. Many studies have compared different routing and scheduling algorithms for different scenarios with different results. A study carried out by J. Grönkvist ([5]) constitutes the scheduling method used in this thesis. Different assignment methods were investigated both with analysis and simulations for two different traffic models, broadcast and unicast traffic. The studied scenario was a communication system which used *Spatial Reuse TDMA* (STDMA). The results were expressed in delay and throughput.

### 1.2.1 Purpose of Study

A missing part in the previous studies is an investigation of QoS for different cell sizes in cellular multihop networks. An economic motivation to manipulate with this parameter, i.e. the AP density, was briefly discussed in section 1.1 and is hence the purpose to this thesis. The density of mobile devices is also of interest. To be able to serve more MSs in a cell is logically more economic and the MS density was therefore also a parameter to be studied.

## 1.3 Thesis Outline

The simulation model is presented in chapter 2. Section 2.2.1 to 2.2.6 describes the network model while the definition of the problem formulation can be found in section 2.4. Definitions of performance measures and variables will also be described here. This chapter is followed by analysis in chapter 3 where approximations of the perfromance measures are derived. These expressions are some of the the main contributions from this thesis. Except analysis of the problem, the thesis also contains simulations. The simulation results are together with the approximated expressions from chapter 3 presented in graphs and discussed in chapter 4. Finally, chapter 5 concludes the results from chapter 4 and proposes a few new areas of research closely related to this thesis.

[3]Only the transmitted powers was included in the measure.

# Chapter 2

# System Model

This chapter first describes the system model used for the performance evaluation in the desired scenarios. This is followed by the definitions of the performance measures and the variables to be used. With these parameters described, a more exact problem formulation can be defined. Last in this chapter, there is an explanation of how the simulation of the networks was implemented.

## 2.1 Delimitation

The thesis had the following requirements on the system model.

- The network should be cellular.
- The network should use a multihop technique.
- The general design of the network should be feasible to implement.

This description of the network is very general. Certain design parameters are thus necessary to decide. Designing a multihopping cellular network involves choosing algorithms and parameters for each protocol layer. The number of feasible combination is huge. It is impractical to examine them all, so a limited set of algorithms and parameters was chosen. However, all these algorithms and techniques should be feasible to implement. The most important choice of parameters for the network is the choice of STDMA as the *medium access control* (MAC) protocol. The reason to choose a deterministic MAC protocol is the need of a more efficient use of the frequency spectrum. Radio communication can not compete with wires where the data rates of today could be gigabits per second. That would mean that a radio link should need a frequency spectrum over 1 GHz. That is of course not possible for this thesis' scenarios described in section 5.2. However, the need for higher data rates is still there and an effective use of the bandwidth will probably be much cheaper than buying more bandwidth. The frequency band for these kinds of networks is hard to predict. The choice is here to simulate an outdoor environment with a frequency band of 100 MHz around 2 GHz. This frequency range is roughly the one used for 3G, which makes new types of networks not implementable in this frequency range. A positive consequence, and a reason for choosing this frequencies, is that this frequency range is well documented. If the central frequency was different, some constants in the propagation model would change, and the average number of neighbours for a node would change. This could either affect the coverage or the spatial reuse. Routing is also a feature that has to be implemented in a multihop network. Unfortunately, different routing algorithms could change the performance drastically. *Minimum Hop Algorithm*, MHA has been used in this thesis due to the delay performance in low trafficed networks and stability[1].

## 2.2 Simulation Model

The simulation environment to be implemented and analysed is presented in detail in this section.

### 2.2.1 Propagation Model

The propagation for a signal is an important part of a radio network. A link from node i to node j, denoted $(i, j)$ has a pathgain, denoted $G_{ij}$, which is an important part and decides the range of a reliable transmission. This is explained in section 2.2.3. An assumption that a link's pathgain is equal in both directions, i.e. $G_{ij} = G_{ji}$ is made. The model, used to determine the pathgain, is taken from [12] and [13]. The pathgain model can be divided into two parts, one deterministic and one stochastic due to fading.

$$G_{ij} = G_d(d_{ij}) + G_f \tag{2.1}$$

where $G_d$ is a deterministic pathgain as a function of the distance $d_{ij}$ and $G_f$ is shadow fading, everything expressed in dB.

#### Distance dependent gain

The value of $G_d$ in a normal cellular system without multihopping has been modelled for many existing systems like the first and second generation mobile telephony. A problem that arises when multihopping is added to a cellular system is that a different propagation model is required. This is due to different types of links, not only MS to/from AP communication. Models have been developed by Xia in [12] and figure 2.1 shows the visual model. This was further described in [13] and the straight forward models from those papers will be used here. Three different models are needed to model three identified situations that can occur with access points and mobile users. The expressions can be divided into three parts. Free space pathloss ($L_{fs}$), diffraction from a rooftop down to a receiving mobile ($L_{rtm}$) and a multiple screen diffraction loss due to propagation past rows of buildings ($L_{msd}$).

The following parameters from the figure will be used in the pathloss expressions

$R$ The horizontal distance between transmitter and receiver.

$h$ Average height on buildings.

$h_m$ Average height of MSs.

[1]Less MSs are involved in the routes

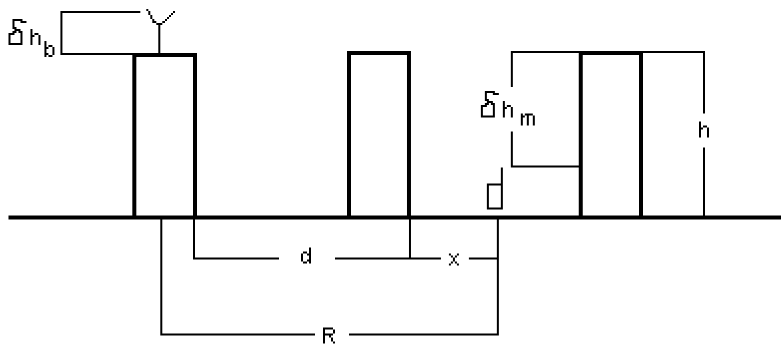


Figure 2.1: Visual model of the propagation path.

$h_b$ Average height of APs.

$\delta h_m$ $h - h_m$

$\delta h_b$ $h_b - h$

$x$ The horizontal distance between the mobile and the diffracting building.

$d$ The average separation between buildings.

$\theta$ Angle to the mobile from the rooftop.

$$\theta = \tan^{-1}\left(\frac{|\delta h_m|}{x}\right) \tag{2.2}$$

$\phi$ Angle to the first rooftop from the transmitting antenna.

$$\phi = \tan^{-1}\left(\frac{|\delta h_b|}{d}\right) \tag{2.3}$$

$r$ The distance to the diffracting rooftop from the receiver.

$$r = \sqrt{(\delta h_m)^2 + x^2} \tag{2.4}$$

The constants in table 2.1 have been used in the simulation and the correspong-ing environment should be a city. The three cases of propagation are

1. AP to/from MS

$$G_{AP-MS} = 10\log_{10}\left(\frac{\lambda}{4\pi R}\right)^2 + 10\log_{10}\left[\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right] + 10\log_{10}\left(\frac{d}{R}\right)^2 \tag{2.5}$$

2. MS to MS

$$G_{MS-MS} = 10\log_{10}\left(\frac{\lambda}{4\pi R}\right)^2 + 10\log_{10}\left[\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right] + \\ + 10\log_{10}\left[\left(\frac{d}{2\pi R}\right)^2 \frac{\lambda}{\sqrt{(\delta h_m)^2 + d^2}}\left(\frac{1}{\phi} - \frac{1}{2\pi+\phi}\right)^2\right] \tag{2.6}$$

3. AP to AP

$$G_{AP-AP} = 10\log_{10}\left(\frac{\lambda}{4\pi R}\right)^2 + 10\log_{10}\left(\frac{d}{R}\right)^2 \tag{2.7}$$

These models are assumed to be valid at non *line of sight* (LoS) propagation. At LoS, a free space model is deployed as follows.

$$G_{LoS} = 10\log_{10}\left(\frac{\lambda}{4\pi R}\right)^2 \tag{2.8}$$

The probability of LoS ($p_{LoS}(R)$) then also has to be expressed. For AP to AP transmission, LoS is assumed not to occur. LoS is not desired due to increased interference between the APs. The APs can probably be placed in a way so LoS does not occur. For AP to MS and MS to AP transmission, this is assumed to be as follows[2].

$$p_{LoS}^{AP-MS}(R) = \begin{cases} 1 & R < d \\ 0 & R \geq d \end{cases} \tag{2.9}$$

Finally, in case of MS-MS the LoS is calculated as follows.

1. Place one MS at a random position between two buildings with a separation of d meter.

[2] The MS is not allowed to be further away from the AP than d (the next building).

| Parameter | value |
|---|---|
| h | 15 m |
| $h_m$ | 1.5 m |
| $h_b$ | 5 m |
| x | 50 m |
| d | 100 m |

Table 2.1: Simulation parameters used in propagation model.

2. Place the other MS at distance R meters away from the first MS. This is done randomly, either to the left or to the right of the first MS.

3. If there is no building between the MSs, LoS occurs, otherwise not.

Notably, this simple model does not cause any correlation in $p_{LoS}$ between different links in the pathgain matrix.

### Shadow Fading

A log-normal shadow fading, $G_f$ will be added to the system in order to model variations in the environment. This is expressed, in dB, as

$$G_f \in N(0, \sigma) \tag{2.10}$$

where $\sigma$ is assumed to change depending on the path. $N(m, \sigma)$ is a gaussian distribution with $m$ as expected value and $\sigma^2$ as variance. Assumptions for the three cases are presented in table 2.2

| Propagation Type | $\sigma$ (dB) |
|---|---|
| AP - AP | 6 |
| AP - MS | 8 |
| MS - MS | 10 |

Table 2.2: Variation of $\sigma$ depending on propagation type

These values of $\sigma$ vary in different environments, but a common value in a city for AP to MS propagation should be around 8 dB and the rougher terrain, the higher value of $\sigma$ should be used. [18] used $\sigma_{AP-MS} = 10dB$ and $\sigma_{MS-MS} = 12dB$, but their city environment contained more buildings with just streets as separation[3]. From these values it is reasonable to assume the approximative values in table 2.2. For more accurate fading, correlation should also be included. If a MS is in a shadow, e.g. a basement or tunnel, the probability of shadow in a near position would increase compared to the average case. However if the MS is behind a building, the result are not the same. This part is not included in the thesis because of simplicity.

## 2.2.2 Link Model

Assume that N nodes exist in a network numbered from 1 to N. A pathgain matrix $G$ can be defined as follows.

$$\mathbf{G} = \begin{pmatrix} G_{11} & G_{12} & \dots & G_{1N} \\ G_{21} & G_{22} & \dots & G_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ G_{N1} & G_{N2} & \dots & G_{NN} \end{pmatrix}$$

$G_{ij}$ is the pathgain of (i,j) as described in section 2.2.1. In order to receive a packet correctly, the SINR at node j, which is denoted as $\gamma_j$ must be above a

[3]Their street width, i.e. d, was 15 meters.

certain threshold $\gamma_0$. For a transmitting node i, $\gamma_j$ for a given timeslot can be expressed as follows.

$$\gamma_j = \frac{G_{ij} G_i^a G_j^a P_i}{\sum_{k \neq i} X_k G_{kj} G_k^a G_j^a P_k + P_{noise}} \geq \gamma_0 \tag{2.11}$$

$X_k$ is a boolean parameter which has value one if node k transmits at the same time instant and zero otherwise. $G_i^a$ is the antenna gain from node i. The antennas are chosen to be omnidirectional for simplicity and the values of the antenna gains are 8.2 dBi[4] for an AP antenna and 2.2 dBi for a MS antenna ([17], [13]). $P_i$ is the transmitted power from node i. The main noise which occurs around 2 GHz is thermal noise which can be approximated to be white gaussian. The noise power will therefore be

$$P_{noise} = kT_0 BF_{sys} \tag{2.12}$$

where $k = 1.3810^{-23}$ J/K is Bolzmans constant, $T_0 = 290$ K, $F_{sys}$ is the receiver noise factor and B the noise bandwidth which is 100 MHz in the frequency band that will be used. A value used in [12] of the noise factor was 9 dB and this value was also used in this thesis. This is the exact expression of the SINR, but when simulating a wide area network, $N$ will be very large and an approximation is needed. The STDMA algorithm, used in this thesis[5] creates a schedule for each cell and a logical approximation would therefore be to approximate the outer cell interference to node $j$ as a constant $I_i^o(j)$. $N$ will then be reduced to the number of nodes in the cell. Equation 2.11 is then replaced with the following equation, where $i, k, j$ are nodes in the cell.

$$\gamma_j = \frac{G_{ij} G_i^a G_j^a P_i}{\sum_{k \neq i} X_{kj} G_{kj} G_k^a G_j^a P_k + I_j^o + P_{noise}} \geq \gamma_0 \tag{2.13}$$

$I_j^o$ is thus the outer cell interference to node $j$ and this is the term to approximate. One way is to do simulation, but in this thesis a simple approximation will be employed which uses the fact that pathgains to any receiver from a AP are much higher than if the transmitter was a MS. Furthermore, the fact that the APs are not transmitting all the time is also considered. According to [15], the total interference could be considered as the first ring of interferers (6 APs) multiplied by a constant depending on the propagation coefficient, which in this thesis case is set to 4. The total number of interferers could then instead be considered as 7.2, all positioned on the first tier. $I_j^o$ results in the following expression.

$$I_j^o = \frac{7.2b G_{ij} G_j^a G_i^a P_{max}}{b+1} \tag{2.14}$$

$P_{max}$ is the maximum transmitted power by the transmitter, i.e. node i, and $\frac{b}{b+1}$ is the relation in traffic load between downlink and uplink. As stated above, this is an approximation made for a wide area network. For a single cell network like WLAN, $I_j^o = 0$.

[4]dBi is the gain compared to an isotropic antenna. ($0dB = 0dBi$)

[5]See section 2.2.6

### 2.2.3 Connectivity

Depending on the pathloss of (i,j), a transmission on this link is either possible or not. A connectivity matrix $C$ with N nodes is expressed as:

$$C = \begin{pmatrix} C_{11} & C_{12} & \dots & C_{1N} \\ C_{21} & C_{22} & \dots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \dots & C_{NN} \end{pmatrix} \tag{2.15}$$

$C_{ij}$ is a boolean variable which takes the value one if a transmission on (i,j) is possible and thus could be part of a route. Such a link is also called a *feasible* link. The link's feasibility depends on multiple parameters. Intra-cell and inter-cell interference ($I_i^o$) and noise decrease the quality of the signal. Inter-cell interference and noise will always be present while the intra-cell interference depends on the medium access scheme, which in this thesis is STDMA. The requirement to transmit with less than the allowed maximum transmitting power and still be above the target SINR at the receiver plus a margin, $\gamma_m$, gives the following expression on the minimum allowed pathgain on (i,j), expressed in dB.

$$G_{ij} \geq G_{threshold} = \gamma_{target} + P_{noise} + I_i^o - P_{max} \tag{2.16}$$

$\gamma_{target}$ is $\gamma_0 + \gamma_m$ and the value of $\gamma_m$ is important. If there does not exist any margin, it would mean that an active link with a pathgain of $G_{threshold}$ must be given an own timeslot and only that link in the whole network can be activated during that timeslot. This means that no reuse is possible, not even in a *wide area network* (WAN). A too high margin implies that the nodes in average have fewer neighbours and therefore in case of low MS density, a risk of not connected nodes arises. This margin also protects some against mobility, i.e. changes in the pathgain matrix[6]. In this thesis, a margin of 1 dB will be used. $P_{max}$ is 0 dBW for both APs and MSs.

### 2.2.4 Traffic Model

It is very difficult to predict the traffic model for future communication system. In order to design a system in a good manner, certain predictions of the existing types of traffic and their amount must be done. Different types could be voice calls, messages, video conferences, web browsing etc. A more advanced traffic model could contain these different services with different probabilities for each service. The model would however, probably not correspond to reality. Who thought, for example, that SMS in GSM should be such a success? Therefore, a Poisson generation of packets is chosen with equal data rate demands for every MS. A system contains active and passive MSs. Active MSs have packets to transmit while passive MSs are silent. A Poisson arrival of $\lambda_i$ packets per timeslot from each active MS $i$ will be considered with the closest AP as destination. When the packet arrives at an AP, an answer will be generated. This answer is modelled as $b$ packets. The value of $b$ depends on the application. For voice calls, $b$ should be equal to 1 because talking and listening exist at about the same amount. This was the value applied for this thesis simulation model.

[6]Higher mobility will of course change **G** faster and errors will occur more often

Notable here is that the parameter b is part of equation 2.14. In a multihop system there is a possibility to be able to communicate to nearby situated MSs without relaying through an AP. This kind of local traffic is however assumed to be very small in a cellular network and is not taken into account in this thesis. This should be almost true for WANs, but also LANs, if the applications are not of a type that implies communication between the local nodes.

### 2.2.5 Routing

A route consists of a number of feasible links. The connectivity matrix, **C**, shows those links and is therefore used for the routing purpose. Many researchers have studied different routing algorithms and the resulting behaviour on a multihop system. The design of the algorithms could for example be to select the route with the lowest pathloss. Consequently, the nodes can transmit with a lower power and thus the interference caused will decrease. Another alternative is to select the route with the least number of hops to the destination. This one is called *Minimum Hop Algorithm* (MHA). An advantage with this algorithm is a decrease of the delay for low traffic loads. Another advantage is that a route made by MHA will always involve less or equal number of relays than any other route which is preferable from a stability point of view. The chance that some relaying MS disconnects from the network decreases. However, changes in the connectivity matrix due to mobility will cause some trouble to MHA. MHA will be used here and the exact algorithm in the system model is as follows.

1. For each nodes i and j, identify the routes that minimize the number of relays and put them in a array.

2. Select from the array the routes that would cause the minumum transmitted power.

The second step in the algorithm could be chosen in other ways, for example just to pick a random route from the array. Selecting the route from the relay that minimizes the transmitted powers is assumed to be more effective and therefore chosen. Suppose that a network contains both active and passive nodes as assumed in section 2.2.4. The STDMA algorithm needs the whole pathgain matrix, **G**, for making the schedule. It could be simplified by just taking active users into account. This simplification is probably a "must" for a STDMA network because signaling about the pathgains is probably the weakest point in the system. The signaling of pathgains would decrease significantly with this decision, but the available relays would also decrease which could affect the coverage. An alternative is to set up stations with relaying as their only task. However, this will also be an infrastructure cost and therefore it is not considered.

### 2.2.6 STDMA

The MAC layer is very important for the network's behavior and a layer that easily can be choosen and designed to optimize the system for a certain aspect. The reason to choose STDMA was the more effective behavior in loaded systems as mentioned in section 2.1. The assumption from section 2.2.4 was that unicast traffic should be used. A previous study [5] concerning the different types of traffic found that link assignment increased the maximal throughput in the system, which is assumed to be important. The STDMA algorithm, which can be found from the same reference will be used in this thesis. The main idea behind the algorithm is to create a short schedule where every link will be assigned at least the relative number of timeslots required for that link. The APs have the responsibility to create the schedule, i.e. that scheduling is centralized. If the scheduling would have been decentralized, every node must know the pathgain matrix. This would have caused more signalling about the pathgain matrix, which consumes bandwidth. Therefore, centralized scheduling would logically be used in cellular networks. The traffic in the cell has to be calculated in the algorithm. For a small cell in the network it will in the uplink case resemble figure 2.2. The roman numbers are the relative number of packets for each link. The downlinks will then contain the same values multiplied by the constant $b$, which was described in section 2.2.4.

Figure 2.2: Relative traffic in an uplink case

An example on the frame and the assignment of its own timeslot and the relaying of other packets can be seen in figure 2.3. In the following STDMA algorithm, $x_i$ denotes a a feasible link where some packets will be routed. $\Lambda_i^x$ denotes the relative traffic on a link $x_i$. The priority between the link sets is set to $\tau_i {\Lambda_i}^x$, where $\tau_i$ is the number of time slots since the link's last transmission. If the link has not transmitted yet in the schedule, $\tau_i$ is the number of timeslots from the beginning of the frame. For each t from 1 to T, the resulting schedule,


Figure 2.3: Example of a STDMA frame

$Y_t$, consists of the links that will be transmitted simultaneously at the time t. T is the length of the frame, measured in timeslots.

**STDMA algorithm**

1. Initialize:
   (a) Enumerate the links.
   (b) Create a list, A, containing all of the links and an empty list B.
   (c) Set $t$ to zero.
   (d) Calculate the number of time slots each link is to be guaranteed and set $h_i = \Lambda_i^x$.
   (e) Reorder list A according to $\Lambda_i^x$, highest priority first.
   (f) Set $\tau_i$ to zero for all links.
2. Repeat until list A is empty:
   (a) Set $t \leftarrow t + 1$ and $Y_t \leftarrow \emptyset$
   (b) For each link $x_i$ in list A:
      i. Set $Y_t \leftarrow Y_t \cup x_i$
      ii. If the links in $Y_t$ can *transmit simultaneously*
         - If $h_i = 1$, remove the link from list A and add to list B
         - Set $h_i \leftarrow h_i - 1$, and set $\tau_i$ to zero
      iii. If the links in $Y_t$ cannot *transmit simultaneously*, set $Y_t \leftarrow Y_t \backslash x_i$. Set $\tau_i \leftarrow \tau_i + 1$.
   (c) For each link $x_i$ in list B but not in $Y_t$:
      i. Set $Y_t \leftarrow Y_t \cup x_i$
      ii. If the links in $Y_t$ can *transmit simultaneously*, set $\tau_i$ to zero.
      iii. If the links in $Y_t$ cannot *transmit simultaneously*, set $Y_t \leftarrow Y_t \backslash x_i$. Set $\tau_i \leftarrow \tau_i + 1$.
   (d) Reorder lists A and B according to the link priority, $\tau_i {\Lambda_i}^x$, highest priority first.

Step 2.b.ii and 2.c.ii require a method to check whether the links can transmit at the same timeslot or not. This is achieved by SIR balancing([14], pp 155-163) and with that method the intial transmitted power of each active link is set and later collected as results. This is done at the AP which should have the needed pathgain matrix for the cell. In reality this power should change via iterative power control([14], pp 172-173) because of changes in the pathgain matrix. This method is optimal in the sense that the minimum SINR of the receivers within the cell is maximized. These transmitting powers is the powers that mostly iterative power control algorithms also converge to, which motivates the use of SIR balancing. The result of this method is thus that iterative power control does not have to be taken into account in the simulation program which will be satisfactory since only snapshots will be examined.

**Problems with schedule length and errors**

A problem arises in the STDMA algorithm when there are more than one type of service. According to this algorithm each link should get the proportional number of timeslots compared to the other users. The larger least common denominator, the longer STDMA schedule, which implies longer time to calculate the schedule. A network that has to recalculate the schedule often will then, of course, not be efficient. Enough computing power is also needed at the AP. If the schedule has to be updated frequently, communication could still be done within the cell. The schedule has to be remade at a time when the first error occurs which is not possible to fix with power control. This probably concerns only one timeslot while the rest of the timeslots in the schedule will work satisfactory. Then a method could be to remove links from the "damaged" timeslot[7] while the AP calculates a new schedule and when it is ready distributes the MSs the new and valid schedule.

**STDMA in WAN, Implementation Aspects**

The STDMA algorithm causes certain problems when designing a network. The algorithm makes it possible to have error free communication and this is because the algorithm estimates the SINR at the receivers in advance. To do that, all pathgains have to be calculated and distributed over the whole network. This will cause much signaling in a WAN. In case of mobility, which a network of mobile devices, of course, is supposed to manage, the refreshing rate of the pathgain matrix ($G$) has to be considered. Many MSs means lots of signaling at every update of $G$ and fast moving MSs implies more frequent updates. Therefore, normal STDMA is not such a good choice for fast moving units in a big network. However, if the bandwidth used for collecting the pathgain matrix data to the AP and the distribution of a new schedule is small compared to the total bandwidth, the problem with big networks will be reduced significantly. A solution to this problem is to divide the WAN into smaller parts and make an own schedule in each part. A natural choice will be to divide the WAN into the already existing cells, defined as the AP and the MSs connected to it[8]. A consequence of this partitioning of the network is not to allow a cell to use the same frequency as its neighbours because the STDMA algorithm would not work satisfactory then. A technique with frequency reuse in different cells must thus be considered. This technique has been used for example in many systems and can be found in [14] (section 4.2). The whole idea with spatial reuse is a bit of a waste, why optimize and try to reuse frequency within the cell when the neighbor cell will not use the same frequency? To give each cell maximimum

[7] Priority could be given to the real time packets.
[8] This is done with help of the routing algorithm in section 2.2.5.

bandwidth, the choice of the cluster size will be the smallest possible, i.e. 3. This is done with the requirement that the outer interference, $I^o$, is acceptable[9]. One more thing to know for making the schedule is to calculate, measure or estimate the outer interference, $I^o$. From section 2.2.1 it is found that MSs and APs have different $I^o$ depending on the propagation model which differs in the two cases. In a real system it should probably be better to measure the interference, but here the estimation from equation 2.14 will be used. The distance to the first ring of interferers, $d_i$, will be three multiplied with the cell radius ([14], pg 77) or as follows, where $R_{cell}$ is the cell radius.

$$d_i = 3R_{cell} \tag{2.17}$$

## 2.3 Variables

Many parameters can of course be varied in the system. The aim of this thesis is to investigate the following variables.

### 2.3.1 AP Density

APs are placed in the system area, each in the middle of a geometric cell, which has the shape of a hexagon. The *AP density* parameter, $\rho_{AP}$, will therefore be

$$\rho_{AP} = \frac{1}{\frac{3\sqrt{3}R_{cell}^2}{2}} \tag{2.18}$$

where $R_{cell}$ is the big radius of the hexagon.

### 2.3.2 MS density

In the whole system area, MSs are placed randomly according to a poisson process. The *MS density* parameter, $\rho_{MS}$, will therefore equal the expected value of the total number of users in one cell, $E(MS)$, divided by the cell area.

$$\rho_{MS} = \frac{E(MS)}{\frac{3\sqrt{3}R_{cell}^2}{2}} \tag{2.19}$$

## 2.4 Performance Measures

One can identify many QoS parameters in a communication system. The purpose of this thesis was to investigate delay and power consumption. The delay is important for certain realtime services and this is a parameter that could be affected negatively with bigger cells that use multihopping. Almost all commercial networks have such services and it is therefore important to investigate. The power consumption is important for mobile users since the battery life is important. [3] showed that multihopping could reduce the used transmitted powers. The power consumption does not only consist of the transmitted power. Three different sorts of powers are identified as follows.

[9]Fewer neighbours of each node is the effect of higher outer interference. A clustersize of 3 does not affect this too much and is therefore choosen

1. Power used when transmitting
   This power will probably not be changed so much in future systems. Better coding and antennas are though possible. This implies lower requirement on the SINR and hence the transmitted power could be lowered.

2. Power used when receiving
   This power is assumed to be constant and is device specific.

3. Other
   Power is also consumed to run applications. The power that a device use when being idle and sleeping is also in this part included. This part is also much dependent on the device.

What can be seen from these three types of power is the dependency on the device, i.e. the MS's hardware and complexity. The ideas behind this thesis lead to a system that does not exist today, but is possible to implement in the future. What then can be assumed is great improvements of the hardware. However, the batteries will also be improved and maybe the power consumption will not be a problem in the future. The transmitted power of a device causes big debates about eventual health problems due to the radiation. It is also the part of power consumption that is not so device dependent and is therefore the measure to be investigated. When more knowledge about devices is achieved, the power used when receiving must also be investigated. A reason for this is that this power will increase and be proportional to the number of receiving nodes in a route.
An example of a device with TDMA equipment is the GSM mobile telephone Nokia 6220, which has a battery which holds for "up to 8 days"([16]) in standby state (sleeping) and "up to 2-4 hours"([16]) when talking. The important factor here is the limit in talk time, which consists of idle time and transmitting/receiving time. The devices in this thesis are not defined, but there will be some type of TDMA equipment, e.g. like in a cellular telephone using GSM.

### 2.4.1 Average Used Transmitted Power per Packet

Let $P_{k,l}$ be the power needed to transmit a packet between the neighbour nodes $k$ and $l$. The measure is then the sum of all transmitted powers during a packet's route from the source $i$ to the destination $j$ and can be expressed as

$$P_{ij} = \sum_{(k,l) \in route(i,j)} P_{k,l} \tag{2.20}$$

where $route(i, j)$ contains all the links needed to route a packet from node $i$ to $j$. The average of $P_{ij}$ for all source nodes i, denoted $\overline{P}$ is the performance measure that is investigated.

### 2.4.2 Average Delay per Packet

Delay is defined as the number of timeslots it takes between the arrival of a packet to the source's buffer and the arrival to the packet's destination. The delay from node i to j, $D_{ij}$, for a route can then be expressed as

$$D_{ij} = \sum_{(k,l)\in route(i,j)} D_{k,l} \tag{2.21}$$

The average of $D_{ij}$ for all source nodes i, denoted $\overline{D}$ is the performance measure that is investigated.

## 2.5 Simulation

When a problem becomes very complex, analysis and approximation are very difficult and a simulation is more suitable. Analysis could be too difficult and approximations have to be verified somehow. This is the case in this thesis and a simulation is thus needed to get the results. It should be very easy if there already existed a free-to-use network simulator suitable for this thesis system model. There exist some programs, for example ns-2 [10] and GloMoSim [11]. However, to build a special program for this thesis was thought to be easier since the propagation model and other special algorithms were not implemented in these programs. The simulation program uses snapshots of different networks and transmits packets for a small time. The network contains 5x5 hexagon cells, but the performance measures was only collected from the inner 3x3 cells. This is to prevent boundary effects from the routing. A MS that is closer to one AP does not necessarily have to be connected to it. The main steps in each snapshot are as follows.

1. Put an AP in the middle of each hexagon and place a poisson number of MSs in the network area. The radius of the cell and the expected number of MSs depends on $\rho_{AP}$ and $\rho_{MS}$.
2. Calculate the gain matrix, $G$, according to the propagation model and the shadow fading in section 2.2.1.
3. Make a routing table according to the MHA algorithm that was described in section 2.2.5.
4. Calculate the STDMA schedule according to the definition in section 2.2.6
5. Generate packets at the MSs and transmit according to the schedule for a number of timeslots. When the startup time is exceeded[10], values of delay and power consumption are stored during the routes. This is repeated until sufficient data to the performance measures described in section 2.4 is collected[11].
6. Collect the performance measures and go back to 1 and iterate for different networks until the performance measures for all networks has converged[12]
7. Go back to 1 and simulate different $\rho_{AP}$ and $\rho_{MS}$.

[10]The startup time in the simulation was set to 10 times the length of the STDMA schedule. At this time, the number of packets in the network had converged (found visually).

[11]The number of timeslots for the performance measures for a specific network to converge was also found visually. 100 times the length of the STDMA schedule was the time used in the simulation

[12]100 iterations was used for the measure to converge. Again, this number was found visually

What could be added to this is what different values of $\rho_{AP}$ and $\rho_{MS}$ to simulate. One requirement is that the coverage should be maintained with very high probability since it is not the scope of this thesis to investigate coverage. This means that all nodes would be connected to the network and it implies that $\rho_{MS}$ and $\rho_{AP}$ should not be too low. From the traffic assumption in section 2.2.4, all MSs have the same traffic demands. This value is set to a constant. If the total amount of traffic in a cell is more than the maximum capacity allows, it will cause overflow in the buffers at the relaying MSs and at the AP. Investigation of the maximum capacity is not the scope of this thesis. This gives upper bounds on $\rho_{AP}$ and $\rho_{MS}$. Trial and error is used to find these situations which set the boundaries of $\rho_{AP}$ and $\rho_{MS}$.

# Chapter 3

# System Hypothesis

The main purpose of this thesis is to investigate the performance measures described in section 2.4. This chapter tries to propose relationships between the performance measures and the variables. What is needed is thus a formula for the average delay per packet as follows.

$$\overline{D} \propto f_D(\rho_{AP})g_D(\rho_{MS}) \tag{3.1}$$

$f_D$ and $g_D$ are functions dependent on $\rho_{AP}$ and $\rho_{MS}$ respectively. Similar, a formula for the average used transmitted power per packet is as follows.

$$\overline{P} \propto f_P(\rho_{AP})g_P(\rho_{MS}) \tag{3.2}$$

$f_P$ and $g_P$ are functions dependent on $\rho_{AP}$ and $\rho_{MS}$ respectively. The functions $f_D$, $g_D$, $f_P$ and $g_P$ are hence necessary to propose hypothetical formulas for.

## 3.1 Average Delay per Packet

The delay of a packet depends on the queueing time at the transmitter and each relay during the route as described in equation 2.21. The STDMA algorithm is traffic based and a certain number of timeslots are given to each link relatively. Therefore, the service rate at each transmitter could be modelled as deterministic. The arrival rate is more difficult to model. When there are packets in the MS before in the route, the arrival rate could also be modelled as deterministic, otherwise it is simply zero. In which state the arrival rate is depends on the generation of packets. The generation is Poisson distributed which makes this approach rather difficult. However, further analysis with help of queueing theory would be good if the purpose was to investigate a specific network configuration. But since the measure of the delay in this thesis is the average of the delay per packet, a more general approach is presented below. This approach assumes that the generated traffic load to the network is not too high and causes overflow in the buffer.

### 3.1.1 MS Density

The MS density is proportional to the expected number of users in the cell. Therefore it is also proportional to the generated traffic to the cell which is approximately proportional to the length of the STDMA schedule. An assumption that the average delay per packet is proportional to the schedule length is now made. This is logical for a circuit switched network with fixed data rates where each transmission from a node belongs to a certain node, either itself or another node. This prevents the nodes from larger queues. A Poisson generation of packets with FIFO queues as it is in this thesis is more difficult to do analysis on, but it is still assumed to be proportional to the scheule length which is proportional to $\rho_{MS}$. One can imagine that a higher user density could give a higher possibility of reuse within the cell, but this will probably be neglectible. This should at least be true for the used values of $\rho_{MS}$. $f_D$ in equation 3.1 will therefore be as follows.

$$f_D \propto \rho_{MS} \tag{3.3}$$

### 3.1.2 AP Density

The effect to the delay from the AP density is harder to predict and varies from case to case. Similar to the $f_D$, one part of $g_D$ is also proportional to the expected number of users and the generated traffic, $(\frac{1}{\rho_{AP}})$. The average number of hops in the route increases with bigger radius of the cell approximately as sketched in figure 3.1. This figure is approximated further so that the aver-

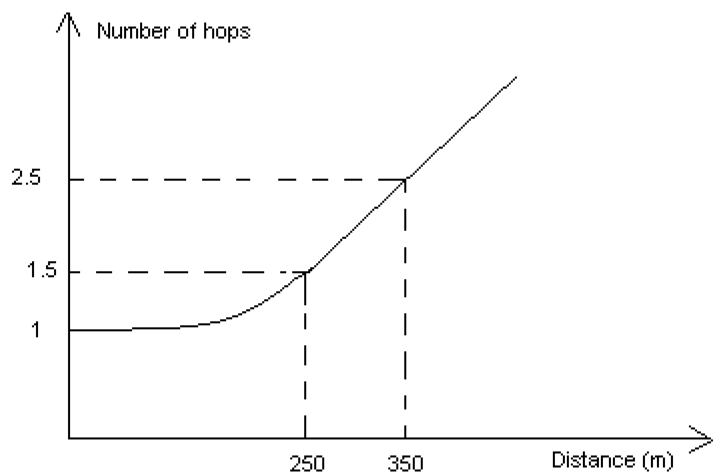


Figure 3.1: The average number of hops as a function of distance

age number of hops at a certain distance is proportional to the distance, i.e. $\#hops \propto distance$. Integration over the cell area of the new function multiplied by the probability density function for a MS, gives the result of the average number of hops for all MSs, $\overline{H}$, as follows.

$$\overline{H} \propto \frac{1}{\sqrt{\rho_{AP}}} \tag{3.4}$$

An argument for the approximation is that it is much more probable for a MS to be on $x + \Delta x$ meters away from the AP then $x$ meters, due to the cell geometry. The simplification should be more valid for more hops away between the AP and the outer MSs according to the curve's appearance, which in fact is not the case for the boundaries in this thesis of $\rho_{AP}$. Equation 3.4 will still be used because better possibilities to compare the approximation for $\overline{D}$ with the simulation results will occur. A positive consequence of an increased cell area is that the reuse will increase, but this is, of course, much less than the impact of the increased average number of hops. For smaller cells with very seldom three hops between a MS and an AP, this will make even smaller impact because reuse of timeslots occurs at quite a few slots. The conclusion of $g_D$ from these arguments is as follows.

$$g_D \propto \rho_{AP}^{-\frac{3}{2}} \tag{3.5}$$

The reuse is better for bigger cells and a simulation would therefore probably mean a positive deviation compared to equation 3.5. It is also notable that the routing algorithm has a big effect on $g_D$. The formula above is however general for all routing algorithms but different algorithms can drasticly change the constants. If one would have used a minimum pathloss algorithm, the average number of hops would have increased but the reuse within the cell would also be much better since every link would use less power.

## 3.2 Average Used Transmitted Power per Packet

The behavior of $\overline{P}$ is affected by the variables from section 2.3. But in opposite to the delay, $\overline{P}$ is not affected by the traffic model. The power control algorithm is, however, more important. The intra cell interference is affecting the SINR most if it exists, i.e. reuse of a timeslot within the cell is performed. If just one packet in the cell can transmit at a timeslot, it will therefore with higher probability be assigned a lower power with SIR balancing. This means that the variation of the result will also for $\overline{P}$ be very wide, but that is not so important since only the average value is of more importance. A MS will probably move away from that position sooner or later.

### 3.2.1 MS Density

This section would have looked different with another routing algorithm than MHA. Adding MSs to an existing cell could give three effects.

1. The new node could act as a relay and reduce the number of hops from the AP to a communicating node. In that case, more power is probably needed since a reduced number of hops probably would mean that each hop is longer.
2. The new node replaces a relay but the number of hops remains the same. This could happen because of MHA.
3. The new node does not affect the route.

The third alternative is most common for all cells and with the AP densities this thesis will use[1], alternative two is more common than alternative one. What

[1]Dense placement where one and two hops for a route are most common.

these three alternatives give to the result is that a higher MS density could give a slightly lower average power per packet. The impact is however small and the following hypothesis is instead used for $f_P$.

$$f_P \propto 1 \tag{3.6}$$

### 3.2.2 AP Density

From the equations for non LoS propagation in section 2.2.1, the signal attenuation for a link is proportional to the distance between the transmitter and receiver raised to four. However, there is a constant pathgain in dB which is much larger when an AP station is part of the transmission and this will of course affect the results. The results also depend on the routing algorithm and the power control algorithm that are used. In a cell without multihopping, the used power per packet should follow the inverse of the propagation model, i.e. in this case proportional to the radius raised to four. However, with a multihop technique, the total distance between an AP and a MS is divided into smaller distances[2] and another propagation model, which is linear instead of proportional to the distance raised to four, can be assumed. Figure 3.2 shows the used

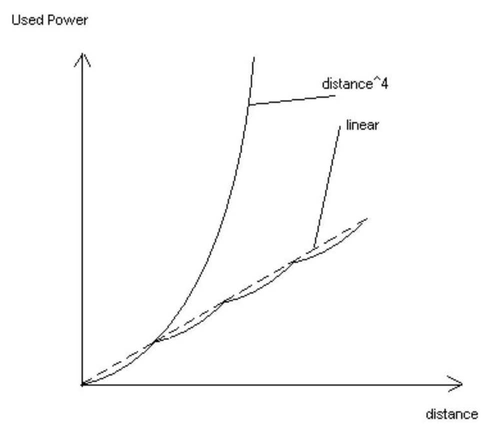


Figure 3.2: The used transmitted power per packet when using multihopping

transmitted power per packet as a function of the distance for both models. The

[2]The routing algorithm has significant influence here.

distance, R, is mapped to the AP density as follows.

$$R \propto \frac{1}{\sqrt{\rho_{AP}}} \tag{3.7}$$

This approach requires a number of hops and is hence not the best approximation for this thesis where three hops very seldom occurs. On the same way as for the delay, the average value for $\overline{P}$ is calculated by integrating the function over the cell area. This is done for both curves in figure 3.2 and it gives that the approximations should be somewhere in between the following functions.

$$g_p^{distance^4} \propto \frac{1}{\rho_{AP}^2} \tag{3.8}$$

$$g_p^{linear} \propto \frac{1}{\sqrt{\rho_{AP}}} \tag{3.9}$$

# Chapter 4

# Results and Discussion

Simulation was made according to the algorithm in section 2.5. In this chapter, these results are presented and compared with the approximations in chapter 3.

## 4.1 Delay

The approximation of the delay was not about finding absolute numbers of the delay, but more about finding the typical characteristics of the curve, i.e. the gradient. The following sections show the relation between the approximations and the simulation results. The following formula was assumed for $\overline{D}$.

$$\overline{D} \propto \frac{\rho_{MS}{}^{y}}{\rho_{AP}{}^{x}} \tag{4.1}$$

### 4.1.1 Single Cell Environment

From chapter 3, the value of y was 1 and $\frac{3}{2}$ for x. Specific for this environment is the absence of outer interference which is what can be assumed in a LAN. In figure 4.1, the average delay per packet is compared to the approximation from equation 4.1. What can be seen from the comparison is that the simulation curves roughly resemble the approximated curves. The gradient is slightly different, which is probably a result from the reuse. Slightly lower delays compared to the approximation curve are experienced for bigger cells, i.e. lower values of $\rho_{AP}$. Figures 4.2[1] and 4.3[2] show that for this simulation, a value of x would be around 1.2 instead. One reason is the actual time spent at a relaying MS. The hypothesis assumed that the time was equal at every node, which would have been the case for streaming traffic. However, if a packet arrives at a relaying MS with an empty queue, the time spent at the relaying MS would then just be until the next timeslot the relaying MS is allowed to transmit on the next link. A relaying MS has more than one timeslot per schedule and the packet could then "steal" a timeslot which was not intended for the packet itself. This will, of course, cause lower delays for the system, especially in bigger cells where the average number of hops between a MS and the AP is bigger. This discussion makes the hypothetical curve to constitute an upper bound on the delay for

[1]The lowest simulation curve in figure 4.1.
[2]The highest simulation curve in figure 4.1.

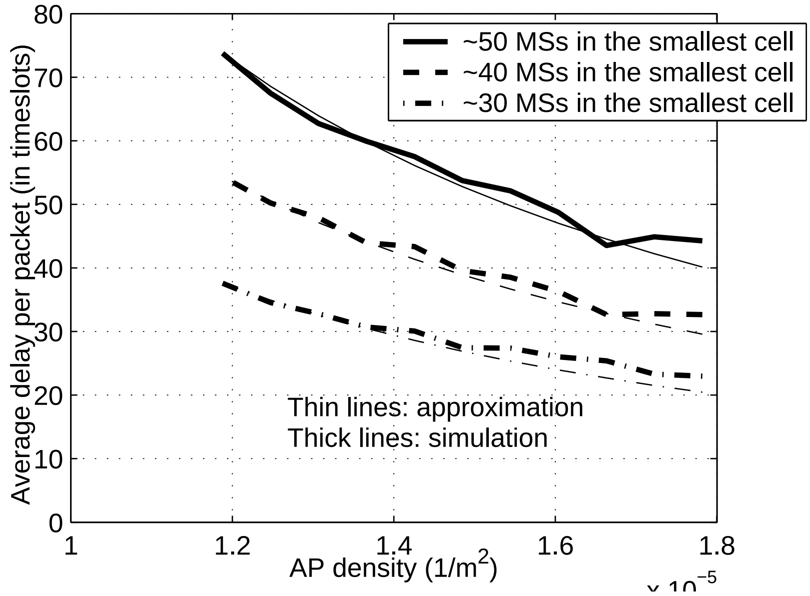


Figure 4.1: Average delay per packet in a LAN

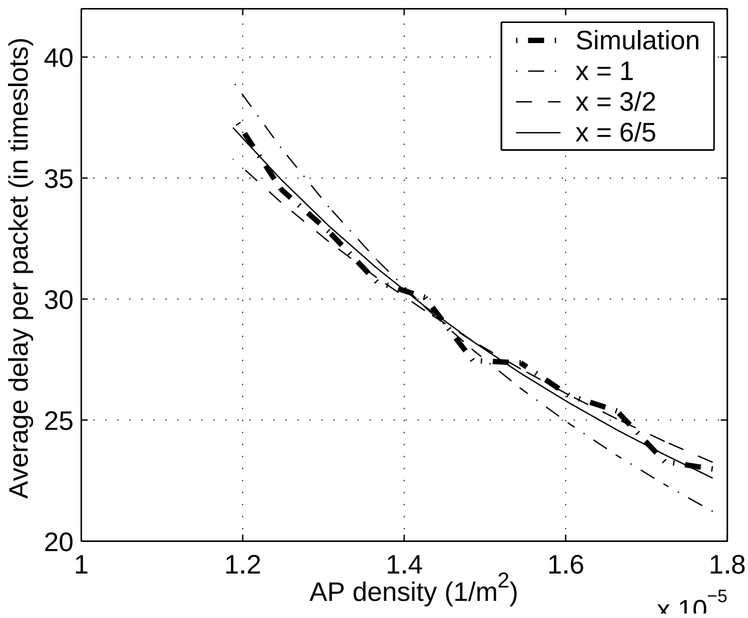


Figure 4.2: Hypothesis test of x in a LAN

an expansion in the coverage[3] of an existing multihop STDMA network. The simulation curves of $\overline{D}$ seem to be slightly more than proportional to the MS

[3]This means bigger cells.

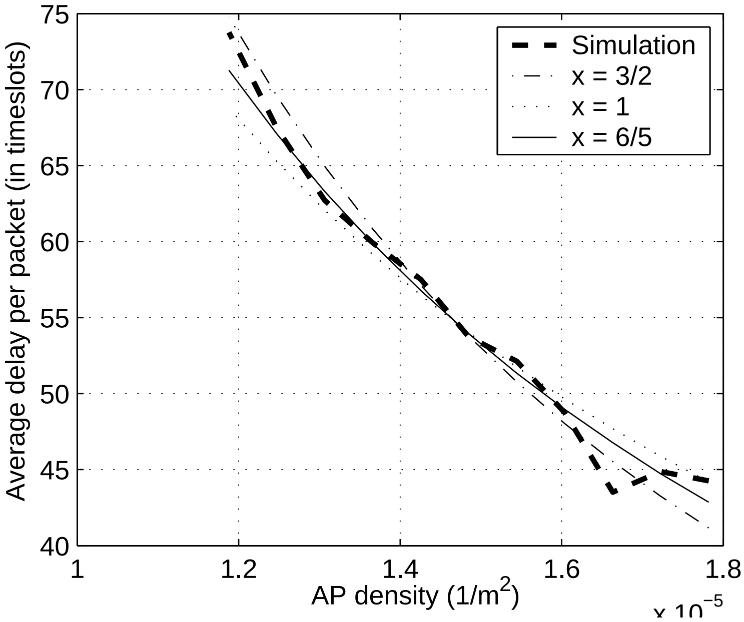


Figure 4.3: Hypothesis test of x in a LAN

density. A reason to this observation could be that high variations have a negative effect on the delay. Namely, queues in the nodes buffers have very negative impact on $\overline{D}$. Higher variations exist in a cell with more MSs because queues will with higher propability occur. Whether Poisson traffic is a good model for the hypothesis could then be questioned. Figure 4.4 shows that a more reasonable value for this simulation environment to assume is around 1.25 for y. If the network was able to manage realtime services like streaming media with high demands on low delay, this delay measure would perhaps not be the best one to investigate. Figure 4.5 shows big variances between different networks. The reason to this is different number of MSs in a cell[4] and different network configurations with different number of average hops for a MS to the AP.

What really matters, in fact, is not the average delay per packet for a specific network, but the average delay and variance for a single packet. This depends on, besides the number of MSs in the cell, the number of hops between the MS and the AP. Poisson generation of packets does, of course, also matter for the variance. A traffic model with Poisson arrival is however not a good model for streaming media, where the generation of packets is deterministic. Priority in the buffers could be a solution to this problem and this is briefly explained more in a proposal to future research in section 5.2.2.

[4]The number of MSs in a cell is a random variable as described in 2.2.4.

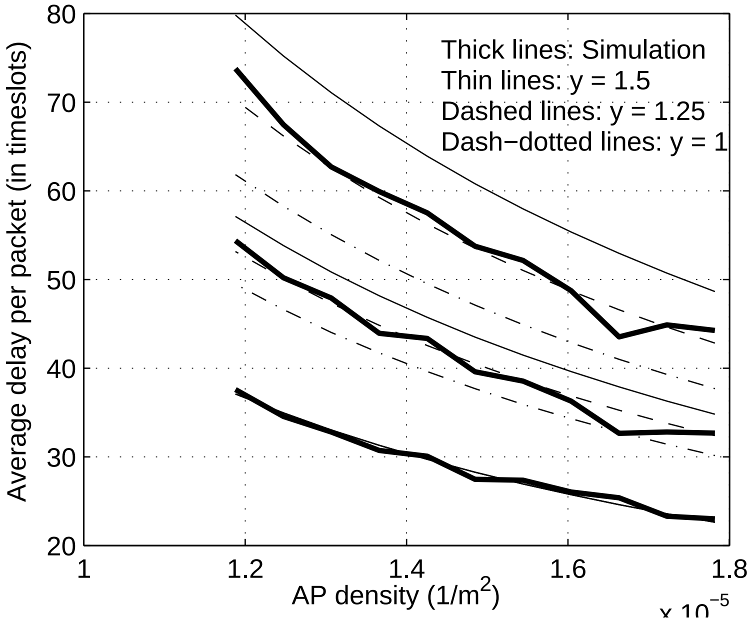


Figure 4.4: Hypothesis test of y in a LAN when x = 1.2

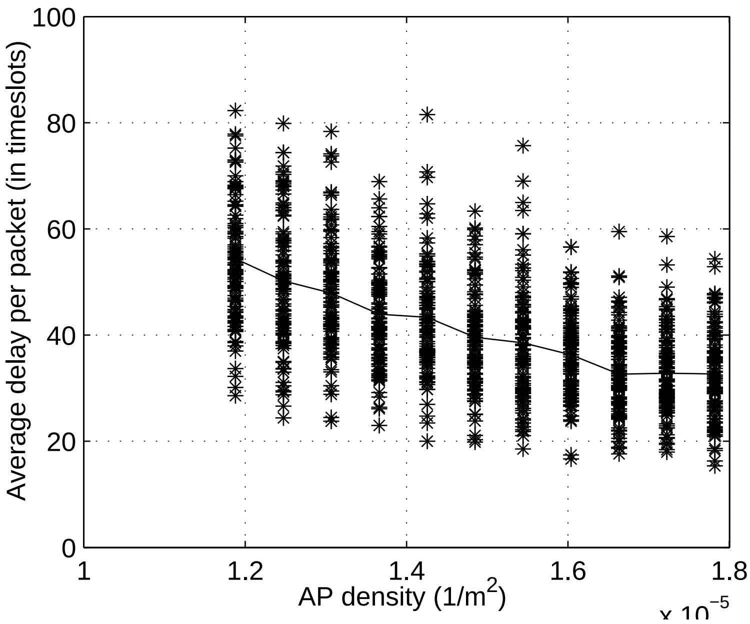


Figure 4.5: Variance of average delay per packet in a LAN

### 4.1.2 Multiple Cells Environment

The arguments from section 4.1.1 explains the results for $\overline{D}$ also in this WAN environment. The only difference is the presence of outer interference which causes shorter maximum distance in the feasible links. This implies other values for $\rho_{AP}$ in equation 3.1. Despite smaller cells, the MSs in the WAN scenario in this simulation experienced higher average number of hops to the AP due to the shorter distances of feasible links. The results of the simulation compared to equation 4.1 are shown in figure 4.6. Again, the gradient is affected by the reuse

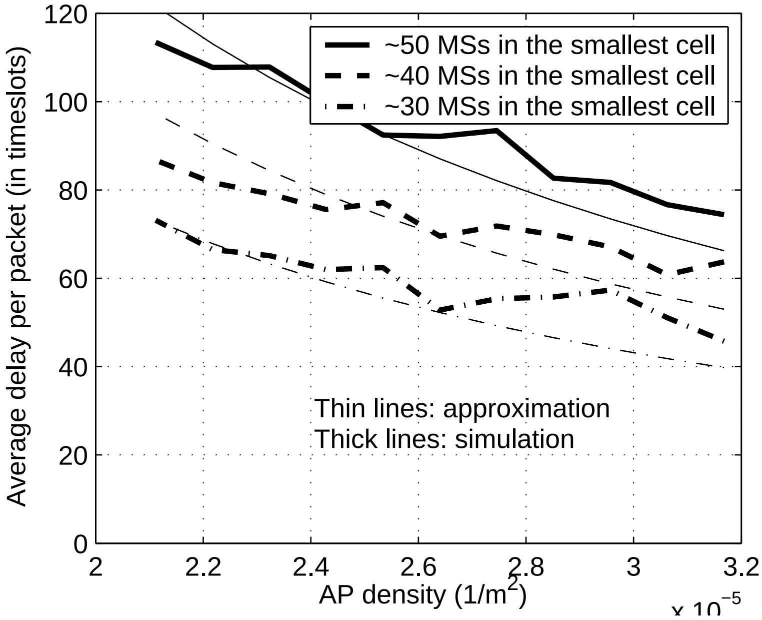


Figure 4.6: Average delay per packet in a WAN

within the cell. The impact of the reuse is bigger in this WAN scenario and the reuse and the result of stealing timeslots, which was discussed in section 4.1.1, is something that really has to be taken into account. The effect of "stealing" timeslots should be bigger for this WAN scenario due to a higher value of average number of hops. Figures 4.7[5] and 4.8[6] show that for this simulation, a value of x would be around 1 instead. Similarly as in section 4.1.1, the parameter y is tested. Figure 4.9 shows that $\frac{2}{3} < y < 1$ for this scenario. It appears to be rather strange that the value of y is below 1 because the opposite was experienced in the LAN scenario. The same argument used in that section(4.1.1) would then contradict this result. The explanation for this case is that the effect of "stealing" timeslots would increase and be dominant, which seems logical. The variation of the result is presented in figure 4.10 and a big variation for the different networks is also here experienced.

## 4.2 Used Power

The transmitted powers was on the same method as for the delay collected and averaged. The approximation part of $g_P$ for $\overline{P}$ in section 3.2 did not come up

[5]The lowest simulation curve in figure 4.6
[6]The highest simulation curve in figure 4.6

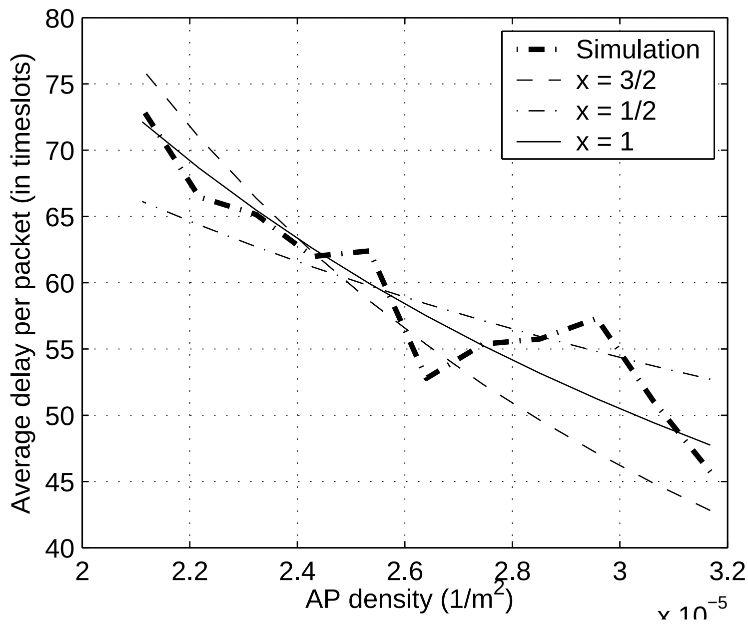


Figure 4.7: Hypothesis test of x in a WAN.

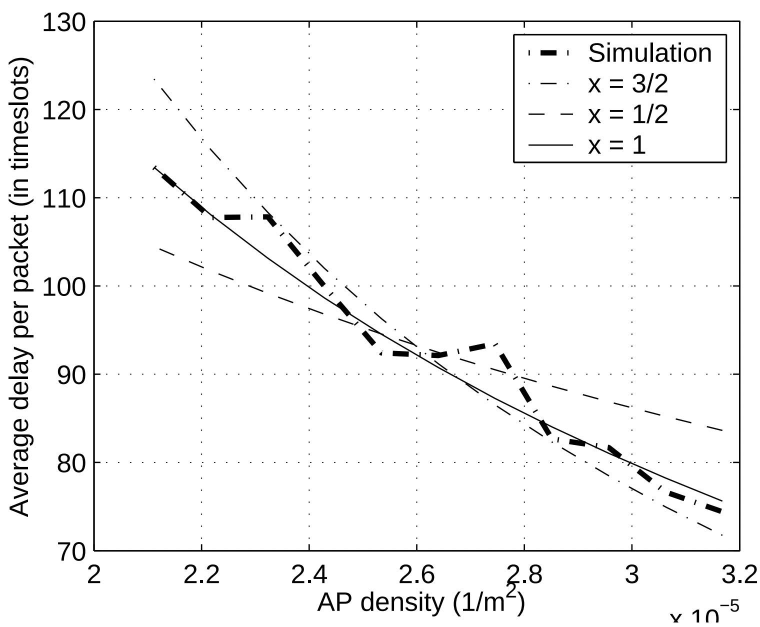


Figure 4.8: Hypothesis test of x in a WAN.

with one formula. Instead, two equations were presented. The approximation

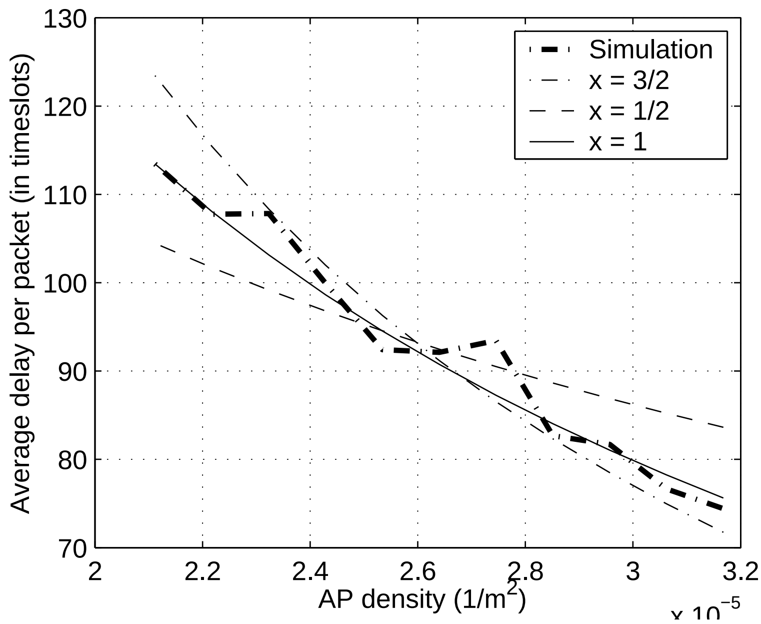


Figure 4.9: Hypothesis test of y in a WAN with x = 1.

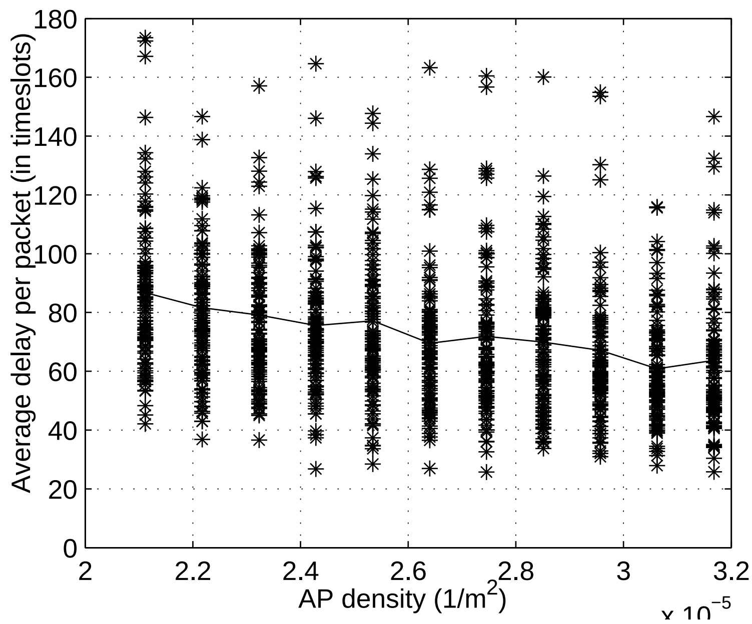


Figure 4.10: Variance of average delay per packet in a WAN

for $\overline{P}$ will be the same since $f_P \propto 1$.

$$\overline{P}^{distance^4} \propto \frac{1}{\rho_{AP}^2} \tag{4.2}$$

$$\overline{P}^{linear} \propto \frac{1}{\sqrt{\rho_{AP}}} \tag{4.3}$$

### 4.2.1 Single Cell Environment

The simulation result of a single cell environment is presented in figure 4.11. What can be conducted from this figure is a very small separation between

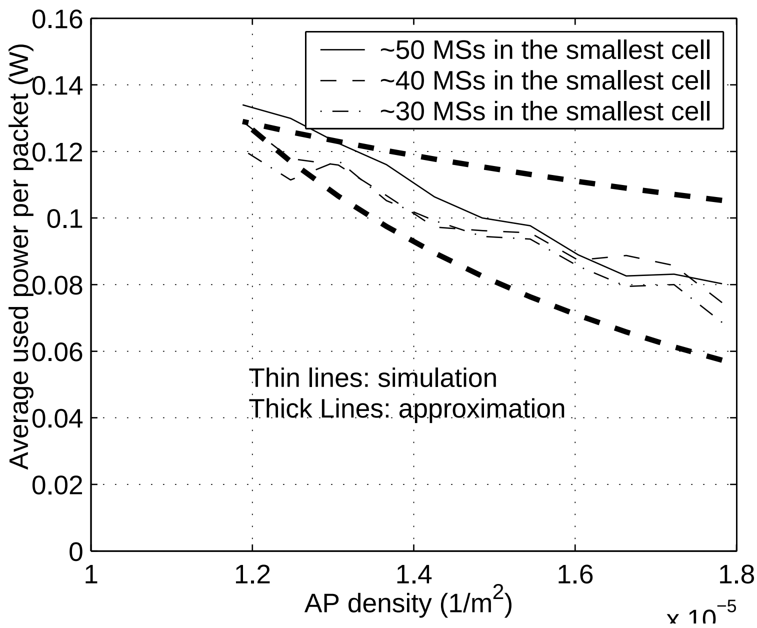


Figure 4.11: Average used transmitted power per packet in a LAN

the different user densities, which confirms the discussion in section 3.2.1. The gradient of the simulation curve in the figure lies within the boundariy equations described in section 3.2.2. A big variance of $\overline{P}$ was expected and is shown in figure 4.12. The impact from different network configurations is thus also significant here. The number of users was assumed not to change the result, but the MSs positions in the cell cause a problem in a multihop network because relaying MSs use their battery much more than other not-relaying MSs which is not fair. This is briefly discussed in section 5.2.3 and could be solved by sensitive routing algorithms and/or economic compensation.

### 4.2.2 Multiple Cells Environment

The only difference from a single cell scenario and a multiple cell scenario is the presence of outer interference. The transmitting power of a single active

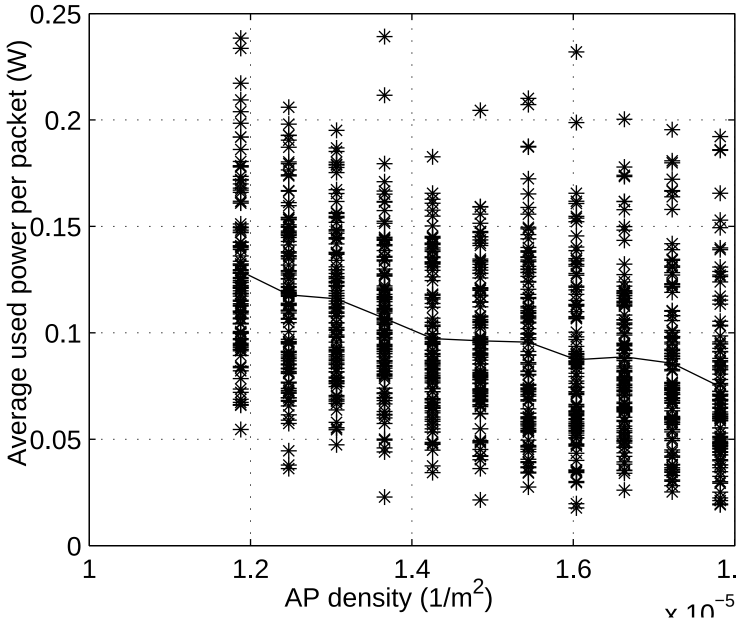


Figure 4.12: Variance of average used transmitted power per packet in a LAN

link in the STDMA schedule will therefore increase significantly. The smaller cell in the simulation and, therefore, closer distances do not counteract this so much. Figure 4.13 shows that the simulation curves also here lies within the hypothetical curves. For this WAN scenario, the curve is closer to the upper approximation curve ($\overline{P}^{distance^4}$) which indicates that the average number of hops is more for this scenario. The absolute values of the powers are here higher than for the LAN scenario, which is a result of existing outer interference. The variance of $\overline{P}$ is also here big as shown in figure 4.14. The reasons are the same as in the single cell environment.

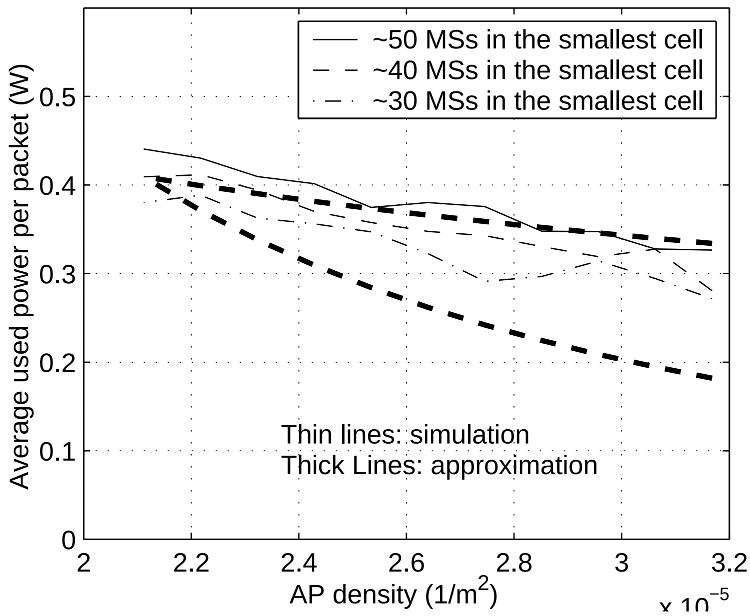


Figure 4.13: Average used transmitted power per packet in a WAN

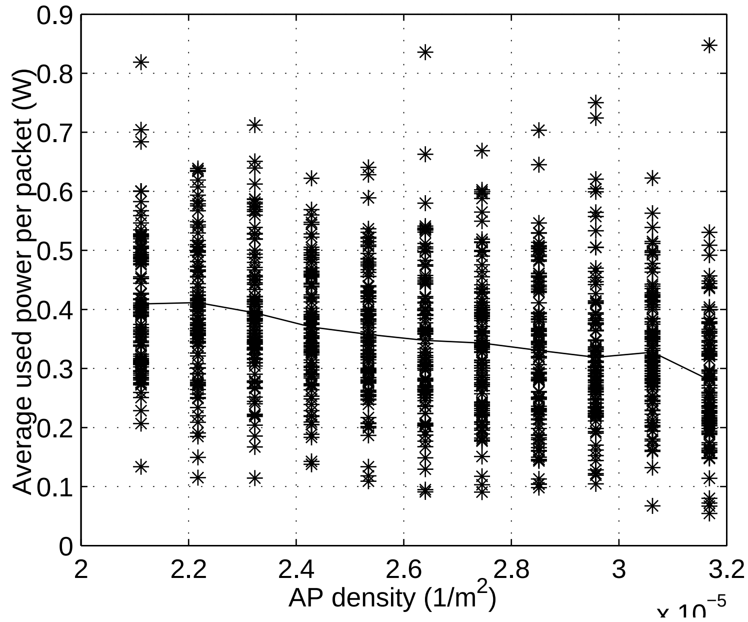


Figure 4.14: Variance of average used transmitted power per packet in a WAN

# Chapter 5

# Conclusions

This final chapter first gives a summary of the thesis and then follows three different brief proposals to future research.

## 5.1 Summary

This thesis has investigated how delay and power consumption are affected in a cellular multihop network using STDMA and MHA. Both single cell and multiple cells scenarios were investigated. Average values of the delay per packet and used transmitted power per packet in the route between a MS and an AP were investigated and the characteristics of the curves were approximated. Simulations were also done and comparisions with the hypothetical formulas gave both similarities and deviations. This was shown in the figures 4.1, 4.6, 4.11 and 4.13. The hypothetical curve for the delay was found to constitute an upper bound on delay on bigger networks which could be valuable knowledge for network designers before an expansion of an existing multihop network is realized. The power was difficult to model due to the network topology. Two hypothetical formulas were proposed and constituted boundary equations for the measure. These measures varied significantly which could cause trouble to realtime applications. Figures 4.5, 4.10, 4.12 and 4.14 showed this and the reason to this was different network configurations, e.g. different number of MSs and their placement in the cell for example. This is more critical for the delay than the used power and could partly be solved by giving higher priority to packets with a source or destination of MSs outside the relaying MSs as is proposed in section 5.2.2. The problem that some relaying stations consume more power than others could be solved with a different routing algorithm or economic compensation as proposed in section 5.2.3. When deciding the system model, some weaknesses of STDMA were also suspected. The use of STDMA could be limited to small systems (e.g. WLANs) with low mobility due to the need of the pathgain matrix. This is further discussed in section 5.2.1.

## 5.2 Future Work

During the decision of the system model and the analysis of the results, some critical points were observed, which would be interesting for further research.

### 5.2.1 Use of STDMA

STDMA was investigated in this thesis and has, of course, major influence on the results. What could be worth considering is the use of STDMA. The excellent theoretical results are not taking into account the amount of signaling of the pathgain matrix. Both bigger networks and high mobility require more signaling and the loss in bandwidth due to the signaling compared to the total bandwidth must be considered. The mobility also requires low delays of the signaling. Relatively small networks are therefore maybe a demand for STDMA if it should be used effectively. Communication systems like 3G where MSs can travel in cars could therefore be avoided. Small cellular networks, e.g. WLANs, could be interesting to investigate further, especially if the amount of local traffic is small because the traffic based algorithm effectively prevent the bottleneck that otherwise occurs at the links closest to the AP. Before any implementation of a network that uses STDMA, the signaling of the pathgain matrix must be investigated further.

### 5.2.2 Fairness in Delay

MSs with more hops away from the AP will experience longer delays. This is not fair to those MSs, especially if the wanted service requires a low delay. Such services are the ones that require a two-way communication, e.g. telephone calls and some games. A possible solution to this problem is to give real time packets from outer regions higher priority in the relays buffers. A timestamp could with advantage be added to the packet when the packet is transmitted from the destination. Packets that has spent more time in the system could then get higher priority. After a realistic algorithm for this is implemented, the variance of this thesis measure, $\overline{D}$, will then be much smaller. With a more realistic traffic model for realtime services, the maximum delay per packet could be an interesting topic.

### 5.2.3 Fairness in Used Power per Node

The impact from different network configurations has significant influence on which MSs are required to use their battery power to relay other MSs' packets. A MS will probably move around and therefore the same MS does not always have to relay other MSs packets. A study of this could be done with a model for mobility among the MSs. If the study for that mobility model will show that this spreads the power almost equally among the MSs, then the problem dissappears and does not have to be solved. If the result's outcome is negative, a need for a solution arises. Routing algorithms, which are sensitive to the amount of energy left in the MSs batteries could be possible and research have been done within this area. Algorithms, which spread the traffic so more MSs have to relay packets. However, in realtime services, it is sometimes practical with a circuit. Another approach is to compensate the relaying MSs economically.

# References

[1] N. Abramson "The ALOHA System - Another Alternative for Computer Communications", 1970 Fall Comput. Conf. AFIPS Conf. Proc., vol. 37 Montval, NJ : AFIPS Press, 1970, pp. 181-285.

[2] H-Y. Hsieh, R. Sivakumar. "On Using the Ad-hoc Network Model in Cellular Packet Data Networks." Mobihoc'02 pp. 36-47, Lausanne, June 2002.

[3] T.J. Harrold, A.R. Nix "Intelligent Relaying for Future Personal Communication Systems." *IEE Colloquium on Capacity and Range Enhancement Techniques for the third Generation Mobile Communications and Beyond*, February 2000.

[4] T.J. Harrold, A.R. Nix "Capacity Enhancement Using Intelligent Relaying for Future Personal Communication Systems." in Proceedings of VTC-2000 Fall, pp 2115-2120.

[5] J. Grönkvist. "Assignment Strategies for Spatial Reuse TDMA." Licenciate Thesis, Radio Communication Systems, Department of S3. Royal Institute of Technology, Stockholm, Sweden, April 2002.

[6] T. Rouse, S. McLaughlin, H. Haas "Coverage-Capacity Analysis of Opportunity Driven Multiple Access (ODMA) in Utra TDD." 3G 2001 Mobile Communications Technologies, IEE Conference Publication 477, pp. 252-256, March 2001.

[7] T. Rouse, I. Band, S. McLaughlin "Capacity and Power Investigation of Opportunity Driven Multiple Access (ODMA) Networks in TDD-CDMA Based Systems." IEEE International Conference on Communications, New York, 2002

[8] M. Sánchez. "Multiple Access Protocols with Smart Antennas in Multihop Ad Hoc Rural-Area Networks." Licenciate Thesis, Radio Communication Systems, Department of S3. Royal Institute of Technology, Stockholm, Sweden, June 2002.

[9] O. Sommariba. "Multihop Packet Radio Systems in Rough Terrain." Licenciate Thesis, Radio Communication Systems, Department of S3. Royal Institute of Technology, Stockholm, Sweden, October 1995.

[10] The Network Simulator - ns-2. http://www.isi.edu/nsnam/ns/, August 2002.

[11] GloMoSim. http://pcl.cs.ucla.edu/projects/glomosim/, August 2002..

[12] H. H. Xia. "A Simplified Analytical Model for Predicting Path Loss in Urban and Suburban Environments" IEEE Transactions on vehicular technonogy, vol. 46, no. 4. pp. 1040-1046. November 1997.

[13] M. Qingyu, W. Wenbo, Y Dacheng, W. Daqing. "An investigation of interference between UTRA-TDD and FDD system" Communications Technology Proceedings, 2000. WCC - ICCT 2000. International Conference, Volume 1, pp 339-346 vol. 1.

[14] J. Zander, S-L Kim. "Radio Resource Management for Wireless Networks". Artech House, Boston, 2001.

[15] Lecture notes available at: http://www.s3.kth.se/radio/COURSES/-/WNETWORKS_2E1512_2002/Slides/WN02chap4_part1.pdf as for 03-03-03.

[16] Brief techniqual information for Nokia 6220 available at http://www.nokia.com/nokia/0,5184,5880,00.html as for 03-04-05.

[17] Sami Tabbane "Handbook of Mobile Radio Networks." Artech House Mobile Communications Library, 2000.

[18] 3rd Generation Partnership Project. "Radio Frequency (RF) system scenarios" (TR 25.942 V6.0.0.). 2002.

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ERIK WALLIN Access Point/QoS Tradeoff in Multihop Cellular Networks Using Spatial Reuse TDMA