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Performance Analysis of Dynamic OFDM-FDMA Systems with Inband Signaling

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Abstract

In this study we investigate the performance of dynamic OFDM-FDMA systems including the cost of signaling. As dynamic OFDM-FDMA systems assign system resources (= sub-carriers, modulation types, power) periodically to different terminals, changing these assignments for the down-link data transmission require the access point to inform terminals about their new resource assignments. Hence, in order to characterize the performance achieved by such a dynamic approach *realistically*, the signaling cost has to be included in the system model.

We introduce two forms of representing the signaling information. In the first case, a fixed scheme is used which does not adapt to the signaling overhead by reducing the number of reassignments, for example. The second approach is more flexible in this sense and is able to reduce the signaling overhead significantly in some cases. However, it exploits the correlation in time of sub-carrier attenuations.

We find that in general dynamic OFDM-FDMA systems still outperform static schemes significantly if the signaling overhead is taken into consideration. However, the performance difference between the dynamic and static schemes is now more sensible to the specific parameter set of the considered transmission scenario such as system bandwidth, sub-carrier number, length of the down-link frames etc. Especially as the system bandwidth increases, the gap between the potential performance achieved by dynamic schemes without considering the signaling cost and the realistic performance of such schemes becomes rather small, such that *especially* for future wireless communication systems a dynamic OFDM-FDMA approach is a recommended option in order to enhance the system performance.

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Chapter 1

Introduction

To overcome the impairment of the wireless channel due to multi-path propagation **O**rthogonal **F**requency **D**ivision **M**ultiplexing (*OFDM*) appears to be quite an attractive technique. In OFDM systems, the total available bandwidth is split into many *subchannels*, also referred to as *sub-carriers* [1, 2]. Instead of transmitting many data symbols consecutively over one channel (as in single-carrier modulation systems), the stream of data symbols is split into parallel ones and then transmitted over the available sub-carriers. The symbol- or baud-rate per sub-carrier is thus significantly reduced, leading to a much lower sensitivity to **I**nter**s**ymbol **I**nterference (*ISI*) , the time-domain manifestation of frequency-selective fading. By adding guard times to the time-domain signal the impact of ISI can be almost eliminated.

From a link layer perspective, this principle advantage of OFDM in frequency-selective channels is accompanied by certain (cross-layer) optimization opportunities. Considering the down-link transmission direction of an OFDM cell, for example, the gain of different sub-carriers usually varies strongly regarding any terminal (due to frequency-selective fading) as well as the gain for one sub-carrier regarding different terminals (due to multi-user diversity). In addition, these gains vary also over time. These variations across frequency, time, and space (i.e., different receivers) can be exploited for example by appropriately constructed, dynamic link layers.

The concept of such a dynamic link layer coupled with OFDM is quite simple: Assume that information about sub-carrier gains (between access point and terminals) is available at the access point. Based on this information, at least two degrees of dynamic adaption are possible: dynamic power assignment and/or dynamic sub-carrier assignment.

Consider first a point-to-point connection between the access point and a certain terminal. If the same amount of power is spent per sub-carrier while the sub-carrier gains vary, the result is a strongly varying **S**ignal–to–**N**oise **R**atio (*SNR*) per sub-carrier. As a consequence either the bit error probability will vary if a fixed modulation type is used or the used modulation type will have to vary in order to achieve a certain target bit error probability per sub-carrier. As sub-carriers in a deep fade require a lot of transmit power in order to achieve a "reasonable" SNR, a suitable heuristic to increase the throughput of such a connection is to assign more power to sub-carriers if their gain is better compared to the other sub-carriers' gains. This concept of dynamically assigning power and modulation types to sub-carriers is known as *bit loading* [3–5]. Compared to static (non adaptive) schemes, bit loading can lead to a throughput increase given a fixed power budget or to a transmit power decrease given a target bit rate. Significant performance gains compared to static schemes are achieved in both cases. However, this performance increase depends on various scenario parameters (fading environment, OFDM system parameters, power budget etc.).

Considering the point-to-multipoint connection between the access point and a couple of terminals in the cell, a second opportunity for adaption appears. Due to multi-user diversity, a certain sub-carrier will have a quite high gain regarding one or more terminals while for others the gain is probably low. Therefore, disjunctive sets of sub-carriers can be assigned to each terminal in an OFDM-FDMA fashion. Such an approach in multi-user systems is referred to as a *dynamic OFDM-FDMA system* [6–8]. Again, the dynamic strategy can be utilized to increase the throughput of a system while consuming a certain limited power or decrease the transmit power while providing a certain bit rate per terminal. As with bit loading, dynamic OFDM-FDMA systems can increase system performance significantly compared to static OFDM-FDMA or OFDM-TDMA systems, but the advantage increase depends strongly on the considered scenario. Note that in the case of the dynamic OFDM-FDMA system nothing specific has been stated regarding the power distribution. Hence, a static or dynamic power assignment is possible in such systems.

In both cases (bit loading and/or dynamic OFDM-FDMA systems), an algorithm at the access point generates periodically new assignments. Due to the volatile nature of the wireless channel, updates of the assignments have to be performed often (i.e. coherence time of the channel as order of magnitude, roughly milliseconds). The running time behavior of the used algorithm is thus of some importance. Obviously, it is more complex to perform both sub-carrier and power assignments than only performing assignments in one of the two dimensions.

Beside the complexity of the approach, at least two other issues are of relevance: the performance impact of the signaling overhead and of realistic channel knowledge. The issue of channel knowledge is obvious: any dynamic adaption will depend on the accuracy of the channel gain knowledge at the access point. In reality, this information will always be an estimate and is therefore a potential source for bit errors during the payload transmission (“too optimistic” assignments are generated because of estimation errors, leading to bit errors). If the knowledge accuracy is poor, a static system might outperform a dynamic system. Very little is known about this issue so far [9].

The performance decreasing impact due to the signaling overhead results from this: Assume a dynamic OFDM-FDMA system. New assignments are generated periodically and the payload for each terminal is consequently transmitted on its actual set of sub-carriers. However, the receiving terminals need the assignment information in order to decode and recombine the information from “their” sub-carriers. Moreover, they also require the information which modulation type has been applied to their sub-carriers. A *signaling* period in which the assignment information is transmitted to the terminals has therefore to be introduced prior to the payload transmission . This will clearly reduce the performance of a dynamic OFDM-FDMA system. For example: Consider a system with 512 sub-carriers, 7 modulation types, and 14 terminals in the cell. As the assignment information consists of the information which terminal has been assigned which sub-carrier with which modulation type, this results in $9+3+4 = 16$ bits per assignment per generation cycle (the sub-carrier, the modulation type and the terminal have to be identified by the signaling, therefore their binary address has to be used). If every sub-carrier is assigned, $16 \cdot 512 = 8192$ bits have to be transmitted to the terminals in order to keep them updated. If the assignment cycles have a length of 2 ms (proposed for HIPERLAN/II [10]), this results in a rate of 4 MBit/s only required for signaling. Thus, the impact of signaling can be quite significant.

In the context of bit loading (for a point-to-point connection) one study including the overhead was presented by Lestable et al., focusing on the compression of the overhead by the Lempel-Ziv algorithm [11]. Here the authors found a compression gain of up to 60%. In [12] this gain was found to be even larger using different compression methods based on run-length coding paired with universal variable length codes and yielding a gain of up to 90%.

For multi-user OFDM-FDMA systems no such study has been published. Therefore, we present here a systematic investigation how the signaling overhead can be considered in the system model, which consequences it has for the optimization of the system performance and by how much the system performance is decreased. As the throughput of an OFDM system is increased by dynamically assigning sub-carriers at the cost of computational requirements, simultaneously it is possible to minimize the impact of the signaling overhead by choosing new assignments with respect to the previous ("old") assignments. However, this leads to a difficult (quadratic) optimization problem, for which we propose a novel solution algorithm. We compare the achieved performance of this novel scheme to two computationally "cheaper" signaling variants, which have been already presented in own previous work in [13] and [14]. The performance comparison is done for a wide range of parameters, revealing the fact that including the signaling overhead leads to a new qualitative behavior of dynamic OFDM-FDMA systems. In many situations there exists an optimal choice of system parameters and used signaling scheme due to the substantial quantitative impact of the signaling overhead on the system performance. This leads us to the proposal of adaptive base stations to be used in dynamic OFDM-FDMA systems, which dynamically change certain system parameters in order to provide the optimal system performance to terminals.

The remainder of the paper is organized as follows: In Chapter 2 we present our system model. We then formulate in Chapter 3 the basic dynamic OFDM-FDMA approach and discuss several methods to incorporate the signaling overhead into the optimization model. In addition, we discuss in this chapter a lower limit of the cost caused by signaling. Chapter 4 presents and compares the performance of the three approaches. Finally, in Section 5 we conclude our study and discuss further issues of investigation.

Chapter 2

System Model

This chapter describes general assumptions regarding the system model as well as specific assumptions regarding the physical layer, the wireless channel model and the medium access control layer.

We consider a single cell of a wireless system with radius r_{cell}. Within this cell one access point coordinates all data transmissions. J terminals are located within the cell and download data continuously from the access point through the down-link. The terminals are uniformly distributed over the area of the cell. Only the down-link data transmission direction is considered here, using OFDM as transmission scheme. Time is divided into units (frames) of duration T_{f}.

2.1 Physical layer

A total bandwidth of B $[\text{Hz}]$ at the center frequency f_{c} can be utilized for data transmission. For this bandwidth, a maximum transmit power of P_{max} is allowed to be emitted by any transmitter. The given bandwidth is split into N sub-carriers with a bandwidth of $\frac{B\,[\text{Hz}]}{N}$ each. In order to guarantee orthogonality between the sub-carriers, the symbol length for all sub-carriers is identical and is related to the bandwidth of each sub-carrier by $\frac{N}{B\,[\text{Hz}]} = T_{\text{s}}$. Although each sub-carrier employs the same symbol rate, per sub-carrier a different amount of bits might be represented per symbol. This is realized using different modulation types out of a set of M available ones.

One OFDM symbol is generated per symbol time. The OFDM symbol denotes the time sequence resulting from applying the inverse fast Fourier transformation to the N (complex) modulation symbols representing the data to be conveyed per sub-carrier [1]. Prior to the transmission of this discrete time sequence, a cyclic extension of length T_{g} is added to the OFDM symbol, the *guard interval*. The length of the complete OFDM symbol is then $T_{\text{s}} + T_{\text{g}}$, which decreases the OFDM symbol rate of the system without violating the prerequisite of orthogonality.

2.2 Wireless channel model

The perceived signal quality per sub-carrier, i.e., their SNR, varies permanently. The instant SNR of sub-carrier n for terminal j at time t is given by $v_{j,n}^{(t)} = \frac{p_n^{(t)} \cdot \left(h_{j,n}^{(t)}\right)^2}{\sigma^2}$, where $p_n^{(t)}$ denotes the transmission power, $h_{j,n}^{(t)}$ denotes the attenuation of sub-carrier n and σ^2 denotes the noise power. The attenuation is primarily responsible for the variation of the perceived SNR; it varies due to path loss, shadowing and fading[1]. Thus, $h_{j,n}^{(t)}$ can be decomposed into three factors modeling these three effects resulting in $h_{j,n}^{(t)} = a_{\mathrm{pl}}^{(t)} \cdot a_{\mathrm{sh}}^{(t)} \cdot a_{\mathrm{fad}}^{(t)}$.

The attenuation of each sub-carrier is assumed to be constant over the time unit T_{f} . Note that this time unit is considered to be smaller than the coherence time of the wireless channel, using the definition of coherence time from [15].

2.3 Medium access control layer

We assume a system where time is divided into frames of length T_{f} (Figure 2.1). In each frame, a fixed time span is reserved for down-link and up-link transmissions. OFDM-FDMA is applied during the reserved down-link transmission. Besides reserving a certain time span in each frame, we do not consider the up-link any further. The time duration of one down-link phase (including the signaling information) is denoted by T_{d} .

The access point generates new assignments of sub-carrier subsets for each terminal in the cell prior to each down-link phase. Delay effects owing to an inadequate processing power at the access point are not considered. Since the terminals do not know the new assignments a priori the access point has to transmit these assignments to the terminals first. Therefore, from the total time reserved for down-link data transmission, a certain time span is subtracted for signaling, the *signaling phase*. The signaling information is transmitted through the same bandwidth which is used for payload data transmission, causing the signaling to be *inband*. In addition, we assume the signaling information to be broadcasted during the signaling phase. A broadcast of the signaling information increases the flexibility of the system such that terminals can easily receive arbitrarily many sub-carriers without loosing synchronization to the sub-carrier assignments (which is not the case if the signaling information is "piggy-backed" to the payload data). The information is transmitted by a fixed modulation type (where the number of bits represented per symbol is denoted by b_{sig}), preferably a robust (but "slow") one. Note that correctly decoding the signaling information is crucial to the system's performance.

The generation of the new assignments per frame is based on the knowledge of the sub-carrier states towards each terminal denoted by the matrix $\mathbf{H}^{(t)} = \left(h_{j,n}^{(t)} | \forall j, n\right)$. It is assumed that this

[1]In this study the terminals are assumed to be stationary, thus the time-selective fading is caused by moving objects within the propagation environment. However, for the time-selective fading (and thus for the correlation in time) one could also assume the terminals themselves to be moving

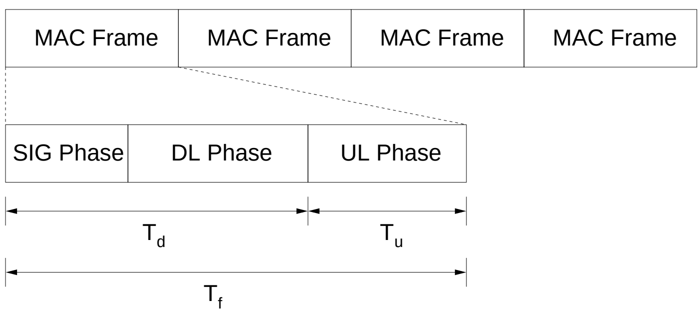


Figure 2.1: Basic medium access control layer layout

knowledge is available. Note that in a real system implementation this “perfect” channel knowledge will not be available. The assignments will actually be based on sub-carrier state *estimates* with some form of feed-back from the terminals to the access point (during the up-link phase). If the length of a frame is chosen sufficiently small compared to the coherence time of the sub-carriers, this channel knowledge will be quite close to the real values during the following frame, i.e. the estimate error will be rather small.

Chapter 3

Signaling schemes and their implementaion

In this chapter, we first introduce the chosen dynamic OFDM-FDMA approach, which is used exemplarily to investigate the consequences of signaling. We then discuss two different models to represent the signaling information stemming from assigning sub-carriers dynamically to terminals. In the first case, the signaling overhead is incorporated statically into the system. In the second case, a more flexible scheme is developed, offering the opportunity to reduce the total signaling overhead by exploiting the correlation in time of the sub-carrier states. For this flexible scheme, two implementations are presented, differing in their complexity and their ability to reduce the signaling overhead. Note that although all these signaling models are discussed in the context of one specific dynamic OFDM-FDMA approach, they can be applied similarly to any other dynamic OFDM-FDMA system approach (for example approaches for which the objective is to reduce the transmit power).

3.1 Dynamic OFDM-FDMA Approach and Modeling Framework

We are interested in an assignment of sets of sub-carriers to terminals for each downlink phase t. Therefore, we encode the assignment decisions in the form of binary variables $x_{j,n}^{(t)}$. They have the following semantics:

$$x_{j,n}^{(t)} = \begin{cases} 1 & \text{if terminal } j \text{ is assigned sub-carrier } n \text{ for downlink phase } t, \\ 0 & \text{otherwise.} \end{cases}$$

All assignment information for downlink phase t is grouped in the *assignment matrix* $\mathbf{X}^{(t)} = \left(x_{j,n}^{(t)} | \forall j, n \right)$. Obviously, each sub-carrier can be assigned to at most one terminal at a time, resulting in the trivial constraint

$$\sum_j x_{j,n}^{(t)} \leq 1 \qquad \forall n \ . \tag{3.1}$$

As stated in Chapter 2.3, we assume that the access point has knowledge of all sub-carrier states (attenuation values) towards all wireless terminals prior to the down-link phase. These sub-carrier states are denoted by $h_{j,n}^{(t)}$. Given this knowledge, different objectives (for example minimization of the consumed power or maximization of the achieved bit rate) might be of interest for a dynamic OFDM-FDMA algorithm and different approaches (optimal solutions or heuristic ones) can be employed to achieve these objectives. In principle, a dynamic OFDM-FDMA system can exploit two dimensions of dynamic assignments simultaneously: dynamic sub-carrier assignments and dynamic power assignments. However, assigning only sub-carriers dynamically in order to maximize the system throughput (under some fairness constraint) is already a computationally complex task on which we focus in this work. In addition to dynamic sub-carrier assignments we employ an adaptive modulation scheme without dynamic power assignments. The transmit power is thus fixed per sub-carrier, each sub-carrier receives a power of $p_n^{(t)} = \frac{P_{\max}}{N}$.

The adaptive modulation scheme works as the following: Together with the noise power and the actual attenuation $h_{j,n}^{(t)}$ per terminal j, the fixed transmission power yields a "potential" SNR value, reflecting the SNR as it would be if sub-carrier n were assigned to terminal j during the next down-link phase. Depending on this SNR value, the modulation type with the highest number of bits transmitted per symbol is chosen out of the M possible modulation types, such that an upper limit for the symbol error probability $p_{\mathrm{sym,max}}$ is not violated. Thus, the matrix consisting of the attenuation values $h_{j,n}^{(t)}$ can be converted into a *bit matrix* with values $b_{j,n}^{(t)}$, denoting the number of bits transmittable per symbol if this pair of sub-carrier and terminal is actually chosen as assignment for the next down-link phase.

The total number of symbols per down-link phase is denoted by

$$S = \frac{T_{\mathrm{d}}}{T_{\mathrm{s}} + T_{\mathrm{g}}} \quad . \tag{3.2}$$

Given a certain assignment realization $\mathbf{X}^{(t)}$, the total number of *bits* that can be transmitted in the entire down-link phase t can be calculated as

$$S \sum_{j,n} b_{j,n}^{(t)} \cdot x_{j,n}^{(t)} \quad . \tag{3.3}$$

However, this has to be seen as a *gross* value as it does not contain the performance loss due to signaling.

Since in a usual cell some terminals are closer to the access point than others, purely maximizing the transmitted amount of data per down-link phase might lead to starvation of the terminals further away. Therefore, each terminal j is allocated a certain (maximum) number l_j of sub-carriers that it receives afterwards by the assignment algorithm[1]. As a linear constraint, this has the form

$$\sum_{n} x_{j,n}^{(t)} \leq l_j \qquad \forall j \quad . \tag{3.4}$$

Using the so far introduced expressions, the considered dynamic OFDM-FDMA approach can be formulated as **M**ixed **I**nteger **P**rogramming (*MIP*) optimization problem operating on the input of the

[1]We follow here a two-step approach where fi rst sub-carriers are allocated (determining the number of sub-carriers each terminal receives) and then generating the assignments, based on the result of the allocation [16, 17]

bit matrix. The problem statement is thus given by:

$$\begin{aligned} \max \quad & S \cdot \sum_{j,n} b_{j,n}^{(t)} \cdot x_{j,n}^{(t)} \\ \text{s.t.} \quad & \sum_j x_{j,n}^{(t)} \leq 1 \qquad \forall n \\ & \sum_n x_{j,n}^{(t)} \leq l_j \qquad \forall j \ . \end{aligned} \tag{PLAIN}$$

(PLAIN) maps to a graph-theoretical problem [18] known as the *bipartite weighted matching problem* which canbe solved by an algorithm with $O\left(N^2 \cdot \log\left(N\right)\right)$ [19]. In practice, the solution of this problem can be generated within milliseconds on standard computers, assuming reasonable system parameters (for example $J = 16$ terminals, $N = 48$ sub-carriers)[20]. In addition, quite good heuristics have been developed for this optimization problem. However, for this study we focus on the optimal solution of Problem (PLAIN).

3.2 Signaling models

As the dynamic algorithm generates the optimal assignments, the assignment information still has to be conveyed to the terminals prior to the down-link data transmission. In order to do so, an inband signaling scheme is employed in which the signaling information is broadcasted, as described in Chapter 2.3. The assignment information itself is contained in the matrix $\mathbf{X}^{(t)}$. In addition to this, also the applied modulation type has to be signaled for each assignment. Therefore the basic information unit of the signaling information consists of the triple:

$$\langle \text{sub-carrier identification}, \text{terminal address}, \text{modulation identification} \rangle \ .$$

These triplets can be transmitted to the terminals in—at least—two different ways. We will call the first, straightforward approach the *fixed size signaling field*. All assignments are broadcasted, regardless of whether an assignment changed from the previous to the current down-link phase or not. The second approach is called *variable size signaling field*. Here, only the changes from one down-link phase to the next one are broadcasted to the terminals. As a consequence, a varying number of assignments are conveyed to the terminals during the signaling phase.

3.2.1 "Fixed size signaling field" approach

We propose for this approach the following procedure, described in Figure 3.1(a) [13, 21]: *All* assignments are transmitted in the bit stream one after the other. Since all N assignments are transmitted in each frame, the position of the tuple

$$\langle \text{terminal address}, \text{modulation identification} \rangle$$

in the sequence already indicates the sub-carrier identification (if this tuple is the fifth one transmitted, then it relates to sub-carrier five). Therefore, per assignment a signaling cost of

$$\lceil \log_2(J) \rceil + \lceil \log_2(M) \rceil$$

bits is required. Transmitting all these assignments results in a total cost (in bits) of

$$N \cdot (\lceil \log_2(J) \rceil + \lceil \log_2(M) \rceil) \quad ,$$

which requires a total of

$$\varsigma = \left\lceil \frac{(\lceil \log_2(J) \rceil + \lceil \log_2(M) \rceil)}{b_{\text{sig}}} \right\rceil \tag{3.5}$$

symbols per down-link phase. Therefore, for payload transmission $S - \varsigma$ symbols remain. Inserting this expression (instead of only S) in Equation (3.3) yields the effective throughput of the system, referred to as *net throughput*.

Since the number of lost symbols due to signaling is constant for a certain system instance (fixed parameter set), maximizing the net throughput is in principle equivalent to maximizing the gross throughput, therefore seeking for the solution of Equation (PLAIN). However, the number of symbols available for payload transmission is adjusted:

$$\begin{aligned} \max \qquad & (S - \varsigma) \cdot \sum_{j,n} b_{j,n}^{(t)} \cdot x_{j,n}^{(t)} & \\ \text{s.t.} \qquad & \sum_{j} x_{j,n}^{(t)} \leq 1 & \forall n \\ & \sum_{n} x_{j,n}^{(t)} \leq l_j & \forall j \ . \end{aligned} \tag{FIX}$$

3.2.2 "Variable size signaling field" approach - optimal model

One option to save overhead is to signal only the "new" assignments of subcarriers that had been assigned to a different terminal in the prior down-link phase. As a consequence, the binary representation of one assignment becomes now more expensive. The sub-carrier identification will need $\lceil \log_2(N) \rceil$ bits. Accordingly, the terminal address and modulation identification will consume $\lceil \log_2(J) \rceil$ bits and $\lceil \log_2(M) \rceil$ bits such that an assignment change from one down-link phase to the next consumes

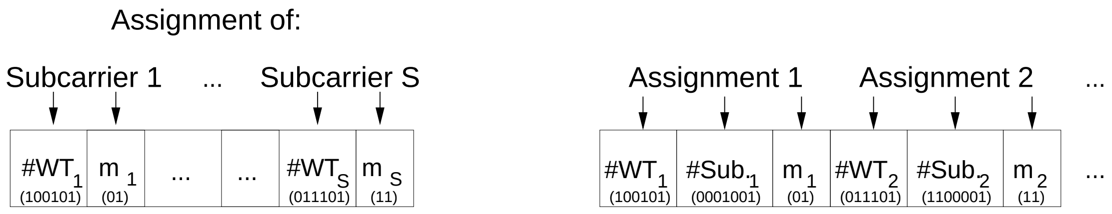
$$C_{\text{sig}} = \lceil \log_2(N) \rceil + \lceil \log_2(J) \rceil + \lceil \log_2(M) \rceil \tag{3.6}$$

bits. The layout of the resulting signaling field is shown in Figure 3.1.

The bit size of C_{sig} is quite practical: It motivates the idea to state an optimization problem in which an assignment of the previous down-link phase is changed only if this generates a higher net throughput – taking into account the signaling costs for this changed assignment which adversely impacts the benefits of changed assignments. Therefore, the obtained throughput would include already the loss due to signaling. Knowing the assignments $\mathbf{X}^{(t-1)}$ for down-link phase $t-1$, the cost for assigning sub-carrier n to terminal j in phase t is

$$c_{j,n}^{(t)} = \begin{cases} 0 & \text{if } x_{j,n}^{(t-1)} = 1, \\ C_{\text{sig}} & \text{otherwise.} \end{cases}$$

Here we use the assumption that signaling cost only applies if the assignment is actually changed with respect to the last down-link phase. Taking into account the assignments of the previous frame when determining new assignments is the crucial difference to the fixed signaling approach.



(a) Fixed size signaling field

(b) Variable size signaling field

Figure 3.1: Representation of assignment information

However, considering only the signaling overhead in terms of bits and subtracting it from the achieved throughput in the down-link is not precise: During the signaling phase a fixed modulation type is used on all N sub-carriers, whereas during the down-link phase adaptive modulation is applied on each sub-carrier. Therefore, the transmission of 100 bits consumes a different amount of symbols during the signaling phase than during the down-link phase. We denote the number of transmitted bits per symbol in the signaling phase by b_{sig}. What has to be optimized is the achieved throughput during the time remaining after transmitting

$$\varsigma = \left\lceil \sum_{j,n} c_{j,n}^{(t)} \cdot x_{j,n}^{(t)} / N \cdot b_{\text{sig}} \right\rceil$$

symbols in order to convey the signaling information. Hence, the resulting optimization problem is formulated as:

$$\begin{aligned} \max \quad & \left(S - \left\lceil \frac{\sum_{j,n} c_{j,n}^{(t)} \cdot x_{j,n}^{(t)}}{N \cdot b_{\text{sig}}} \right\rceil \right) \cdot \sum_{j,n} \left(b_{j,n}^{(t)} \cdot x_{j,n}^{(t)} \right) & & \\ \text{s.t.} \quad & \sum_j x_{j,n}^{(t)} \leq 1 & \forall n & \qquad \text{(VAR OPT)} \\ & \sum_n x_{j,n}^{(t)} \leq l_j & \forall j \; . & \end{aligned}$$

This problem is nonlinear and cannot be solved by standard optimization software for linear programming. Our solution approach is described in the appendix. Compared to (FIX) the key difference is that ς now varies from frame to frame, depending on the number of new assignments. The new assignments are only chosen if the caused signaling overhead pays off in the net throughput.

3.2.3 “Variable size signaling field” approach - approximation

Given an assignment of the previous down-link phase, the solution to (VAR OPT) is optimal for the representation of the signaling information introduced as variable size signaling field. However, due to the quadratic nature of the problem, the generation of this solution is computationally difficult. Alternatively, we suggest to consider the resulting throughput as pure difference between signaling cost caused by changing some assignments and the throughput gained by this, neglecting the influence of the uniform modulation type during the signaling phase (and so neglecting the influence of the consumed symbols for the signaling) [14].

The number of raw bits transmitted under a certain assignment is given in (3.3). Combining this with $\sum_{j,n} c_{j,n}^{(t)} \cdot x_{j,n}^{(t)}$, the number of bits needed for signaling information, we obtain the following optimization problem:

$$\begin{aligned} \max \quad & \sum_{j,n} \left(S \cdot b_{j,n}^{(t)} - c_{j,n}^{(t)} \right) \cdot x_{j,n}^{(t)} & \\ \text{s.t.} \quad & \sum_{j} x_{j,n}^{(t)} \leq 1 & \forall n \\ & \sum_{n} x_{j,n}^{(t)} \leq l_j & \forall j \ . \end{aligned} \tag{VAR APP}$$

Note that (VAR APP) is equivalent to (FIX) with the difference that assignment coefficients are adapted to reflect the cost of signaling. The resulting system throughput of (VAR APP) is not the net throughput, since this again has to be computed from the assignments and the number of signaling symbols ς. However, by varying C_{sig} in this case an incentive is given to reduce or increase the number of new assignments. This can be used as an approximation to (VAR OPT).

3.2.4 Bit errors in the signaling field

As the correct reception of the signaling information is a requirement to benefit from dynamic assignments, it is obvious that the “cost” of signaling by purely considering the transmission of the signaling overhead is not quantified correctly. Introducing a signaling scheme and considering its impact requires also to consider the influence of bit errors occurring in the signaling part.

In case of the fixed size signaling field approach a bit error leads to a loss of the following down-link data transmission. In order to detect a bit error at least a CRC field has to be added to the signaling field which requires a few bits. A terminal that examines a bit error in its signaling field will discard the following payload data transmission and indicate this loss to the access point during the up-link phase. Then, during the next frame, this terminal receives a correct signaling field information again and the access point retransmits the data during the payload transmission phase. In this case the error during the signaling phase would only effect the down-link net throughput of the terminal with the erroneous signaling data.

In the case of the variable size signaling field approach, a bit error when decoding the signaling field has in principle the same consequences as in the case of the fixed size signaling field scheme: the loss of the following payload information for the specific terminal. However, this terminal is not automatically “resynchronized” to the complete assignment information during the next signaling phase. Therefore, if in this scheme a bit error occurs to the signaling part, one possible recovery scheme would require the access point to transmit the specific assignments of the terminal with erroneous signaling data during the next signaling phase to resynchronize this terminal for the next down-link phase. This way, the terminal would not have the complete, correct signaling information but at least it would have its specific assignments during the next down-link phase and could track changes to these in future signaling phases. Note that in this case the bit error sensitivity of the signaling phase would not only effect the down-link net throughput of the specific terminal with the erroneous data, but during the next frame it would also effect ς and therefore would decrease the net throughput for all terminals.

For both approaches, the impact of bit errors on the achieved payload performance depends strongly on the modulation/coding combination used during the signaling phase (b_{sig}). If the resulting bit error probability for the terminals in the cell is small, the impact of errors in the signaling phase is negligible.

Chapter 4

Performance Evaluation

In this chapter, we study the performance of the various discussed signaling models. At first we discuss our methodology, then we present the chosen parameters and finally the results.

4.1 Methodology

From a system point of view, one is interested in metrics such as the average data rate which can be provided per terminal. However, the result of performing one of the optimizations, as presented above, is a certain number of bits that can be transmitted per down-link phase to each terminal. Thus, in order to obtain system level results, we proceeded as this: Initially we generated channel trace files of the attenuation values of each sub-carrier regarding each terminal. Each attenuation value was composed of the path loss, shadowing and fading components, as discussed and parameterized in Section 4.2. Especially the correlation of the fading process in time and frequency was very important, therefore we implemented the fading process in the trace file generator by the method of Rice (superposition of appropriately parameterized harmonic functions in order to model a colored Gaussian random process) [22]. Using this model for the fading, one sample was generated for every down-link phase and sub-carrier per terminal.

Once the trace file of the attenuation values was generated, for each down-link phase all attenuation values were transformed into the bit matrix $\mathbf{B}^{(t)}$. Using these bit matrices, a linear program file was generated, using the tool ZIMPL [23][1]. This file was then passed to CPLEX [24], a solver for linear programming problems. After solving the linear program, CPLEX wrote the resulting assignments to a file, which was read by a script. Using this script, the complete results for each trace file were collected and statistically analyzed. Typically, the trace files represented a couple of seconds (equaling a few thousands of down-link phases). Therefore, from the total amount of bits transmitted to each terminal, we obtained the throughput per terminal.

4.2 Scenario parameterization

The impact of the presented signaling models on the throughput of a dynamic OFDM system depends obviously on a couple of parameters, such as the number of terminals in the cell J, the number of sub-

[1] We gratefully thank Torsten Koch from ZIB for enabling the usage of ZIMPL

carriers in the system N and the number of modulation types M. These three parameters directly influence the number of bits in the signaling bit-stream, whether the fixed-size model is considered or the variable-size signaling models.

Further relevant parameters are the maximum speed $v_{\max}$ together with the frame time T_{f} and the delay spread $\Delta\sigma$ of the propagation environment. The speed influences the correlation of the channel states; for settings with a slow speed or a short frame time T_{f}, the cost for the variable size signaling fields will be different than for high speed or a long frame time. The delay spread $\Delta\sigma$ influences the correlation in the frequency domain and therefore can also have an impact on the behavior of the variable-size signaling model. In addition, the available system bandwidth B $[\text{Hz}]$ will have a high impact on the correlation as well as on the total throughput of the system.

All these parameters might influence the net throughput of the system by either causing a higher or lower signaling overhead or by increasing or decreasing the gross throughput. For example a higher number of terminals in the system will lead to an increase of the multi-user diversity, which increases the net throughput of the system. However, more terminals will also increase the cost of signaling, leading to a decrease of the net throughput.

In order to distinguish between parameters with a high impact and a low impact, we first performed a sensitivity analysis following the method of the 2^k factorial design [25]. Then, we further investigated the most relevant parameters, discovered in the first step. The metrics considered for the sensitivity analysis are the average gross throughput per terminal, the average percentage of symbols per down-link phase required to transmit the signaling information (ς/S), and the average computation time. Note that we could not use the net throughput directly for the sensitivity analysis, since it has maximum points within the range of the considered parameter instances, which do not allow a correct statement regarding the impact of each parameter on this metric.

Beside the above mentioned parameters which were further investigated regarding their impact on the system performance, we chose the following simulation scenario. The cell radius was set to $r_{\text{cell}} = 100$ m. The system bandwidth B $[\text{Hz}]$ was spaced around a center frequency of $f_{\text{c}} = 5.2$ GHz. The maximum transmit power allowed for this band is $P_{\text{max}} = 10$ mW, thus per sub-carrier a transmit power of -7 dBm was applied. The guard interval length was fixed at $T\_g = 0.8$ μs (all these parameters correspond to the U-NII lower band of the standard IEEE 802.11a [26]). Note that although the delay spread was varied the guard interval was fixed, the delay spread variation were all much smaller than the considered guard interval length.

The sub-carrier attenuations $h_{j,n}^{(t)}$ were generated by obtaining values for the path loss, the shadowing and the fading. All three values were then multiplied together in order to receive $h_{j,n}^{(t)}$. For the path loss a standard model was assumed; it determines path loss by the distance between transmitter and receiver d, the path loss exponent $\alpha$and the normalized loss over one distance unit K, resulting in $a_{\text{pl}}^{(t)} = K \cdot \frac{1}{(d^{(t)})^{\alpha}}$ [15]. As parameter instances, we used $K = 46.7$ dB and $\alpha = 2.4$, according to a large open space propagation environment. For the shadowing we assume independent stochastic samples ($a_{\text{sh}}^{(t)}$) from a log-normal distribution, characterized by a zero mean and a variance of $\sigma_{\text{sh}}^2 = 5.8$ dB. The samples were regenerated every second. While the path loss and shadowing components were the same for all sub-carriers of each terminal for one frame time, each sub-carrier experienced its own fading component. Each sample $a_{\text{fad}}^{(t)}$ of the fading process was assumed to be Rayleigh-distributed where the frequency and time correlation of a_{fad}^2 were characterized by a Jakes-like power spectrum and an exponential power delay profile. The Jakes-like power spectrum is parameterized by the maximum speed of the terminals in the cell $v_{\max}$ and the center frequency

f_c and the exponential power delay profile is characterized by the delay spread $\Delta\sigma$. The noise power σ^2 was determined by considering the thermal noise in a receiver at an average temperature of 20° C over a bandwidth per sub-carrier of $\frac{B\,[\mathrm{Hz}]}{N}$.

For the adaptive modulation scheme, we chose a maximum tolerable symbol error probability for the adaptive modulation of $p_{\mathrm{sym,max}} = 10^{-2}$. During the signaling phase, the modulation type was BPSK with a rate $1/2$ convolutional coder with soft decision, resulting in $b_{\mathrm{sig}} = 0.5$. Therefore, using the above mentioned path loss model and including a 10 dB fading margin, at the maximum distance between access point and terminal in the cell still a SNR of 4 dB could be achieved, yielding a bit error probability in the signaling part of 10^{-4} [27], therefore we did not consider the performance loss of the system due to errors in the signaling part.

The length of a frame T_f was equally split between down-link and up-link phase, if for example the frame length was $T_f = 2$ ms then the down-link phase had a length of $T_d = 1$ ms.

4.3 Sensitivity analysis

For the sensitivity analysis, we picked two instances for each of the discussed seven parameters (Table 4.1) and then obtained the average gross throughput per terminal, the percentage of symbols required for signaling per frame and the average computation time per problem. These metrics were computed for each optimization approach presented ((PLAIN), (FIX), (VAR OPT) and (VAR APP)), as well as for the static comparison scheme. Therefore, we ran $2^7 = 128$ simulation runs for each approach.

Parameter	**Instance** 1	**Instance** 2
Terminal number J	4	16
Sub-carrier number N	64	512
Number of modulations M	2 (BPSK and QPSK)	5 (BPSK, QPSK, 16-,64, and 256-QAM)
Maximum speed $v_{\max}$	1 m/s	10 m/s
Delay spread $\Delta\sigma$	0.05 μs	0.25 μs
Frame length T_f	1 ms	10 ms
System bandwidth B	3 MHz	50 MHz

Table 4.1: Parameter instances for the sensitivity analysis

First, we present the average results for each approach regarding each metric, also showing the results achieved for the net throughput. (For the net throughput we can of course obtain an average value by the method of performance analysis. However, judging on the influence of different factors on the variation of this average is not possible due to the local optima within the range of the parameters.) This is given in Table 4.2. Considering the net throughput per terminal, the approach (VAR OPT) is the best, providing a performance gain of 30% compared to the static scheme. Note that the net throughput reflects the average over all configurations, including configurations where the dynamic approaches all together can not outperform the static one very much. For example, all configurations in which the number of modulations is low ($M = 2$) lead to very small performance differences between the static and dynamic approach. Also, if the number of terminals in the cell is low, $J = 4$, the performance difference is low due to a low multi-user diversity of the cell.

Regarding the signaling overhead, however, the approach (VAR OPT) achieves quite a significant improvement, cutting the percentage of required symbols per frame from a ratio of 0.25 for the fixed-size signaling field approach down to a ratio of 0.03. Interestingly, as the approach (VAR OPT) reduces the number of signaling symbols, it also reduces the gross throughput, it is lower for this approach compared to all other approaches beside the static one. The net throughput of this scheme though is the best one achieved.

The downside of the approach (VAR OPT) is the average time required for obtaining the optimal result. Although this figure depends on other parameters as well (algorithm implementation, computational power etc.), this high average number already indicates, that this approach is more difficult in terms of computational complexity than the other ones considered. Note that for approach (VAR APP) the computation time is smaller than for approach (FIX), although the complexity of both approaches is similar.

	Gross throughput	**Signaling percentage**	**Net throughput**	**Computation time**
Static assignment	1.638 MBit/s	0	1.638 MBit/s	0
(PLAIN)	2.283 MBit/s	0	2.283 MBit/s	0.077 s
(FIX)	2.283 MBit/s	0.267	2.059 MBit/s	0.077 s
(VAR APP)	2.278 MBit/s	0.112	2.085 MBit/s	0.0518 s
(VAR OPT)	2.186 MBit/s	0.027	2.120 MBit/s	4.172 s

Table 4.2: Average metric results stemming from the sensitivity analysis for the five different considered approaches to the OFDM-FDMA system

Besides a first analysis of the average values, the sensitivity analysis following the method of the 2^k factorial design allows also to determine factors, i.e. parameters, which have a strong (weak) impact on the variation of the considered metric. Beside single factors (for example the number of terminals) also factor combinations might be significant (for example the number of sub-carriers and the number of terminals).

Regarding the signaling cost (percentage of symbols required per frame for signaling) Table 4.3 shows the impact of selected factors and factor combinations on the variation for the three different presented signaling approaches.

It is not surprising that for the fixed signaling field approach only the factors B, T_f, N, M, and J have an influence on the amount of signaling overhead per down-link phase. Note that out of these the given system bandwidth B, the frame length T_f and the number of sub-carriers N influence the overhead most strongly. Beside these two, the factor combination of both also contributes quite strong on the variation of the overhead results.The influence due to stochastic variations is zero, which is also quite reasonable when considering the design of the fixed signaling field approach. Interestingly, there are combinations where the total signaling overhead consumes the *complete* down-link phase resulting in a zero net throughput for these cases. This happens whenever the bandwidth is low ($B = 3$ MHz), the number of sub-carriers is high ($N = 512$) and the frame length is short ($T_\mathrm{f} = 1$ ms) (in fact, to transmit the complete signaling information would require in these cases a lot more than one down-link phase, however the technical upper limit of the proposed system leads to a resulting signaling ratio of 1). In the opposite cases (high system bandwidth $B = 50$ MHz, low number of sub-carriers $N = 64$ and a long frame length $T_\mathrm{f} = 10$ ms) the average signaling percentage is quite low at about 0.04. In these cases the influence of the number of modulation types M and the number of terminals

Parameter	**Approach** (FIX)	**Approach** (VAR APP)	**Approach** (VAR OPT)	**Average**
System bandwidth B	35.9 %	8.2 %	0 %	14.7 %
Frame length T_{f}	25.2 %	0.1 %	0 %	8.4 %
Number of sub-carriers N	16.2 %	4 %	2.1 %	7.4 %
Number of modulations M	0.7 %	4.9 %	2.4 %	2.7 %
Maximum speed $v_{\max}$	0 %	2.5 %	4.6 %	2.4 %
Delay spread $\Delta\sigma$	0 %	0.7 %	1.5 %	0.7 %
Number of terminals J	0.7 %	0.2 %	0 %	0.3 %
Stochastic variation	0 %	18.7 %	46.6 %	21.8 %
B and T_{f}	10.2 %	6.7 %	17.3 %	11.4 %
N and T_{f}	2.5 %	10.2 %	1.4 %	4.7 %
B and N	6.2 %	0.8 %	5.5 %	4.2 %
T_{f} and $v_{\max}$	0 %	1.2 %	3 %	1.4 %

Table 4.3: Variation percentage of selected factors and factor combinations regarding the signaling overhead for the three signaling models introduced

in the cell J is higher than indicated by Table 4.3.

While for the fixed size signaling field approach the stochastic influence on the variation of the overhead was zero, for the two approaches regarding the variable size signaling field approach this is not the case any more. Consider first approach (VAR APP) of the variable size signaling field method. The factors with the highest impact on the signaling cost are the system bandwidth B, the number of modulations M, the number of sub-carriers N and the speed of the terminals $v_{\max}$. Surprisingly, the number of terminals J as well as the length of a frame T_{f} have almost no influence on the variation of the results as *single* factor. As already mentioned in general, the stochastic influence on the variation of the signaling overhead is quite high for this approach with about 20 %. The length of a frame is quite important though, when considering it in combination with other factors, the most significant combinations are the length of frame T_{f} together with the number of sub-carriers N and the length of a frame T_{f} together with the system bandwidth B. In the mentioned cases (low bandwidth, short frame length, high number of sub-carriers) where the fixed size signaling field approach suffered from a signaling percentage of 1 (thus the complete down-link phase had to wasted for transmitting the signaling information), this version of the variable size signaling field approach turns into the *static* scheme. Over the length of many down-link phases no single assignment is changed due to the very high cost.

As the observations regarding the factors influence differ quite a bit when comparing approach (FIX) with approach (VAR APP), the differences between approach (VAR APP) and approach (VAR OPT) are smaller. For approach (VAR OPT) the influence as *single* factor of the bandwidth B, the frame length T_{f} and the number of terminals J is zero, which is quite surprising. The parameters number of sub-carriers N and number of modulation types M have the highest impact of all single factors, while the influence of the speed $v_{\max}$ and the delay spread $\Delta\sigma$is rather small. Interestingly, the stochastic influence is the highest of all studied approaches, accounting for around 45 % of all the variation of the signaling cost for this approach. Out of the factor combinations, the impact of the system bandwidth B together with the length of a frame T_{f} is the most significant one. However, the factor combination of the system bandwidth and the number of sub-carriers as well as the combination of the frame length and the maximum speed within the environment also have some influence on the variation. As with the approach (VAR APP) in some cases the approach (VAR OPT) does not change any sub-carrier assignment at all due to the very high cost of already assigning one sub-carrier.

4.4 Parameter investigation

For any combination of dynamic assignment algorithm and signaling method the resulting net throughput is obtained by considering the remainder of the gross throughput multiplied by the amount of symbols left over for payload data transmission for each down-link phase. Thus, any analysis regarding the signaling percentage can only highlight the performance of a combination regarding this metric. These results do not necessarily transfer to the net throughput because some parameters might have a low variation impact on the signaling cost, but a high impact regarding the gross throughput.

Therefore for specific chosen parameters we considered the behavior of all three metrics (signaling percentage, gross and net throughput) in more detail. While the results for the net throughput are of most interest, the deeper understanding of these results stems from the behavior for the signaling percentage and the gross throughput.

From the signaling percentage point of view, the single factors system bandwidth, length of a frame, and number of sub-carriers had the highest impact on the variation. Therefore we varied these parameters primarily in order to investigate the behavior of the net throughput. In addition, we also investigated the behavior of the system when considering an increasing number of terminals in the cell. Dynamic OFDM-FDMA system are known to gain specifically from such a situation as the multi-user diversity increases in these cases.

For the following description of the simulation scenarios and the results all parameters not specifically mentioned have been set as introduced in Chapter 4.2.

4.4.1 Varying the number of sub-carriers N

We varied this parameter between $N = 64$ and 512. The available system bandwidth was fixed at $B = 16.25$ MHz while $J = 8$ terminals were present in the cell and $M = 4$ (BPSK, QPSK, 16-QAM and 64-QAM) modulation types were available. The transmit power was fixed at $P_{\text{max}} = 10$ mW. Two scenarios for the speed were considered: $v_{\text{max}} = 1$ m/s and $v_{\text{max}} = 10$ m/s. The delay spread was fixed at $\Delta\sigma = 0.15$ μs. The frame length was set to $T_{\text{f}} = 2$ ms equally divided into up- and down-link phase.

Increasing the number of sub-carriers while keeping the total transmit power and the total system bandwidth fixed leads to an increase in throughput for any OFDM system. The reason for this is quite simple: The more sub-carriers there are, the lower is the bandwidth of each sub-carrier, hence the symbol time per sub-carrier increases (doubling the amount of sub-carriers leads to a doubling of the symbol times). However, in order to reduce the impact of ISI prior to each symbol a cyclic extension of the time-domain symbol is sent, which is discarded at the receiver. The length of this guard period is not influenced by the number of sub-carriers, it depends directly on the delay spread of the propagation environment. If the symbol durations increase, the percentage of time each sub-carrier is utilized for data transmission increases compared to the time used in order to mitigate ISI, hence more time is spent on data transmission, leading to a higher system throughput. However, a higher number of sub-carriers leads to difficulties in the frequency synchronization [1], which has not been considered in this study.

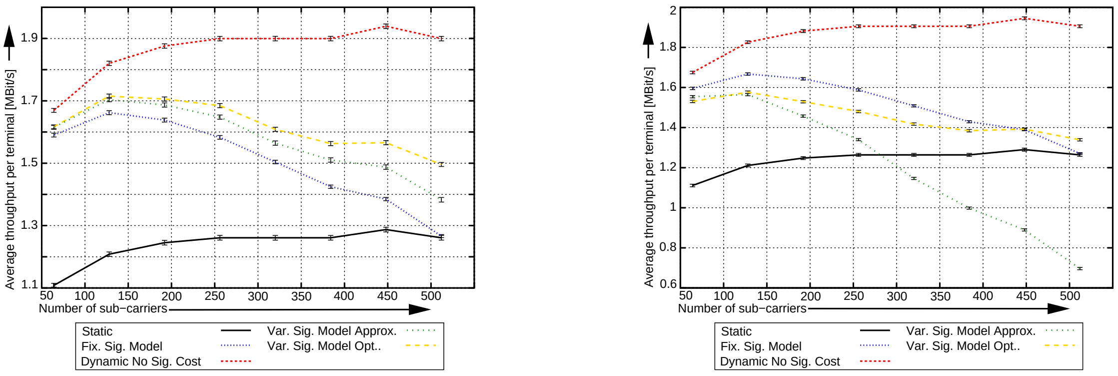


Figure 4.1: Average net throughput per terminal for an increasing number of sub-carriers at a fixed overall bandwidth for a maximum speed of $v_{\max} = 1\ \mathrm{m/s}$ (left) and of $v_{\max} = 10\ \mathrm{m/s}$ (right)(both with a confidence level 0.99).

The focus of this study is signaling cost. Obviously, the more sub-carriers there have to be addressed by a dynamic frequency assignment algorithm, the higher the signaling cost which should lead to the reduction of the net throughput, obviously calling for a trade-off when considering the throughput enhancing effect of increasing the number of sub-carriers.

Figure 4.1 depicts the net throughput for all five discussed variants (dynamic OFDM-FDMA approach without signaling cost, fixed size signaling field model, both variable size signaling field approaches, and the static approach[2]) while varying the number of sub-carriers for two cases: One case where the maximum speed within the propagation environment is rather low (left graph) and one case where the maximum speed is rather high. Note that the maximum speed has a direct influence on the strength of correlation of the sub-carriers' attenuation.

As described above, the net throughput of the static approach and the dynamic OFDM-FDMA without signaling increase as the number of sub-carriers increases. The dynamic approach gains slightly more from the increase of sub-carriers, the net throughput increases by $250\ \mathrm{kBit/s}$ on average per terminal while the static gains by $200\ \mathrm{kBit/s}$. The advantage of the dynamic approach without signaling compared to the static approach is at about $600\ \mathrm{kBit/s}$ which equals more or less 50% of the net throughput of the static scheme as maximum gain achievable by using dynamic schemes.

When considering also the signaling cost, however, the behavior of the system changes qualitatively. For all dynamic schemes with signaling cost the net throughput first increases up to a maximum point and decrease thereafter. The reason is that from a certain point on the signaling cost increases that much that it consumes all the throughput gain obtained from increasing the number of sub-carriers. Not all signaling schemes are affected in the same way. If the correlation in time of the sub-carrier attenuations is high, the variable signaling field approaches perform better than the fixed size signaling field approach. At the maximum net throughput point (at about $N = 150$), the performance advantage on average per terminal is still about $500\ \mathrm{kBit/s}$ for both variable size signaling field approaches compared to the static assignment scheme. The fixed signaling field approach has slightly lower throughput than the variable size signaling field approaches, the performance ad-

[2]In all performance studies regarding the static scheme the results are rather optimistic, since even for the static scheme a signaling scheme would be required to indicate the different modulation types used per sub-carrier

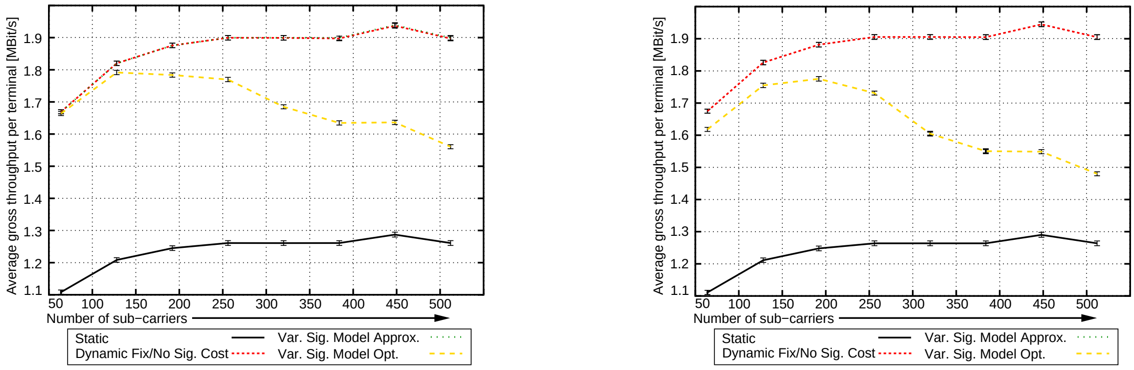


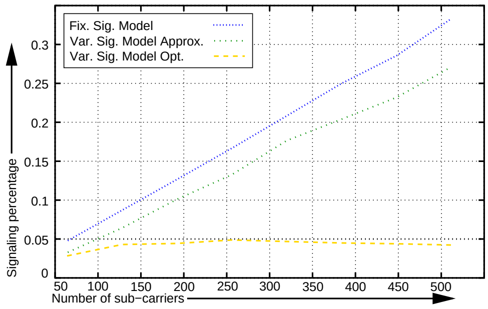
Figure 4.2: Average gross throughput per terminal for an increasing number of sub-carriers at a fixed overall bandwidth for a maximum speed of $v_{\max} = 1$ m/s (left) and of $v_{\max} = 10$ m/s (right)(both with a confidence level 0.99).

vantage compared to the static approach is about 450 kBit/s. While the optimal solution for the variable size signaling field approach achieves at the maximum point only a slightly better result than the approximation, beyond the maxim point (in terms of sub-carriers) the difference between all three signaling approaches becomes more evident. At the highest number of sub-carriers ($N = 512$) the fixed size signaling field approaches achieves the same net throughput as the static approach, while the performance gain of the variable size signaling field approaches reduces to 150 kBit/s on average per terminal and 250 kBit/s, respectively.

If the correlation in time of the sub-carrier attenuations is rather weak, this performance behavior changes (Figure 4.1, right graph). In these cases there exists still a throughput-optimal point in terms of sub-carriers. However, the variable size signaling field approaches perform by 50 kBit/s per terminal worse than the fixed size signaling field approach, which achieves still a performance gain of 450 kBit/s compared to the static approach. As the number of sub-carriers increases the net throughput for all dynamic approaches with signaling cost decreases again, however the approximation of the variable size signaling field model drops at $N = 270$ sub-carriers below the throughput of the static scheme, while the optimal solution to the variable size signaling field model can still maintain a substantially higher net throughout than the static scheme and even outperforms the fixed size signaling field approach at very high numbers of sub-carriers.

How do the different signaling schemes achieve the shown net throughput? In order to study this, Figure 4.2 shows the corresponding gross throughput values for each approach while in Figure 4.3 the signaling percentage per frame is given for each approach. It is interesting to observe that while the optimal solution for the variable size signaling field approach has a quite different behavior both in gross throughput and signaling percentage, the approximation of the variable size signaling field approach differs only quantitatively compared to the fixed size signaling field approach. In case of the gross throughput for the fixed size signaling field model the throughput increases constantly as well as for the approximation of the variable size model. In contrast, the gross throughput of the optimal solution of the variable size model has a maximum point around $N = 150$ (lower for the scenario with low velocity, higher for the scenario with high velocity).

For the signaling percentage per frame the fixed size signaling approach has a linear increase as



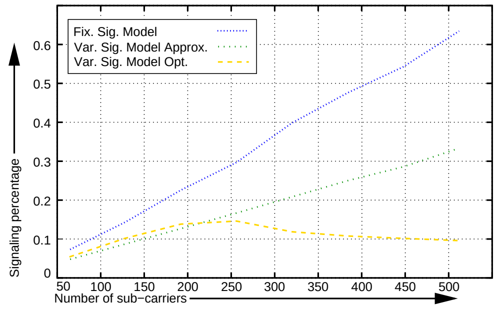


Figure 4.3: Average signaling percentage per frame for an increasing number of sub-carriers at a fixed overall bandwidth for a maximum speed of $v_{\max} = 1\ \mathrm{m/s}$ (left) and of $v_{\max} = 10\ \mathrm{m/s}$ (right)(both with a confidence level 0.99).

the number of sub-carriers increases. Note that the number of symbols required for signaling stays constant, as indicated by Equation 3.5, however the total number of symbols available for down-link data transmission decreases due to the increasing length of one OFDM symbol, as stated in Equation 3.2. Therefore the ratio of the two, the signaling percentage, increases. Interestingly, the signaling percentage for the approximation of the variable size signaling approach has also a linear increase, in contrast to the optimal solution of this signaling variant, which nearly has a constant amount of signaling percentage for an increasing number of sub-carriers. For the high velocity scenario this signaling percentage is twice as large as for the low velocity scenario.

Thus, the optimal solution of the variable size signaling field approach achieves its net throughput by decreasing the signaling percentage drastically at the cost of gross throughput. In contrast, the approximation decreases the signaling percentage only slightly while still maintaining a high gross throughput. In case of a low velocity this can be done quite well by exploiting the correlation in time, at high velocities however, the cost for maintaining the high gross throughput becomes to0 high (a single reassignment consumes more bits in the variable size signaling field approach than in the fixed size signaling field approach).

In principle, for any scenario there exists an optimum amount of sub-carriers the bandwidth should be split into while using a dynamic OFDM-FDMA approach. Depending on the correlation in time, beside adapting the amount of sub-carriers also different signaling field approaches should be applied, if the correlation is high, a variable size signaling field approach provides a better performance, if the correlation in time is low, the fixed size signaling field approach provides a better performance. However, even if the signaling cost is taken into consideration, the dynamic approaches achieve a *significantly* better performance than the static approach, which should not be neglected.

4.4.2 Varying the frame length T_{f}

Next, we varied the length of the frame T_{f} . The frame length was varied between $1\ \mathrm{ms}$ and $10\ \mathrm{ms}$, always splitting the frame equally into down-link and up-link phase. These variations were performed for two different numbers of sub-carriers N: 64 and 512. The number of terminals was fixed at $J = 8$ while $M = 4$ (BPSK, QPSK, 16-QAM, and 64-QAM) modulation types were available. The maximum speed within the propagation environment equaled $v_{\max} = 2\ \mathrm{m/s}$. The delay spread, system bandwidth and transmit power equaled the setting of varying the number of sub-carriers (Chapter 4.4.1), as described in the paragraph above ($\Delta\sigma = 0.15$ μs, $B = 16.25$ MHz and $P_{\text{max}} = 10$ mW).

As the length of a frame increases, the number of symbols per down-link phase increases, too. Thus, a dynamic algorithm can reassign sub-carriers less often. On the one hand this is quite fortunate since for a system with a frame length of 10 ms sub-carriers are reassigned ten times less often then in the case of frame length of 1 ms. However, the sub-carrier attenuations are much more uncorrelated now, leading to a number of necessary reassignments, increasing the signaling cost at least for the variable size signaling field approaches.

In general, a longer frame length is quite attractive from a system point of view. If the frame length is longer, the access point has more time to generate the new assignments which makes the real-time constraint less restrictive. In addition, intuitively the signaling cost can be decreased quite significantly, as discussed above. The downside though is the accuracy of the channel knowledge, which will degrade in general the longer the frame length is. A lower accuracy of the channel knowledge might lead to a higher bit error probability during the payload transmission, depending on the coding scheme used. On the other side, the usage of a longer frame length might enable the usage of sophisticated channel estimation techniques, which would improve the accuracy of the channel knowledge again. This trade-off is not studied here, though.

In Figure 4.4 the net throughput is given for all five investigated schemes in a setting with $N = 64$ sub-carriers (left) and $N = 512$ sub-carriers (right). In both cases the above mentioned effect can be observed well. While an increasing frame length has no effect at all for the static scheme as well as for the dynamic scheme without signaling cost, a longer frame length leads to a higher net throughput for the dynamic schemes with signaling cost. This effect is much more significant in the case with a high number of sub-carriers than in the case with a low number of sub-carriers. In both cases, the potential benefit from using a dynamic approach is about 550 kBit/s on average per terminal which is about 50% more throughput per terminal than in the static scheme. If the length of the frame is low, the fixed size signaling field approach yields the lowest net throughput of all dynamic schemes with signaling cost. The optimal solution of the variable size signaling field approach yields the best net throughput in these cases. Note that in case of the low number of sub-carriers the difference between worst and best dynamic scheme with signaling cost is rather small whereas in the opposite case the net throughput of the fixed size signaling field approach is much lower even than performance of the static scheme.

For a frame length between 3 ms and 4 ms this performance behavior changes. After this point the fixed size signaling field approach performs better in terms of net throughput than the variable size signaling field approaches. This is not that significant in the case of a low number of sub-carriers since the throughput gain in general is quite low for the dynamic schemes as the frame length increases. However, if the system design includes a high number of sub-carriers, the performance difference between fixed size signaling approach and variable size signaling approach is substantial, around 150 kBit/s on average per terminal which equals 10% of the average throughput per terminal (at no additional cost). Note that although the net throughput increases constantly for the dynamic schemes including the signaling cost as the frame length increases, the highest gains are achieved for rather small frame lengths. In general, for a frame length exceeding 5 ms, the additional net throughput gain is no longer significant. Reducing the frame length from 10 ms down to 5 ms would therefore enhance the accuracy of the channel knowledge without causing a dramatic loss of net throughput.

As to the net throughput results from the performance behavior for each scheme in terms of the

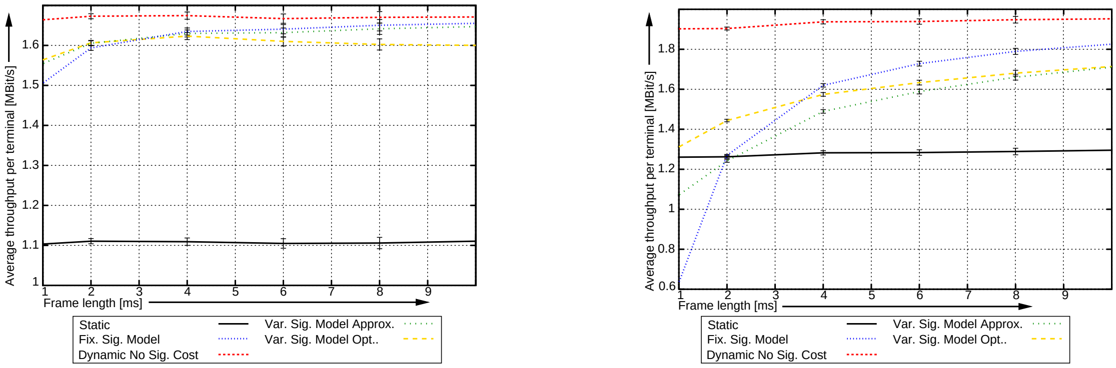


Figure 4.4: Average net throughput per terminal for an increasing frame length with $N = 64$ (left) and $N = 512$ (right) (both with a confidence level 0.99).

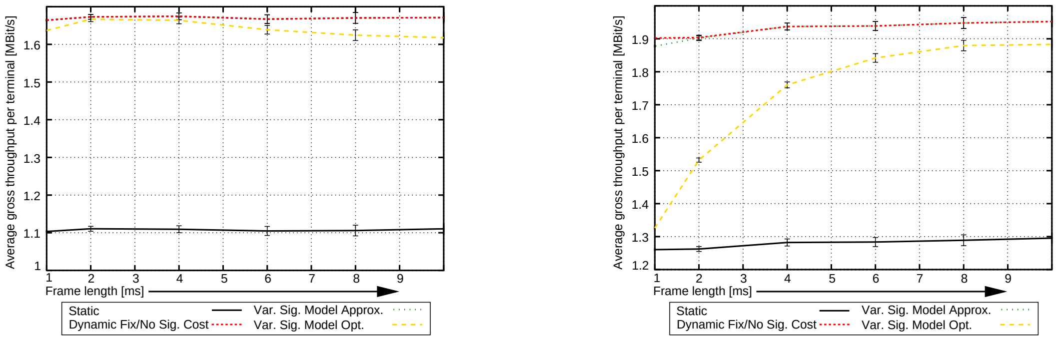
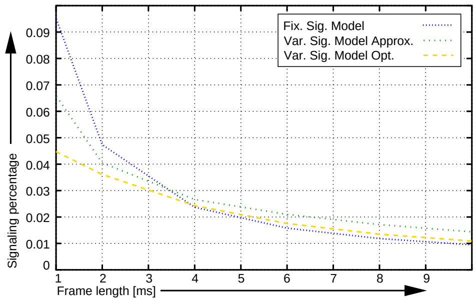


Figure 4.5: Average gross throughput per terminal for an increasing frame length with $N = 64$ (left) and $N = 512$ (right) (both with a confidence level 0.99).

gross throughput and the signaling percentage per frame, the behavior regarding these two metrics are given in Figure 4.5 and Figure 4.6 (always including both cases of sub-carrier numbers).

In case of the gross throughput ,the optimal solution for the variable size signaling field approach adapts to the varying signaling cost due to the varying frame length. In case of the low number of sub-carriers this adaption is not very high, in fact the optimal solution of the varying signaling field approach has a decreasing gross throughput for longer frame times than 4 ms while the signaling percentage also drops constantly. For a high number of sub-carriers, the gross throughput of the optimal solution for the variable size signaling field approach increases constantly as the frame lengths increase while the signaling percentage initially increases up to 10% at a frame length of 4 ms and then remains constant at this value. The other two dynamic approaches perform almost identical in terms of gross throughput for both cases of sub-carrier numbers while the fixed size signaling field approaches signaling percentage is initially higher than the one of the variable size signaling field approach but drops soon below its signaling percentage. This is probably due to the fact that the correlation in time becomes weaker and weaker from frame to frame for an increasing frame length such that the approximation of the variable size signaling field scheme has to reassign sub-carriers to often in order to reach the highest gross throughput. As in case of the variable size signaling field



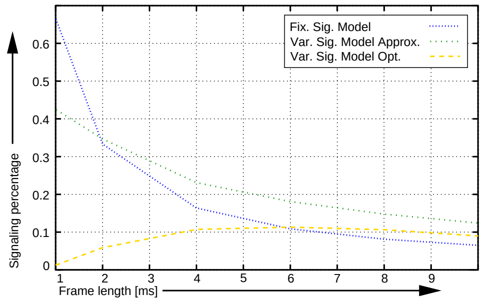


Figure 4.6: Average signaling percentage per frame for an increasing frame length with $N = 64$ (left) and $N = 512$ (right) (both with a confidence level 0.99).

scheme the signaling cost is higher than in the case of the fixed size scheme from a certain point of reassignments on, the signaling percentage of the fixed size scheme drops below the one of the variable size signaling field model (at $T_\mathrm{f} = 2$ ms in case of the low number of sub-carriers and at $T_\mathrm{f} = 4$ ms in case of the high number of sub-carriers).

Thus, as the frame length increases the performance loss due to signaling decreases too. The gap between the dynamic performance without signaling cost and the dynamic schemes with signaling cost depends on the other system parameters influencing the signaling cost such as the number of sub-carriers, the number of terminals in the cell and so on. For each scenario setting there exists a specific frame length from which on the performance degrading effect of the signaling becomes less important (here at $T_\mathrm{f} = 4$ ms, however this value depends probably on the system bandwidth as well as on other parameters). If the parameters ruling the signaling lead to a high signaling cost per reassignment, the usage of the fixed size signaling field approach outperforms the variable size signaling field approach if the length of the frame is high and thus the correlation of the sub-carrier attenuations is low. If this correlation is high, the variable size signaling field approach is the better pick.

4.4.3 Varying the system bandwidth B

Thirdly, we varied the available system bandwidth between $B = 1$ MHz and 50 MHz. In each case, the bandwidth was split into $N = 256$ sub-carriers. Here the transmit power increased with the increasing system bandwidth. However, the ratio between total transmit power and system bandwidth was kept constant at 0.6 mW/MHz. The number of terminals was fixed at $J = 8$, again the number of modulation types, the delay spread and the maximum speed of the propagation environment were chosen as in the previous investigations.

As we have seen from the sensitivity analysis, varying the system bandwidth has a strong impact on the variation of the signaling percentage. As the bandwidth increases, the throughput of any OFDM system will increase. As we keep the number of sub-carriers fixed, increasing the bandwidth leads to a higher symbol rate per sub-carrier. Per frame more and more OFDM symbols can be transmitted. However, as the length of a symbol becomes smaller and smaller, the length of the guard period becomes more dominant. Effectively, this leads to a result contrary to the one in the case of increasing the number of sub-carriers: As the symbol length decreases, more and more time is spent mitigating the effect of ISI by transmitting the guard. Therefore, despite the fact that the bandwidth is increased, the ratio between guard period and symbol length increases. Per down-link phase more and more time is thus spent on transmitting the cyclic extension. The throughput gain by increasing the bandwidth by a certain amount is therefore limited to some extent by the guard period. One way to deal with this performance limiting effect is to increase the number of sub-carriers, which has not been studied in this investigation.

In general, the more OFDM symbols can be transmitted per frame length the lower is the impact of the signaling overhead, i.e. the signaling percentage decreases. Therefore for a higher bandwidth, the net throughput achieved by a dynamic OFDM approach with any form of signaling should come quite close to the achieved gross throughput.

In Figure 4.7 the average net throughput per terminal and the average spectral efficiency per cell is given for increasing the bandwidth. Note that the spectral efficiency is obtained by dividing the overall net throughput of the cell (average net throughput per terminal multiplied by the number of terminals in the cell) by the overall system bandwidth. As the duplex mode assumed here is **T**ime **D**ivision **D**uplex (*TDD*) splitting each frame equally into down-link and up-link phase, any net throughput value as well as any spectral efficiency value is reduced by the factor two.

As already discussed, the net throughput increases for all considered approaches while increasing the system bandwidth. The dynamic approach potentially outperforms the static approach for all bandwidth values; the gap between the static and dynamic approach appears to be constant from the logarithmic plot. For very small bandwidths ($1\ \mathrm{MHz}$, for example) the variable size signaling field approaches achieve roughly the same throughput as the static scheme while the fixed size signaling field approach has a net throughput of $0\ \mathrm{kBit/s}$ due to the fact that signaling the complete information already consumes the entire frame length. At about $10\ \mathrm{MHz}$, the fixed size signaling field approach starts to outperform the static approach and as the overall system bandwidth further increases, all approaches considering the signaling cost become more and more equal in their performance while approaching the potential performance of the dynamic scheme.

Considering the spectral efficiency of this scenario validates the observations from the net throughput on a finer scale of granularity. Initially, the variable size signaling field approaches achieve the same performance as the static approach. As the system bandwidth is now increased, the optimal solution for the variable size signaling field approach can outperform the static scheme already while the approximation of this signaling field approach falls behind the performance of the static scheme. From $10\ \mathrm{MHz}$ onwards, the fixed size signaling field approach and the approximation of the variable size signaling model outperform the static scheme, beyond this system bandwidth all dynamic schemes become more or less equal in terms of their performance. Note that at the highest system bandwidth of $50\ \mathrm{MHz}$ the spectral efficiency of the dynamic schemes with signaling is almost 50% higher than the spectral efficiency of the static scheme. Also note that the spectral efficiency is *falling* for all schemes after a bandwidth of $30\ \mathrm{MHz}$ (for some schemes as the static one this effect can be observed prior to the point of $30\ \mathrm{MHz}$). This is due to the increasing influence of the guard period during each down-link phase, as described above.

In Figure 4.8, the gross throughput per terminal and gross spectral efficiency is given for the considered approaches. Here basically only the optimal solution of the variable size signaling field approach has a different behavior for an increasing system bandwidth. All other approaches have a steep increase in their performance between $1\ \mathrm{MHz}$ and $5\ \mathrm{MHz}$. After this point, their performance increases only slightly before the decreasing effect discussed above comes into play. For high values of the bandwidth, the gross throughput of the dynamic schemes becomes equal, the performance gain compared to the static approach is slightly above 50%.

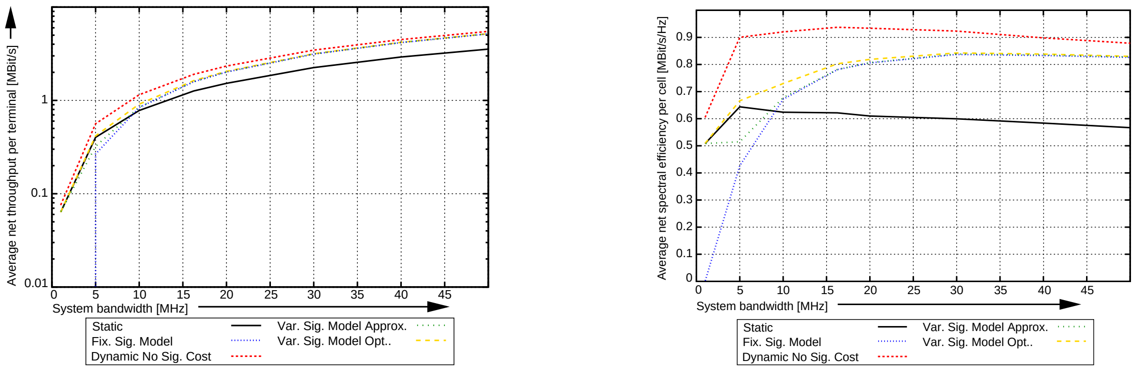


Figure 4.7: Average net throughput per terminal (left) and average spectral efficiency per cell (right) for an increasing system bandwidth (with a confidence level 0.99).

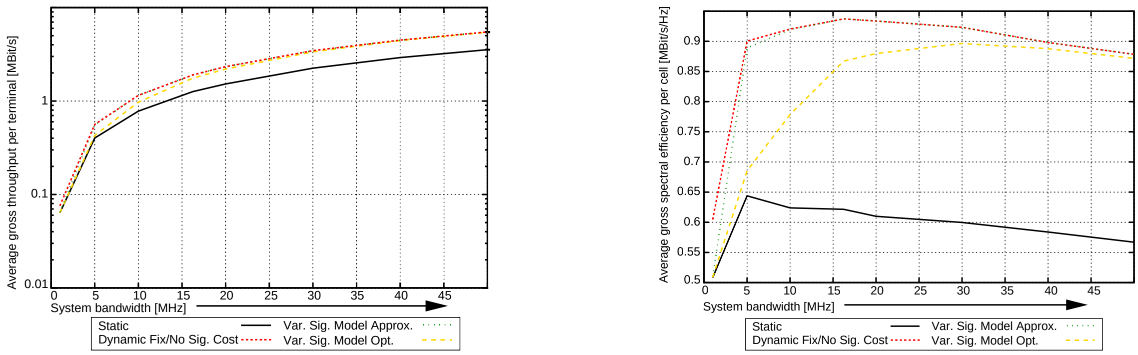


Figure 4.8: Average gross throughput per terminal (left) and average gross spectral efficiency per cell (right) for an increasing system bandwidth (with a confidence level 0.99).

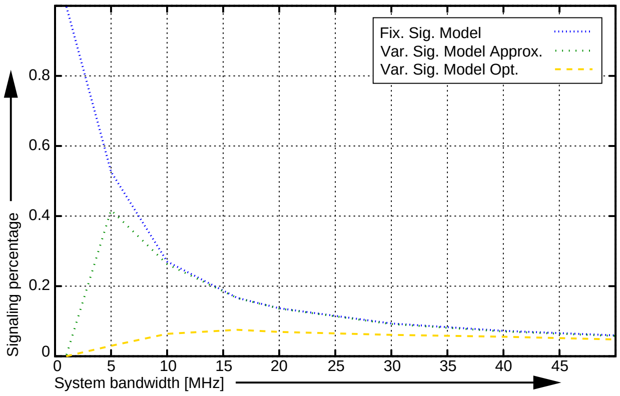


Figure 4.9: Average signaling percentage per frame for an increasing system bandwidth of the cell (with a confidence level 0.99).

In Figure 4.9, the average signaling percentage per frame is shown for the three different dynamic approaches including the signaling cost. Here the advantage of the variable signaling field approaches becomes quite apparent as the signaling percentage for the fixed size signaling field approach is at 100% for a bandwidth of 1 MHz. As the bandwidth increases, the signaling percentage drops down to 4%. The variable signaling field approaches, in contrast, limit the signaling overhead at very small bandwidths to a minimum. With a system bandwidth of 1 MHz not a single assignment is actually changed, the variable approaches therefore achieve performance similar to the static scheme. As the bandwidth increases, however, their signaling overhead increases too up to a certain maximum percentage (40% at 5 MHz for the approximation, 7% at 15 MHz for the optimal solution).

Summarizing the results for the variable system bandwidth, we find that in general the higher the given system bandwidth is the better is the net performance of dynamic schemes including the signaling cost compared to the static approach. For a system with a high bandwidth, the usage of a specific signaling scheme is less important, at least as observed for this specific setting. As certain other parameters change, for example the number of sub-carriers the bandwidth is split into, this might change though. One reason to change the number of sub-carriers as the bandwidth increases is the here observed loss in spectral efficiency due to the otherwise dominating effect of the guard period. A better utilization could be achieved with a higher number of sub-carriers, for example choosing the optimal number of sub-carriers in terms of net throughput as discussed in Chapter 4.4.1.

4.4.4 Varying the number of terminals in the cell J

Finally, we varied the number of terminals in the cell between $J = 1$ and 16. Again, we chose two different scenarios where the number of sub-carriers equaled 64 and 512 while the given bandwidth was $B = 16.25$ MHz. The frame length was fixed at $T_f = 2$ ms while the maximum speed in the propagation environment was set to $v_{max} = 2$ m/s. Four different modulation types were available: BPSK, QPSK, 16-QAM and 64-QAM. The delay spread and transmit power were as in the scenarios before.

Although we learned from the sensitivity analysis that varying the number of terminals is not a primary factor influencing the signaling cost of our models, it is well known that due to the increase of multi-user diversity the throughput of a dynamic OFDM-FDMA system is improved by increasing the number of terminals in the cell. Therefore, the gross throughput was expected to vary quite a bit while the number of terminals in the cell increased. Even combined with only a small variation of the signaling cost, we were interested in the resulting net throughput per cell.

This is given in Figure 4.10 for the two different scenarios chosen with a sub-carrier number of 64 (left) and 512 (right). As the number of terminals increases, indeed the net throughput of the dynamic schemes does increase. However, also the throughput of the static schemes increases, though not that much. In case of a low number of sub-carriers all schemes start off from a value of about $6\ \mathrm{MBit/s}$ on average per cell. The static schemes increases then by about $3\ \mathrm{MBit/s}$ up to $9\ \mathrm{MBit/s}$ per cell if 16 terminals are present. If no signaling cost is considered in the dynamic approach the increase is about $9\ \mathrm{MBit/s}$ reaching an overall throughput per cell of $14\ \mathrm{MBit/s}$, which is around 55% higher than in the case of the static scheme. If we now consider the net throughput according to the signaling field models introduced, the potential throughput of the dynamic scheme is decreased by $1\ \mathrm{MBit/s}$, such that the dynamic schemes with signaling cost still achieve a total throughput of $13\ \mathrm{MBit/s}$ per cell. As the number of terminals increases the approaches including the signaling cost loose performance compared to the potential throughput achievable by dynamic schemes. Between the different signaling scheme approaches is a rather small difference—if any—, which seems to be reasonable considering the results from the sensitivity analysis.

If the number of sub-carriers is high, though, the qualitative behavior stays the same. However, the quantitative relations between the different approaches change. First of all in this case does the throughput increase starting at $7\ \mathrm{MBit/s}$ and rising up to $10.5\ \mathrm{MBit/s}$ for the static approach. This increase is almost the same as it was with the low number of sub-carriers (raise of about $3\ \mathrm{MBit/s}$). However, the raise for the dynamic scheme without signaling cost is higher, reaching now at 16 terminals in the cell a value of $16\ \mathrm{MBit/s}$, corresponding to a raise of $9\ \mathrm{MBit/s}$. Next, the gap between the potential throughput of the dynamic schemes and the schemes including the signaling cost is much larger due to the higher overall cost to reassign a sub-carrier. In the best case, the net throughput is only $1.5\ \mathrm{MBit/s}$ higher than the net throughput of the static scheme. This net performance is also only achieved in case of the optimal solution for the variable size signaling field approach. The two other dynamic approaches with signaling cost outperform the static scheme only slightly, in fact for more than 8 terminals in the cell the performance is worse than the one of the static scheme (corresponding to the results in Chapter 4.4.1). Therefore, if the signaling cost is quite high due to factors other than the number of terminals, increasing the number of terminals leads not to a significant performance gain (as it is in the case without signaling cost), it may even worsen system performance.

These results described so far are even better highlighted if we consider the gross throughput and the signaling percentage per frame. The gross throughput results are given in Figure 4.11, as before for both scenarios, the one with the low number of sub-carriers (left graph) and the one with the high number of sub-carriers (right). Here in case of the low number of sub-carriers it is interesting to observe that the gross throughput for all dynamic approaches is more or less the same for the whole range of considered terminal amounts. In each previously investigated scenario, this has not been the case, as the optimal solution to the variable size signaling field approach always had at least a slightly different behavior. In the scenario investigated here, the signaling cost is therefore quite small at all for the whole range of terminal amount considered. Not so in case of a higher number of sub-carriers. In this case, the basic cost per reassignment is that high that the optimal solution to the variable size signaling field approach can only achieve a gross throughput in the middle between the

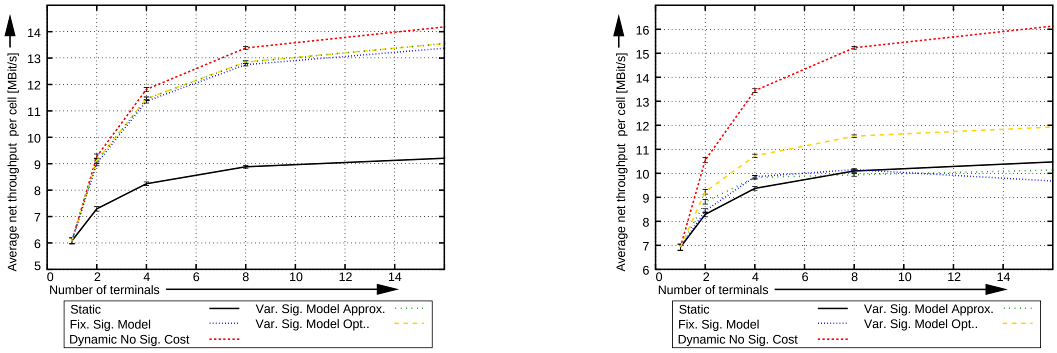


Figure 4.10: Average net throughput per cell for an increasing number of terminals in the cell with a fixed bandwidth divided into $N = 64$ sub-carriers (left) and $N = 512$ sub-carriers (right) (both with a confidence level 0.99).

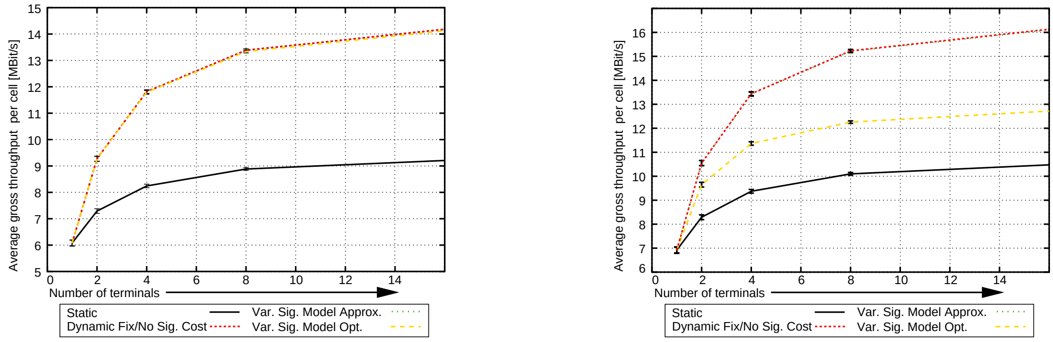
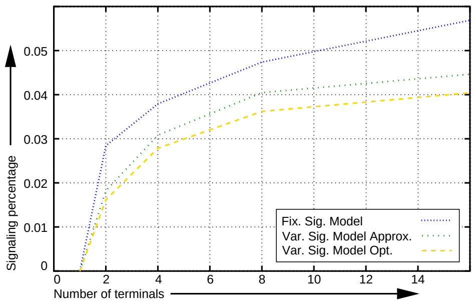


Figure 4.11: Average gross throughput per cell for an increasing number of terminals in the cell with a fixed bandwidth divided into $N = 64$ sub-carriers (left) and $N = 512$ sub-carriers (right) (both with a confidence level 0.99).

gross throughput of the other dynamic schemes and the static scheme. As the number of terminals increases, the gross throughput of the optimal solution of the variable size signaling field model increases, as does the gross throughput of all other introduced schemes.

In Figure 4.12 we finally present the signaling percentage per frame as the number of terminals increase in the cell. In case of the low number of sub-carriers basically all signaling variants perform quite similar: As the number of terminals increases, increases the signaling percentage slightly up to a maximum of 6%. The worst scheme is the fixed size signaling field model, the best variant in terms of signaling percentage is the optimal solution to the variable size signaling field model. However, the performance differences are rather small. If the number of sub-carriers is high, the optimal solution to the variable size signaling field model reduces the amount of reassignments to a minimum such that the signaling percentage is at about 6% at maximum even for the largest number of terminals in the cell considered. The other two schemes including the signaling cost suffer from an ever increasing signaling percentage to which they cannot adapt efficiently. This degrades of course the net performance of these two schemes as observed in Figure 4.10.



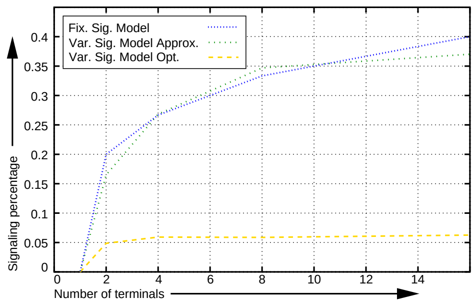


Figure 4.12: Average signaling percentage per frame for an increasing number of terminals in the cell with a fixed bandwidth divided into $N = 64$ sub-carriers (left) and $N = 512$ sub-carriers (right) (both with a confidence level 0.99).

Chapter 5

Conclusions and Future Work

Dynamically assigning sub-carriers has the potential to improve the performance of a centralized OFDM system significantly. However, when considering the performance of such an approach compared to schemes known and applied so far, one also has to take into account the overhead caused by dynamically changing the resource assignments for different terminals of the cell, hence the cost of signaling.

In order to study the impact of this overhead, a representation of the signaling information is required as well as assumptions regarding the way of transmitting the data from the access point to the terminals (where is the information placed in a frame, is the information broadcasted or not etc.). In this study, we assume the usage of an inband broadcast signaling system: The signaling data is transmitted prior to the payload transmission through the total available system bandwidth and the data is broadcasted such that any terminal is informed about all assignments for the following down-link phase. As discussed, this form of data transmission enables quite a lot of flexibility for the dynamic OFDM-FDMA system.

We introduce on top of these assumptions two different form of representing the signaling data: the fixed size signaling field model and the variable size signaling field model. For both schemes, we describe methods in order to solve the assignment problem optimally. We then study the resulting performance of the approaches, always comparing the performance of the approaches including the signaling cost with a static scheme and a dynamic scheme where no signaling cost is assumed. So far, dynamic OFDM-FDMA systems have always been investigated neglecting the cost of signaling.

We find that the qualitative and quantitative behavior of the performance of dynamic OFDM-FDMA systems is significantly changed when considering the signaling cost. However, it is important to stress that despite the signaling cost the performance of dynamic OFDM-FDMA systems still is superior to the one achieved by static schemes, for example in OFDM-FDMA. Therefore, in general the usage of dynamic OFDM-FDMA systems is a viable performance enhancing option for the system design of future and existing wireless communication standards.

However, the point of operation (i.e. the system parameters) becomes now more important. As the signaling cost is influenced by various parameters, in certain cases the usage of the dynamic approach becomes indeed impractical due to a too large overhead. These situations are characterized by a low overall system bandwidth and a high signaling cost per reassignment where the number of sub-carriers, the number of terminals in the cell, the number of available modulation types and the modulation/coding scheme used for the broadcast of the signaling information rule this cost. However, as the bandwidth of the system increases, the impact of these parameters ruling the cost per reassignment decreases. Therefore, especially for systems with a high bandwidth (as it is expected for 4G systems) the usage of dynamic OFDM-FDMA approaches is effected only marginally by the signaling cost.

In certain cases, the usage of techniques reducing the signaling cost can improve the performance. In this study we investigated a scheme exploiting the correlation in time in order to reduce the signaling overhead. This works well in cases where the correlation in time of the sub-carrier attenuations is strong (for example for a low mobility in the propagation environment). However, these schemes add computational complexity to the dynamic approach which is a potential drawback for such schemes.

For a certain setting of parameters that can not be influenced by the access point (for example the mobility in the environment, the number of terminals which are associated to the access point and the available system bandwidth) there exists an optimal choice or at least a preferred choice of system parameters the access point can influence (number of sub-carriers the bandwidth is split into, usage of a certain number of modulation types, usage of different signaling schemes). This could motivate the usage of *adaptive* access points which choose a certain set of operation parameters depending on the set of external parameters, due to a significant performance increase gained at these preferred points of operation.

Appendix

We reformulate optimization problem (VAR OPT) by considering the already introduced integer variable ς denoting the number of OFDM symbols required for conveying the signaling information:

$$\begin{aligned} \max \quad & (S-\varsigma)\cdot\sum_{j,n}\left(b_{j,n}^{(t)}\cdot x_{j,n}^{(t)}\right) \\ \text{s.t.} \quad & (3.1),\ (3.4) \\ & \varsigma \geq \frac{\sum_{j,n} c_{j,n}^{(t)}\cdot x_{j,n}^{(t)}}{N\cdot b_{\text{sig}}} \\ & \varsigma \text{ integral.} \end{aligned} \tag{VAR'}$$

This problem is quadratic since the objective involves the product of (integral) variables. In linear optimization, there are several ways of dealing with this. A quadratic programming approach does not apply here since the matrix of coefficients is not positive definite. A possible way out is a reformulation that essentially introduces one integral variable and two constraints for each product of ς with a binary variable. However, in our context there are very few possible values that ς can take: There can be at most N assignments that change with respect to the last down-link phase $t-1$ (if all sub-carriers are reassigned). This implies that

$$0 \leq \varsigma \leq C_{\text{sig}}/b_{\text{sig}} \quad .$$

In the scenarios considered here, C_{sig} as calculated in (3.6) is never greater than 20. Even when assuming a quite small value for the transmission bit-rate during the signaling phase, that is, $b_{\text{sig}} = 0.5$, enumerating all possible values for ς is a viable alternative.

To avoid enumeration of *all* possible values for ς, we employ the following scheme: we divide the problem into subproblems by imposing bounds $0 \leq l \leq u \leq C_{\text{sig}}/b_{\text{sig}}$ on the number of symbol times used for signaling:

$$\begin{aligned} \max \quad & \text{VAR'} \\ \text{s.t.} \quad & l \leq \varsigma \leq u \end{aligned} \tag{VAR'$\langle l,u\rangle$}$$

We can estimate the value of the optimum and obtain feasible solutions by solving the easier problem (FIX) with some additional constraints, that is,

$$\begin{aligned} \max \quad & \text{FIX} \\ \text{s.t.} \quad & l-1 < \sum_{j,n} c_{j,n}^{(t)}\cdot x_{j,n}^{(t)}/N\cdot b_{\text{sig}} \leq u \end{aligned} \tag{FIX$\langle l,u\rangle$}$$

and applying the relation

$$(S-l)\text{FIX}\langle l,u\rangle \le \text{VAR'}\langle l,u\rangle \le (S-u)\text{FIX}\langle l,u\rangle \quad . \tag{5.1}$$

In particular, if $l = u$, we obtain the optimal solution. Our solution approach then works as follows:

1. Obtain a starting value ς_0 by computing the number of symbol times used for signaling when using the optimal solution of (FIX).

2. Check for better solutions with ς_+ = ς_0 + 1,2,... symbol times spent on signaling by solving (VAR'$\langle l,u\rangle$) with $l = u = \varsigma_+$, stopping as soon as $(S-\varsigma_+)\cdot\text{FIX}\langle\varsigma_+, C_{\text{sig}}/b_{\text{sig}}\rangle$ is less than the currently best solution value (all higher values of ς can then be excluded.)

3. Check for better solutions with ς_- = ς_0 - 1,2,... bits spent on signaling by solving (VAR'$\langle l,u\rangle$) with $l = u = \varsigma_-$, stopping as soon as $S\cdot\text{FIX}\langle 0,\varsigma_-\rangle$ is less than the currently best solution value. (All lower values of ς can then be excluded.)

Empirically, the optimal solution is always very close to ς_0 and enumeration of most possible values for ς can be skipped by the above method.

However, the above mentioned solution approach depends on the complexity of problem (FIX$\langle l,u\rangle$). We suspect this problem to be *NP*-hard, but we can not prove it at the moment. In order to solve problem (FIX$\langle l,u\rangle$) we propose a suboptimal algorithm.

The basic underlying problem which has to be solved in the above presented method for the quadratic problem is to solve the weighted bipartitie matching problem where a certain number of "old" matches has to be kept for the next matching. The set of old matches is larger than the number of matches that have to kept. The set of old assignments is available from the assignment matrix $\mathbf{X}^{(t-1)}$, denote the number of assignments to be kept as κ.

Initially, sort the old assignments in $\mathbf{X}^{(t-1)}$ according to their actual bit value in $\mathbf{B}^{(t)}$. From these sorted assignments, keep the κ largest ones. These assignments are kept fixed. Delete the rows and columns of the $\mathbf{B}^{(t)}$ which are covered by all assignments to be kept. For the reduced bit matrix, denoted as $\tilde{\mathbf{B}}^{(t)}$, solve the weighted bipartite matching problem, using the efficint algorithm based on b-matching in [19].

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