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INVESTIGATIONS ON COCHANNEL INTERFERENCE IN AN INDOOR TDMA-SYSTEM AT 60 GHZ

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Abstract— *In this paper, cochannel interference in a TDMA-system at 60 GHz is investigated. Based on a static coverage prediction for the base stations we investigate the cochannel interference in the system caused by randomly placed mobile stations, thus modeling the dynamic behavior of a cellular network. We will show that frequency division duplex is not necessary due to cochannel interference and the frequency reuse factor can be very small. Simulations on outage probabilities confirm a very reliable system behavior even in those cases.*

I. Introduction

A future wireless broadband system for the indoor environment has not only to support narrowband services like speech or fax. A system which has the design goal to be the only telecommunications network in a future office or office-like environment has to support different demands in terms of data rate, burstiness, bit error rate, and cost. A possible system concept for such a network in the 60 GHz band was introduced in [2]. In this paper we will show how system design parameters like the frequency reuse factor, and principles like the duplex technique, have an influence to the cochannel interference. Many researchers have shown multiple ways to investigate and improve cochannel interference conditions in a cellular TDMA-System so far. But, due to the high attenuation of electromagnetic waves, in an indoor environment at 60 GHz we have a quite different scenario. The microwave propagation in each single network cell is nearly limited to the room's physical borders, such as walls and doors. So, cochannel interference only occurs at special cases like open doors or rooms with windows which face each other.

In our system we placed the base stations according to the results of a static coverage prediction for an indoor environment following [1]. In a time-domain-dynamic simulation we then investigated the cochannel interference which was caused by randomly occuring and vanishing mobile stations, which are also randomly placed over the entire indoor environment under investigation. We calculated the average signal to interference ratio in different system designs and could therefore study the influence of the system design parameters on the system's performance.

This paper is organized as follows. In Section II we summarize a possible air interface and system design for a multimedia cellular network in the 60 GHz band which is introduced in detail in [3]. Section III gives an overview of the 60 GHz indoor radio propagation channel based on a literature review. Lateron we introduce the architecture of our simulation environment and software and discuss the system's parameter to investigate in Section IV. We show and discuss our results in Section V. Finally, we give a system design suggestion as a summary in Section VI and discuss further improvements to our simulation which are still to be done.

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II. System Description

An air interface for our multimedia system in the 60 GHz band was designed as follows [3]. We have one or two 1 GHz frequency bands allocated. If necessary, both can be divided into five to seven bands at maximum, each having a bandwidth of 140 to 200 MHz. Due to limitations of the signal's dynamic range we use a time division multiple access scheme (TDMA). Furthermore, uplink and downlink are separated by time-division duplexing (TDD). But, since we have different and varying demands on bandwidth and transmission capacities, we introduced a dynamic TDMA-scheme in [2]. That means, the frame length is not necessarily symmetrically separated between uplink and downlink slots. One user can have one or more slots, depending on its demands and the system capacity currently available. Since both can change with time, we have a gliding border between uplink and downlink slots. The frame duration is 3 ms. Each frame is divided into 20 slots, reserving the first two slots for the common signaling channel (network access and connectivity channel NACCH).

This system has one transponder in each cell. These transponders are connected via fiber optics to a central base station. The transponders are not time-synchronized allowing for frames in different cells to start at different times. Thus, we have an asynchronous system.

In our system we allow two or even more data rates, each having its own modulation scheme [3].

III. The indoor radio channel at 60 GHz

Our system works at the microwave frequency of 60 GHz. Several investigations were made on propagation issues in the 60 GHz frequency band and are well documented in the literature, e.g. [4]-[10]. First of all, the additional attenuation in the oxygen absorption band has nearly no effect in an indoor environment, because of the small distances. The high attenuation through brick and concrete walls (up to 6 dB/cm) [4] allows and demands that one room in the building has to be one network cell, thus having one base station or transponder in each room. For several reasons described below we will lateron use a path loss model to calculate the microwave propagation. One of a path loss model's key parameters is the path loss exponent n, which is well known to be equal to n=2 for free space propagation. In a multipath environment n depends on the presence or absence of a line-of-sight path (LOS) and, especially in the 60 GHz band, on the room's size and shape and the material of walls, floors, and ceilings. From [5] we have values of a little more than 1 for n in the LOS case and in rooms which are restricted by non-metallic materials. Metallic walls let the path loss exponent rise up to nearly 5. For the non-line-of-sight case (NLOS), n has an average value of 3. The fading is in the literature mostly described as Rice- or Rayleigh fading [6] [7]. Depending on the distance between transmitter and receiver, the fading depth changes. In the transmitter's vicinity the fading is not as deep as at a greater distance. The reason is a relatively strong direct path and weak reflected path in the range up to 4 or 5 meters from the transmitter. At a larger distance the direct path is weaker due to attenuation, but the reflections have more influence [7] [8]. The fading is deeper, but the channel still has a good coverage. Another effect was observed in [7] for the far end of a hall which has glass doors on either end and the transmitter is situated at one end of the hall. Here the direct path's reflections from the glass doors become increasingly dominant over reflections coming from walls the closer one comes to the hall's opposite end. The overall mean of the fading's standard deviation is with 90 % probability not worse than 8 dB and with 97 % probability not worse than 13 dB for broad beam antennas [6]. It can drastically be reduced by using narrow-beam antennas [6] or reducing the system's bandwidth [8]. The use of horizontal polarization [9] or, even better, circular polarization instead of vertical polarization reduces the effects of multipath fading drastically. The reason is that second order reflections have a major influence on the multipath effects of propagation. They can be reduced dramatically by using circular polarization [10].

IV. Simulation Architecture

A. Simulation's environment

The environment for our simulations is chosen to be a part of our department's building. The room's locations are depicted in Fig.1. Their arrangement is very typical for an office environment. We have one big lab, two long corridors with smaller offices on each side and a corner with stairs to other floors. Since microwave attenuation at 60 GHz through thick concrete ceilings and floors is very high, we just investigated one floor. The overall size of that area is about 500 m^2 in the offices and the labs, excluding floors and stairs.

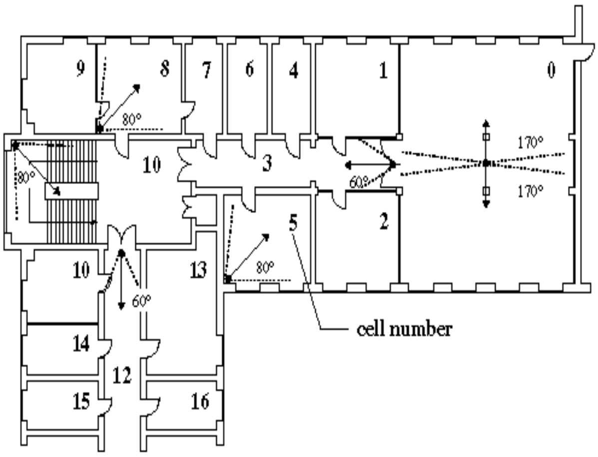

Fig. 1. topography

B. Traffic model

We use the following traffic model. Referring to [11] we assume 1 user per 20 m^2 as a peak value for office buildings, thus having 25 users in our rooms. This is very close to the current density and therefore confirms the assumptions in [11] and our use of them. Each user produces an independent traffic stream as a poisson arrival process of average λ. The call service time is assumed to be exponentially distributed with average μ^{-1}. Since we do not use a model for the user's movements through and inside the rooms, we place the users randomly and uniformly distributed in the whole area of the simulation environment. Therefore we model active users in the sense that when one of the 25 poisson sources demands a call, we give it a randomly chosen position inside our environment and thus assign it to one cell. The same user can have its next call in a totally different cell.

C. Propagation model

Since it is not our goal to predict the exact field strength at each point in our environment, we do not use a ray tracing model with its high computational cost. Instead, we use a simple but computationally fast path loss model. Thus, we calculate the mean path loss as following:

$$\overline{PL}(d) = PL(d_0) - 10 \cdot n \cdot \lg\left(\frac{d}{d_0}\right) \quad [dB] \quad (1)$$

The reference path loss value $PL(d_0)$ is clearly

$$PL(d_0) = 20 \cdot \lg\left(\frac{4\pi d_0}{\lambda}\right) \quad [dB] \quad (2)$$

where d_0 is the reference distance and λ ist the wavelength. The reference distance is for practical and mathematical reasons chosen to be 1 meter. The wavelength is 5 mm for 60 GHz. Attention to the channel's fading behavior can be paid through

$$\overline{PL}(d) = PL(d) + \sigma \quad [dB] \tag{3}$$

The standard deviation of the fading's probability density function (PDF) is hereby denoted as σ. From the discussions in Section III we can use a path loss model to predict coverage areas with a fading margin of about 10 dB. This fading margin has to be taken into account in the discussions of our results. In the contrary, [12] realized a difference between measured values and a coverage prediction with a ray-tracing tool of 5 dB, too. So, a path loss model is a good trade-off between computational costs and accuracy needed to predict coverage and thus calculating interference.

D. Simulation software

The simulations were carried out using the Ptolemy software environment of UC Berkeley. Our software is built on the discret event domain of Ptolemy, thus modeling our system using a discret event model of computation. It consists of a traffic source, which includes the 25 independent poisson sources to give the start times of calls and 25 independent exponential distributions for the service times, respectively. Furthermore, we implemented a uniform distribution to generate the positions of our mobiles. As a consequence to the randomly chosen position each time a mobile demands a transmission, it is assigned to a base station in the appropriate cell. Our path loss model is implemented, too. The floor plan which is shown in Fig.1 was implemented in an AutoCAD file format. The path loss is calculated from the AutoCAD file. The behavior of the mobile and base stations are modeled. Finally, we calculate the cochannel interference and save the results in files for future analysis and evaluation. We also implemented a graphical animation for demonstration and debugging reasons.

E. System designs under investigation

We made investigations for two different system architectures. The first one is a frequency division duplex (FDD) system. Because of the higher transmission power of base stations, we studied the downlink cochannel interference. The uplink transmissions are in a different frequency band and do not interfere with downlink transmissions. So, using the described path loss model we calculated the cochannel interference at the randomly changing mobile's positions as

$$CIR = C_{BS} - \sum I_{BS} \quad [dB] \tag{4}$$

and observed it over the time under changing parameters described below.

In the second system we modeled a time division duplex (TDD) system. Uplink and downlink transmissions are in the same frequency band and can thus interfere with each other. Here we study the cochannel interferences in the more interesting uplink. The interference coming from adjacent base stations and randomly placed mobile stations are calculated at the base station's position using:

$$CIR = C_{MS} - \sum I_{BS} - \sum I_{MS} \quad [dB] \tag{5}$$

In both systems we investigated the cochannel interferences by changing the following parameter:

1. frequency reuse factor —Our path loss model calculates the power level at the receiver's position. The power level which is transmitted by the sender is attenuated due to the space between transmitter and receiver and mainly through penetration loss of obstacles in that path. In our environment these obstacles are walls, windows, and doors made from different materials. By changing the frequency reuse factor we can investigate the influence of those obstacles. We studied the variations of cochannel interference with a frequency reuse factor of 1 (each cell = each room has the same carrier frequency), 3 (each third cell has the same carrier frequency) as well as 5 and 9. With a frequency reuse factor of 1 we would have a bandwidth of nearly 1 GHz in each cell. With a frequency reuse factor equal to 9 we could offer more than 100 MHz bandwidth to each cell, regarding to the system's parameter introduced in Section II.

2. base station's antennas —All simulations were done with two different scenarios regarding the base station's positions and antennas. In one run all cells have their base station exactly in the middle of the room and all antennas have an omni-directional radiation pattern. In the second scenario we optimized the positions and radiation patterns of the base stations in some rooms. Especially radiation in the directions of glass doors and windows are now suppressed. So, both long halls and the stair case have directed antenna beams. Furthermore, the rooms at the corner got antennas which do not radiate in the windows' direction, thus suppressing interferences here. For details refer to Fig.1 All mobiles are assumed to have omni-directional antennas in either case.

3. synchronous/asynchronous system and symmetric/asymmetric separation between uplink and downlink —As introduced in Section II we have a system, in which the frames in all cells are not necessarely synchronized. Moreover, because of different demands on transmission capacity in a multimedia network, we allow a sliding separation between uplink and downlink slots in each frame. Thus, we have 4 possible system design issues: a synchronous or an asynchronous system with each having symmetrical or asymmetrical slot assignment. Case (a), the symmetric and synchronous system, is modeled with no time offsets of the frame start points between the cells. For the examined uplink frames, possible interferers are the cochannel uplink sig-

nals. Case (b), the symmetric and asynchronous system, is modeled by introducing time offsets of 10...100 % of a frame length. Strong downlink signals may be additional interferers. Cases (c) and (d) as asymmetric, either synchronous or asynchronous systems are modeled in the same way. Thus, in the average value of many simulations, all cases of interfering base- and mobile stations are included.

In the simulations for the second system design (TDD) we always assume to have a fully loaded downlink part of each frame, thus taking multicast transmissions caused by our *multichannel-simulcast-handoff* into account [3].

4. traffic —In this paper we do not specially investigate blocking probabilities caused by traffic loads in each cell. The cochannel interferences depend slightly on the traffic load of each of our independent users, as will be shown below.

V. Results

First, we show how the frequency reuse factor, base station's antennas, synchronous/asynchronous system and symmetric/asymmetric separation between uplink and downlink as well as traffic load influence the cochannel interferences in the FDD-system. Then, the same parameters were changed in the TDD-system. Finally, we compare both system designs.

The cochannel interference was analyzed as follows. For each time slot we calculated the signal to interference ratio using Eqn. 4 or 5, respectively. This has been done each time a new user occurs or one user vanishes in the environment. So, we observed all possible interference situations during a simulation period of more than 24 real time hours. During this time we counted all time slots and the time slots which have a CIR worst than 1...100 dB, thus getting the average outage probability. The modulation techniques which are used in our system require practical CIR values of 6...24 dB [3]. For the outage probability we got the following curves as results.

1. influence of the frequency reuse factor — Both system show a similar behavior in Figs.2 and 3. With a frequency reuse factor equal to one (each room transmits in the same frequency band) and three we have outage probabilities which are in the practical region of 6 to 24 dB raise up to 10 % and more. Even for a CIR of 7 dB, which is well known to be the required CIR for coherent detection of MSK modulated signals in the AWGN-channel, we have outage probabilities of about 3 % in the TDD system and a little more than 1 % in the FDD system. Since MSK is our chosen modulation technique for the NACCH [3], we do not want to tolerate these probabilities of outage. In both systems we have nearly no difference between a frequency reuse factor of one and three. With a frequency reuse factor of five we have acceptable outage probabilities up to a CIR of 25 dB in the TDD system and nearly no cochannel interference in the interesting region in the FDD system. A frequency reuse factor of

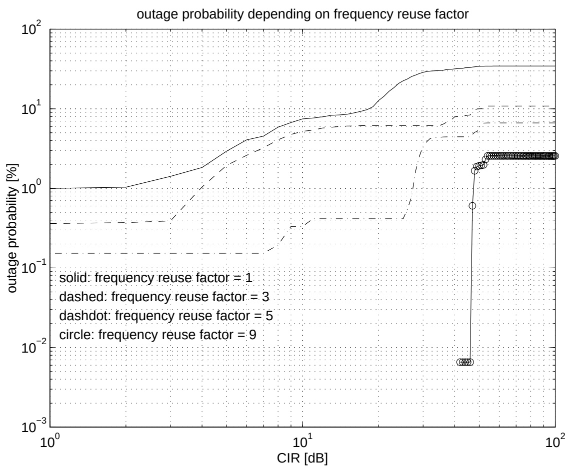

Fig. 2. influence of the frequency reuse factor in the TDD system

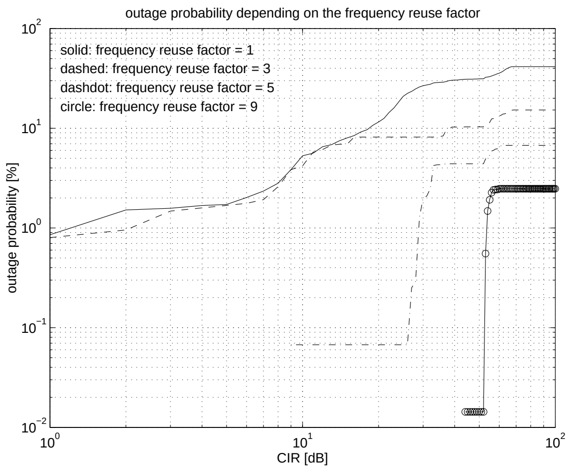

Fig. 3. influence of the frequency reuse factor in the FDD system

nine does not cause any interference worse than 40 dB in both system designs.

2. influence of a synchronous/asynchronous system —In the following investigations we always use a frequency reuse factor of one. Here we have the highest interference and thus can study the other parameter's influences in the best way. In the TDD system we have the higher interference the more asynchron the system is, as shown in Fig.4. The behavior has the following reason. In the TDD system we investigate the chochannel interference in the uplink. Hence, interferers may be other mobiles and in a asynchronous system base stations as well. In this case the frames are asynchronous and some base stations can interfere with the mobiles. The more asynchronous the system is, the more probable is a case of an interfering base station. The FDD system shows a different behavior. For small time offsets up to 10 % of the frame length the interference raise as well. But then, with more asyn-

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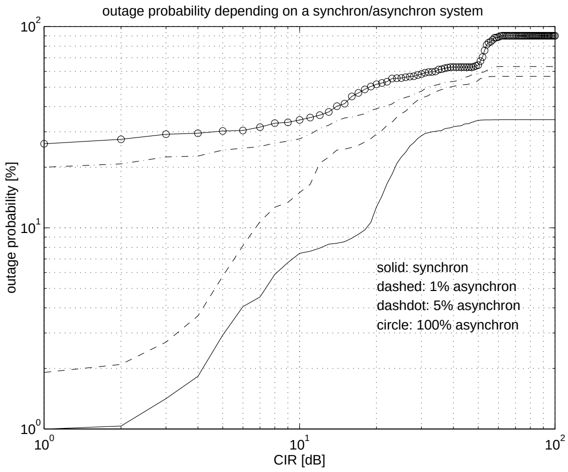

Fig. 4. influence of a synchronous/asynchronous system in the TDD system

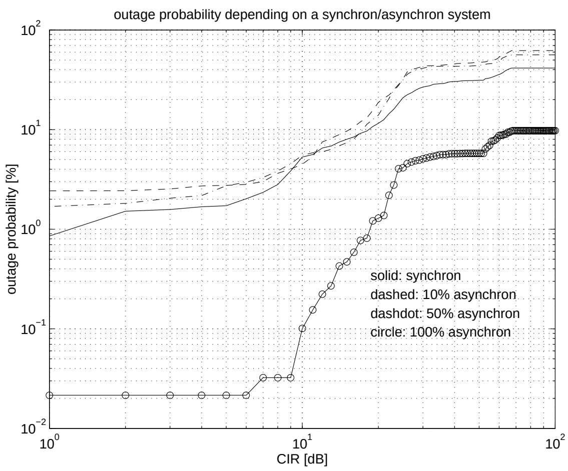

Fig. 5. influence of a synchronous/asynchronous system in the FDD system

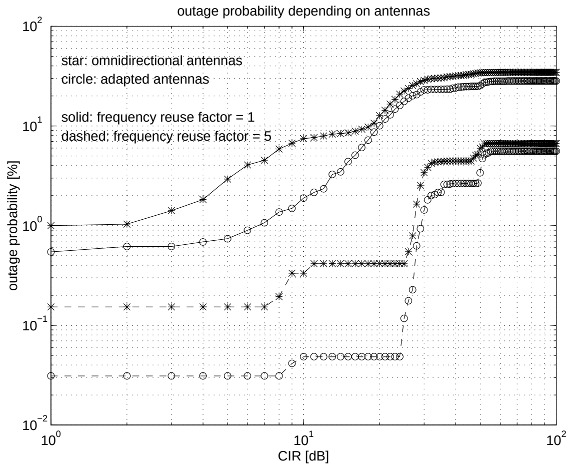

Fig. 6. influence of antennas in the TDD system

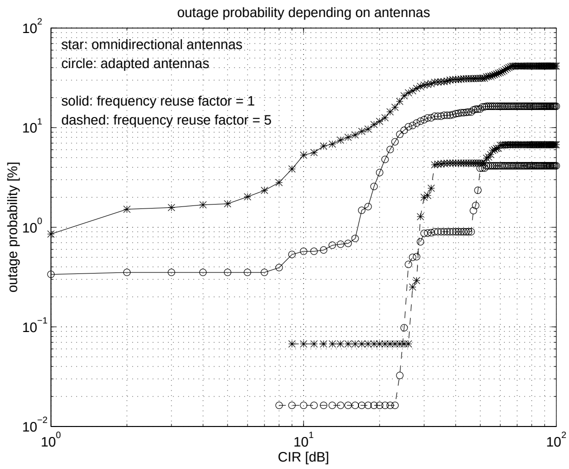

Fig. 7. influence of antennas in the FDD system

chronous frame starts, the interference get down and can fall below the interference level of a synchron system. In the FDD system we study the interference in the downlink. We have ten time slots in each duplex frame. The first two time slots are always allocated for the NACCH. The following time slots are allocated according to the traffic, which is randomly started. So, with a small asynchron time offset of less than 10 % of the frame length the always allocated first two time slots can interfere with the next time slots carrying traffic information. As the time offsets raise up to 100 % of the frame length, the first two time slots are put off between traffic carrying time slots and do not interfere anymore with any other time slots. Thus, the outage probability goes down.

3. influence of antennas —For both systems the signal to interference ratio's improvement by the use of to the room's shape adapted antennas at the base stations is clearly visible in Figs.6 and 7. These investigations were carried out with a synchronous system.

4. influence of traffic —Only a slight dependency on the traffic could be remarked. We compared the cochannel interference with a traffic of 30 mErl of each mobile with a traffic of 300 mErl of each mobile. Additional, for the TDD system we tested 1000 mErl per user. The results are shown in Figs.8 and 9. The other parameter were set like in the investigations on antennas.

5. comparison of the TDD and the FDD system —As one can see in Fig.10 the overall differences in outage probabilities between the FDD and the TDD system designs are not very important. For this comparison a frequency reuse factor of one, omnidirectional antennas, synchronous systems, and a traffic load of 30 mErl per mobile user were used. In most cases the FDD system design has a slightly better performance than the TDD system.

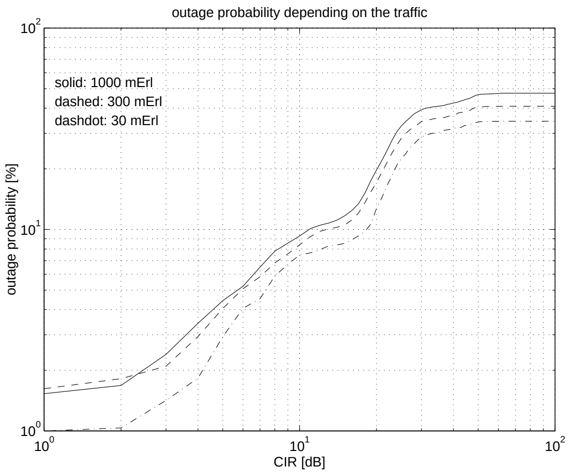

Fig. 8. influence of traffic in the TDD system

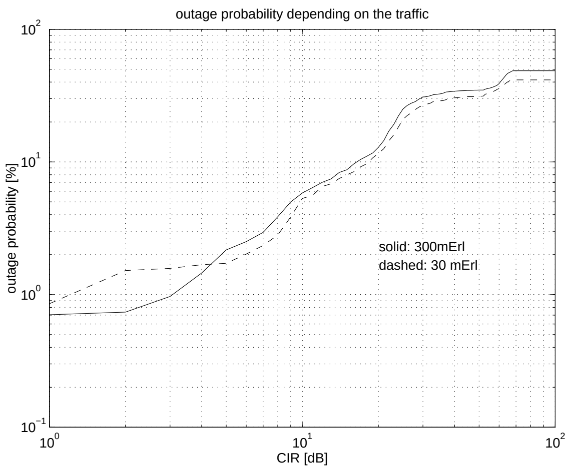

Fig. 9. influence of traffic in the FDD system

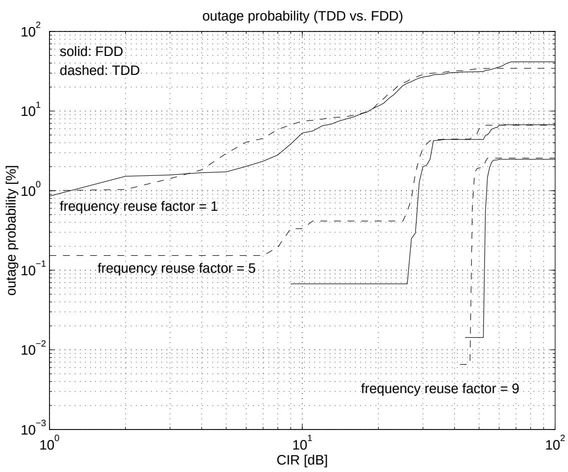

Fig. 10. comparison of the TDD and the FDD system

VI. Summary

This paper has described investigations on cochannel interference in a TDMA system which is designed for the use in the indoor environment at the microwave frequency of 60 GHz. Our investigations were carried out by time-domain-dynamic simulations. We placed base stations in a typical indoor environment and let mobiles randomly and thus dynamically appear and vanish. We observed the cochannel interference during this simulations and while changing system's parameter.

Alltogether, from our simulation's results we suggest to design a TDMA-system for the 60 GHz indoor channel as follows:

1. An additional FDD to a TDD system is not necessary. FDD has slight advantages in terms of outage probabilities, but the additinal cost for hardware especially at 60 GHz is very high.
2. The use of directed antennas improves the signal to interference ratio. Especially in the indoor enviroment one has to care about glass doors, windows at corners, and long corridors.
3. A frequency reuse factor of five is suggested. At lower frequency reuse factors the cochannel interference is too high. But decreasing the cochannel interference by a higher frequency reuse factor means a further reduction of the bandwidth per cell.

With a system which is designed following our instructions we can guarantee outage probabilities lower than 1 % up to a signal to interference ratio of 25 dB (dashdot graph in Fig. 2). Please note, that our path loss model does not include fading behavior. So, a fading margin has always to be added to the required CIR for a chosen modulation technique.

Currently we are improving our model by programming an interface to a ray-launching tool which was built by the RF department of Dresden University and by carrying out further investigations on the medium access control.

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