In Proc. of 2nd WiOpt'04 (Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks),
Cambridge,United Kingdom, March 2004,

Throughput Optimization of Dynamic OFDM-FDMA Systems with Inband Signaling[⋆]

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Abstract. Dynamically assigning subcarriers to terminals in an OFDM-FDMA system optimizes various performance metrics. However, it also requires that terminals are periodically informed about their assigned subcarriers. Hence, the signaling overhead has to be taken into account for both system design and performance evaluation.

We investigate two possibilities how to design an inband signaling system, with either a fixed or variable overhead per MAC frame and characterize them as linear optimization problems. We provide performance results for both schemes under a varying number of subcarriers and different terminal speeds and show that the variable scheme outperforms the fixed one for low speeds, that the performance difference vanishes as terminal speeds go up, but also that the fixed scheme is more sensitive to variations in the number of subcarriers.

1 Introduction

Within the last decade **O**rthogonal **F**requency **D**ivision **M**ultiplexing (*OFDM*) has become a quite attractive transmission scheme for various applications. Although the technical aspects of OFDM have been discussed for over 30 years now [1, 2], recent advances mainly in the field of signal processing have turned OFDM technology into a mass market product.

The new popularity of OFDM is mainly due to two properties of this transmission scheme. First, OFDM has a higher spectral efficiency compared to traditional **F**requency **D**ivision **M**ultiple **A**ccess (*FDMA*) systems. In addition to this are OFDM systems not effected by frequency–selective fading channels, at least unless the system parameters are chosen reasonable compared to the characteristics of the propagation environment. As a consequence, there is no need for equalization at the receiver, a costly task in single–carrier modulation systems. This advantage is especially significant in the context of wireless communications.

In OFDM the given system bandwidth B is not considered to be a single transmission channel. Instead, B is split into S subchannels, also referred to as subcarriers. Instead of transmitting data serially over a single channel, the data is transmitted in parallel over the S subcarriers. By this the symbol duration per subcarrier is extended by the factor S (compared to a single–carrier system), which reduces the impact of **I**nter**s**ymbol **I**nterference (*ISI*) significantly. In other words, each subcarrier becomes now a flat fading channel, whereas a single–carrier modulation system would experience frequency–selective fading.

Furthermore, to improve the spectral efficiency of the system all adjacent subcarriers are separated by a specific bandwidth $\Delta f = \frac{1}{T_\mathrm{s}}$ equivalent to the symbol rate of each subcarrier. As a consequence at each subcarriers center frequency the spectra of all other subcarriers are zero, a property named orthogonality. An example of such an OFDM system spectrum is given in Figure 1.

[⋆] This work has been supported by the German research funding agency 'Deutsche Forschungsgemeinschaft (DFG)' under the graduate program 'Graduiertenkolleg 621 (MAGSI/Berlin)'

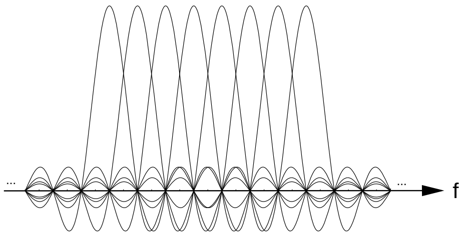

Figure 1. Spectrum of an OFDM system. Notice in particular the prevention of **I**nter**c**hannel **I**nterference (*ICI*) at each subcarrier's center frequency by spectral nulls of all other subcarriers while the overall spectra are heavily overlapping.

Although OFDM systems are employed already in multiple different environments [3–5], several issues are currently under research. One specific topic is related to the medium access control scheme to be employed with an OFDM system in the context of multiuser, wireless scenarios. In a multiuser wireless scenario the subcarriers' fading processes cause a high degree of possible adaption within such a system. Regarding one wireless terminal do the subcarriers have a changing attenuation at any time instance, however these attenuations change also over time. In addition does the attenuation for any subcarrier behave statistically independent regarding multiple different terminals. Therefore a FDMA scheme is most promising for multiple access: while certain subcarriers will be in a "good state" for some terminal and others are not, these "bad state" subcarriers might be in quite a good state for different terminals.

The working principle of such a dynamic OFDM–FDMA system (also called multiuser OFDM–FDMA or OFDMA) is therefore quite straightforward. Out of the complete set of subcarriers an algorithm generates disjoint subsets of subcarriers which are assigned to different terminals intending to receive or transmit data (in this study we focus on the downlink transmission direction). These subcarrier *assignments* are recomputed periodically to react to subcarrier attenuation changes that occurred during the meantime. In general the assignment algorithm can also allocate varying power levels per subcarrier and determines the used modulation/coding combination per subcarrier. In this context various optimization problems have been studied where dynamic system solutions can improve metrics such as the consumed power (minimization) [6] or throughput (maximization) [7] compared to static FDMA schemes or TDMA schemes at the cost of an increase in computational complexity (due to the changing nature of wireless channels the real-time requirements for such dynamic solutions are quite high, a typical channel is likely to change its state significantly within a few milliseconds). In order to reduce the complexity of the problem heuristics have been introduced which of course decrease the systems performance [6–9]

Beside the complexity issue another disadvantage of such dynamic concepts is the requirement of resources, i.e. bandwidth, for signaling: Suppose a single cell with an access point and multiple wireless terminals associated to it. Since the access point generates new assignments periodically, these assignments have to be signaled to the terminals prior to the data transmission. For this purpose a signaling system is employed, the resource consumption of which reduces the performance advantage of dynamic OFDM systems. This required bandwidth for signaling depends on multiple variables such as the flexibility granted to the assignment algorithm, the total number of employed subcarriers in the system or the correlational behavior of these subcarriers. For example, the less the algorithm has to change assignments (in order to react to significant subcarrier state changes), the lesser is the required bandwidth for the signaling system.

In the context of this tradeoff it is not obvious how to design the OFDM system as well as the signaling system. In this paper we study two different approaches to the system design, where each approach consists of a used dynamic assignment algorithm and an employed signaling system. In the first case the assignment algorithm purely maximizes for throughput while the signaling system always conveys all generated assignments. The second case studied consists of a signaling system able to handle variable amounts of assignments while the assignment algorithm also considers that the change of an assignment from one downlink phase to the next one increases the overhead. We will compare these two approaches with respect to the average throughput per terminal that they can achieve, under a variety of conditions.

The remaining paper is organized as follows. In Section 2 we describe the system model as well as the channel characteristics taken into consideration. In Section 3 the two approaches are discussed in detail where each approach consists of a signaling system paired with an assignment algorithm. Next the performance of the approaches is compared in Section 4. Finally, we conclude the paper in Section 5.

2 System Model

We assume a single cell of radius R with J wireless terminals. Any data transmission is managed by the access point; we only consider downlink transmissions. The provided bandwidth B with center frequency f_{c} is split into S subcarriers where the spacing between the subcarriers ΔS is a multiple of $\frac{1}{T_{\mathrm{s}}}$ with T_{s} being the data symbol duration per subcarrier. T_{g} denotes the length of the guard interval. The resulting duration of an OFDM symbol is thus given by $T_{\mathrm{g}} + T_{\mathrm{s}}$. Over the whole bandwidth B no more power than $P_{\max}$ is allowed to be transmitted.

The subcarrier attenuations vary due to path loss, shadowing and fading. For the fading a certain correlation behavior in time and frequency is assumed, characterized by an exponential power delay profile and a Jakes-shaped power spectral density. We assume the terminals to move within the cell with a maximum speed of $v_{\max}$, the delay spread of the propagation environment is given by $\Delta\sigma$ (the delay spread as well as the maximum speed together with the center frequency encountered in a transmission environment directly influence the correlational behavior of the channel in frequency and time [10, 11]). At time t the attenuation of the OFDM system is fully described by the matrix $A(t) = (a_{j,s}^{(t)})$, where $a_{j,s}^{(t)}$ denotes the attenuation of subcarrier s towards terminal j at time t. The **S**ignal to **N**oise **R**atio (*SNR*) at time t for this subcarrier s regarding wireless terminal j is thus given by $\frac{p_s^{(t)} \cdot (a_{j,s}^{(t)})^2}{\sigma^2}$, where $p_s^{(t)}$ denotes the amount of power assigned to subcarrier s during t and σ^2 denotes the noise power experienced per subcarrier.

Depending on the SNR of a subcarrier, different modulation types are utilized for data transmission (note that multiple studies consider Shannon capacity instead of the usage of so far known modulation/coding combinations. However, we are interested in performance metrics attainable with yet implementable systems where restrictions on interleaving sizes and so on forbid the transmission of data at Shannon capacity). In principle we assume M different constellations to be available. Out of these the modulation with the highest data rate and a symbol error probability lower than P_{s} is chosen. As mentioned above does the SNR depend of course on the power level assigned to the specific subcarrier. Due to complexity reasons we assume here a uniform power distribution, i.e. per subcarrier the power fraction $\frac{P_{\max}}{S}$ is used to convey data. Therefore a certain subcarrier attenuation a directly maps into a SNR value and then results in a certain modulation type to be used. This mapping between the attenuation of a certain subcarrier towards a specific terminal and the chosen modulation type is denoted by the function $F(a_{j,s}^{(t)})$. It describes the number of bits that could be transmitted in total during the next downlink phase on subcarrier s to terminal j if this pair is chosen as assignment.

At the access point data destined for the terminals arrives via a backbone. This data is queued at the access point until its transmission. For simplicity we assume that the queues are never empty and that the data rates of the streams arriving at the access point for each terminal are equal.

Every T_f milliseconds the access point generates new assignments based on the knowledge[1] of the state matrix $A(t)$. The overall goal is to maximize the payload throughput per terminal. To do so, the access point assigns disjoint subsets of subcarriers to terminals which are valid throughout the next downlink phase. The size of the sets is equal among the terminals, hence each terminal receives the same amount of subcarriers per downlink phase (note that this assumption is just for illustration purposes. Prior to the assignment of subcarriers an allocation algorithm could determine the number of subcarriers to be assigned per terminal, following a two step approach with subcarrier allocation and assignment [12, 13]).

3 System Approaches

Since the goal of this investigation is to maximize the resulting throughput per terminal, an optimization problem can be formulated where the solution is the assignment yielding the maximum number of bits to be conveyed per downlink phase and hence yielding the maximum throughput rate per terminal considering many consecutive frame solutions. The optimization problem is given by Equation 1. $X(t) = (x_{j,s}^{(t)})$ denotes the binary assignment matrix of subcarriers to terminals ($x_{j,s}^{(t)} = 1$ if and only if subcarrier s is assigned to terminal j for the downlink phase starting at t).

$$\begin{gathered}\max_{X(t)} \quad \sum_{\forall j,s} F\left(a_{j,s}^{(t)}\right) \cdot x_{j,s}^{(t)} \\ \text{s.t.:} \quad \forall s : \sum_{\forall j} x_{j,s}^{(t)} \leq 1 \quad \wedge \quad \forall j : \sum_{\forall s} x_{j,s}^{(t)} \leq \text{ const.}\end{gathered} \tag{1}$$

However, the assignments still have to be signaled. Here we assume an *inband* signaling system. Prior to each downlink phase the newly generated assignments are conveyed to the terminals via a broadcast on all subcarriers. Broadcasting the signaling information reduces the impact of transmission errors in the signaling part. Assume that a certain terminal receives the signaling information with a bit error. If the data is not broadcasted at well known time instances with a previously known modulation type, this terminal looses synchronization to the assignments. Not so in the broadcasting model: in this case the terminal just waits till the next signaling phase starts and will simply rejoin the next transmission phase without going through an admission phase.

In an extreme case, the optimal solution to the problem stated by Equation 1 will consist of completely new assignments, where a “new” assignment stands for the change of an assignment compared to the previous downlink phase. Since there is no restriction on the amount of new assignments generated by the optimal solution to Equation 1, a signaling scheme for this setting is proposed with a fixed length signaling field (always transmitting all assignments for the next downlink phase). As a consequence of the fixed size signaling field a constant amount of data per downlink phase (hence, per second) is required to transmit this information, which is subtracted from the achieved bit rate per terminal. This amount of data required per second, which is denoted as D_Sig, is given by Equation 2: Per downlink phase (length T_f), the assigned terminal (requiring $\lceil \log_2(J) \rceil$ bits) and the assigned modulation type (requiring additional $\lceil \log_2(M) \rceil$ bits) for each of the S subcarriers has to be represented (the subcarrier identification, the third necessary information part of an assignment is indicated in this scheme by the position of the terminal address and modulation identification, which are transmitted pairwise, in the bit stream, as shown in Figure 2).

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[1] In this paper we do not consider the process of acquiring this knowledge, however it might be transmitted during the previous uplink phase.

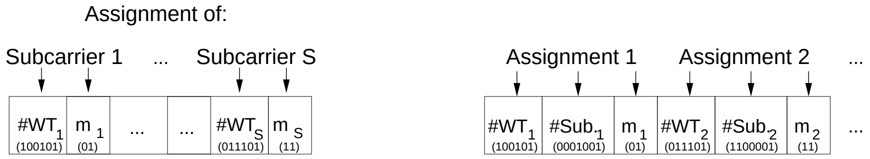

Figure 2. Representation of the assignment information in the fixed size signaling model case (left) and the variable size signaling model case (right).

$$D_{\text{Sig}} = \frac{S \cdot (\lceil \log_2(J) \rceil + \lceil \log_2 M \rceil)}{T_{\text{f}}} \tag{2}$$

This first signaling scheme is simple and efficient if indeed a large number of subcarriers have to be reassigned from one downlink phase to the next one; it wastes resources if only a small number of reassignments would achieve a comparable performance in terms of throughput per terminal.

Therefore, as second approach we consider a more flexible one. If for example only a small fraction of assignments of the previous downlink phase are changed for the following phase, then only these new assignments should be signaled. However, this implies the design of a variable length signaling field. Each new assignment causes per downlink phase and per terminal a certain signaling cost. We propose a scheme where a new assignment is specified by first indicating the specific subcarrier and then conveying the assigned terminal and modulation type. Hence, per reassignment $C_{\text{Sig}} = \lceil \log_2(S) \rceil + \lceil \log_2(J) \rceil + \lceil \log_2 M \rceil$ bits have to be transmitted (Figure 2).

Such a signaling scheme gives an incentive to reduce the number of new assignments to a minimum (in the case of a complete change of assignments, this signaling method costs $S \cdot \lceil \log_2(S) \rceil$ bits more per downlink phase than the one mentioned above). However, reducing the number of new assignments might restrain the assignment algorithm from fully exploiting the diversity of the system (it will show a tendency to stick with the previous frame's assignments), thus likely reducing the throughput per terminal. Since the signaling cost per new assignment can be quantified, it is possible to include the cost of a new assignment directly in the optimization problem of Equation 1. Therefore, it allows to optimize the transmitted number of bits per downlink phase *taking into account* the signaling cost resulting from this variable length signaling system. Thus, the optimal solution to the tradeoff is found. This optimization approach is formalized in Equation 3.

$$\max_{X(t)} \sum_{\forall j,s} \left(\left(b_{j,s}^{(t)} - c_{j,s}^{(t)} \right) \cdot x_{j,s}^{(t)} \right) \tag{3}$$

$$\text{s.t.:} \quad \forall s : \sum_{\forall j} x_{j,s}^{(t)} \leq 1 \quad \wedge \quad \forall j : \sum_{\forall s} x_{j,s}^{(t)} \leq \text{ const.} \quad \wedge \quad c_{j,s}^{(t)} = \begin{cases} 0 & \text{if } x_{j,s}^{(t-1)} = 1, \\ J \cdot C_{\text{Sig}} & \text{otherwise.} \end{cases}$$

4 Performance Evaluation

For the comparison of the two approaches we investigated the case where the number of subcarriers, which the system bandwidth is split into, is varied as well as varying the average terminal speed. By increasing the number of subcarriers for a fixed bandwidth the length of a symbol per subcarrier increases. In many OFDM systems the usage of a guard period of a fixed length is quite common, thus fully mitigating the effect of ISI [14]. Increasing the subcarrier number leads to a higher and higher usage of each subcarrier for payload transmission, leading to an increasing average throughput per terminal. However, by increasing the subcarrier number clearly also the signaling cost increases, leading to a higher and higher overhead.

The question is hence – depending on the system approach – what a good number of subcarriers is (maximizing this tradeoff between better efficiency per subcarrier and higher signaling cost). Furthermore, we were interested in the resulting average throughput per terminal for each approach at these “good” subcarrier numbers. The evaluation was performed by means of simulation. In these simulations, the optimization problems described above where solved using the software CPLEX, a standard program for linear optimization problems.

The simulation scenario was chosen as follows. The cell radius was set to $100\ \mathrm{m}$. The system bandwidth was $B = 16.25\ \mathrm{MHz}$ spaced around a center frequency of $f_\mathrm{c} = 5.2\ \mathrm{GHz}$, the guard interval length was fixed at $T\_g = 0.8\ \mu\mathrm{s}$ (all equaling IEEE 802.11a [3]), the length of a frame was set to $T_\mathrm{f} = 2\ \mathrm{ms}$, a downlink phase had half the length. Initially, the maximum speed of the terminals was set to $v_\mathrm{max} = 1\ \mathrm{m/s}$, the delay spread equaled $\Delta\sigma = 0.15\ \mu\mathrm{s}$. Per subcarrier, a transmission power of $P_\mathrm{tx} = -7\ \mathrm{dBm}$ was used equaling a maximum power of $10\ \mathrm{mW}$ for the whole bandwidth. We considered $J = 16$ wireless terminals in the cell. For the adaptive modulation scheme we chose $M = 5$ different constellation types to be used: BPSK, QPSK, 16-QAM, 64-QAM and 256-QAM. The maximum tolerable symbol error probability was chosen at $P_\mathrm{s} = 10^{-2}$.

Figure 3 shows the results for the two different approaches over a varying number of subcarriers per cell. The solid line shows, as a comparison case, the throughput of a hypothetical system with dynamic assignments, solving the optimization problem of Equation 1, without considering any signaling costs. First of all it can be observed how an increasing number of subcarriers per cell positively influences the average ideal throughput per terminal. However, for the fixed signaling field length approach the signaling cost increases linearly with S, the number of subcarriers the bandwidth is split into, causing the overall real average throughput per terminal for this approach to be at a maximum around $S = 80$ subcarriers. Prior and especially after this point the average throughput per terminal is significantly lower.

Using the other discussed approach yields a different behavior. Here the achieved average throughput per terminal increases first as well up to a maximum around $S = 110$ subcarriers. Beyond this point the average throughput decreases constantly, but not as severely as in the case of the fixed signaling field approach. Comparing these two approaches reveals a clear advantage of the variable signaling field scheme, at their respective maximum points they differ by $250\ \mathrm{kBit/s}$ which corresponds to roughly 10% of the average throughput of the fixed signaling field approach.

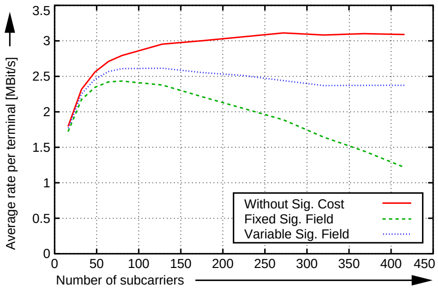

Figure 3. Throughput comparison of the two different system approaches for a varying number of subcarriers S per fixed available system bandwidth in the cell with a maximum speed in the scenario of $1\ \mathrm{m/s}$

Figure 4 shows the same comparison for faster speeds of the terminals, in this case the maximum speed is set to $5\ \mathrm{m/s}$ and $10\ \mathrm{m/s}$. If the terminals move faster, the subcarrier states become statistically more independent (the length of a frame is fixed to $2\ \mathrm{ms}$). As a consequence the performance of the variable signaling field approach is decreased, since the correlation of the channel states in time is weaker and weaker. Compared to the fixed signaling field approach the maximum points of both now only differ by $20\ \mathrm{kBit/s}$, a much smaller difference compared to the case with a speed of $1\ \mathrm{m/s}$. However, while the fixed signaling field approach throughput decreases beyond the maximum, for the variable signaling field approach the throughput almost stays the same.

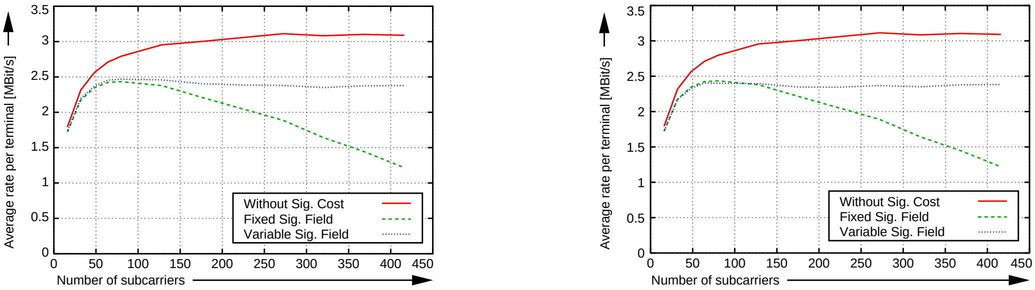

Figure 4. Throughput comparison of the two different system approaches for a varying number of subcarriers S per fixed available system bandwidth in the cell with a maximum speed in the scenario of $5\ \mathrm{m/s}$ (left) and $10\ \mathrm{m/s}$ (right)

This tendency is even more evident when considering a terminal speed of $10\ \mathrm{m/s}$. In this case the two approaches hardly differ at all in terms of resulting throughput per terminal at the maximum point. Beyond that maximum point the variable signaling field approach achieves an almost stable throughput (where the values are all quite close to the maximum) while the throughput for the fixed signaling field approach decreases as in all other previously discussed cases.

Figure 5 shows more details about the impact of the signaling model versus the speed of terminals and the number of subcarriers used per bandwidth B. Here the average percentage of changed assignments is given on a per-frame base for both signaling schemes at a speed of $1\ \mathrm{m/s}$ and $10\ \mathrm{m/s}$. Obviously, in the case of $1\ \mathrm{m/s}$ do both approaches reassign subcarriers more seldom than in the case of $10\ \mathrm{m/s}$. However, as the number of subcarriers increases does the fixed signaling field approach reassign an almost constant amount of subcarriers from frame to frame. In contrast does the variable signaling field scheme react sensitive to the increasing cost of changing assignments from one frame to another by reducing the number of reassignments while the number of subcarriers increases. If the subcarrier attenuations are quite uncorrelated from frame to frame (as in the case of a terminal speed of $10\ \mathrm{m/s}$ and a frame time of $T_\mathrm{f} = 2\ \mathrm{ms}$) then the variable signaling field approach suffers from a much lower number of reassignments it can actually perform and thus the diversity gain is lower.

In Figure 6 we finally present measurements for the average run time of the solution algorithm for both optimization problems. Interestingly, the solving time for the variable signaling field optimization problem is faster than in the case of the fixed signaling field approach. In this case the solution time increases linearly with the number of subcarriers while in the case of the variable signaling field scheme the solution time increases rather logarithmically. For small numbers of subcarriers the run time difference is at most half, for higher numbers of subcarriers the run times differ by more than a half. This is due to the fact that adding signaling cost to the description of the problem offers the solution algorithm more information about the

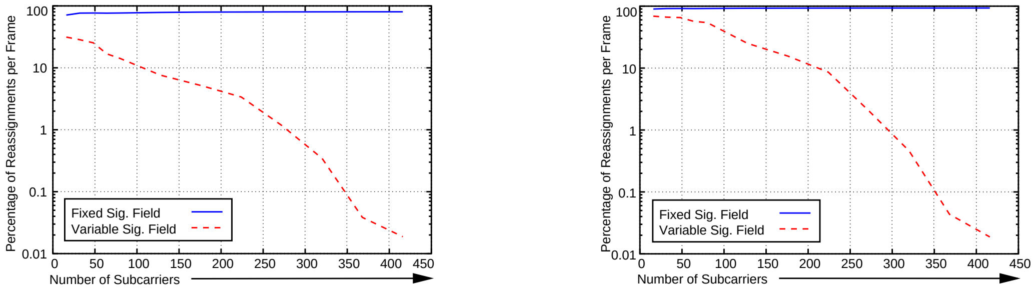

Figure 5. Average percentage of reassignments per frame (logarithmic scaling) for both signaling schemes for a varying number of subcarriers S per fixed available system bandwidth in the cell with a maximum speed in the scenario of $1\ \mathrm{m/s}$ (left) and $10\ \mathrm{m/s}$ (right)

problem to solve and hints to a possible solution. This leads to much faster execution times of the algorithm. The behavior of the run times does not change for an increase of the speed of the wireless terminals. Therefore even if the subcarrier states are not very much correlated the information feedback to the problem description is beneficial in terms of run times.

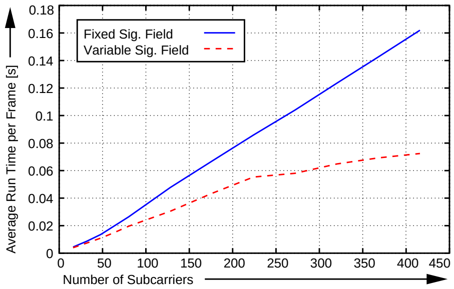

Figure 6. Average run times per frame for the generation of the optimal solution in both signaling field approaches per frame for a varying number of subcarrier S per fixed available system bandwidth in the cell with a maximum speed in the scenario of $1\ \mathrm{m/s}$

5 Conclusions

In this paper we presented two different approaches to the system design of a dynamic OFDM-FDMA system including inband signaling. In one approach a fixed size signaling field is used in combination with an assignment algorithm seeking to provide the maximum throughput per terminal. The other approach consists of a variable size signaling field, being able to indicate differing amounts of newly generated assignments to terminals, in combination with an overhead-aware optimization algorithm, seeking the best tradeoff between reassigning subcarriers for throughput increase and keeping other assignments unchanged for overhead reduction.

For a fixed given bandwidth we find that the usage of the variable signaling system is more beneficial in terms of throughput than the usage of the fixed signaling approach. For both combinations there exists an optimum number of subcarriers the given bandwidth should be split into. However, the variable signaling field approach outperforms the fixed one by at most $10\ \%$. The throughput advantage reduces as terminals move faster. This is due to the reduction of correlation between sequential subcarrier states, which is a prerequisite for the variable signaling field approach. Interestingly, the variable signaling approach is basically never worse than the fixed signaling field approach. The second advantage of the variable signaling length approach is that its performance is considerably more stable over a wide range of subcarrier numbers, whereas the fixed signaling approach is very sensitive to a variation in this number. Hence, as factors in addition to those considered in this paper might influence the choice of subcarriers, an approach with a stable performance characteristic is preferable. As third characteristic we find that the variable signaling field approach is better in terms of run times, where it outperforms the fixed signaling field approach roughly by a half. Note that the actual complexity of the two optimization approaches is the same.

A clear downside of the variable field signaling approach is its sensitivity to transmission errors. Since only the new assignments are transmitted per frame, a bit error occurring in the transmission of this information at some terminals receiver will lead to a potential loss of assignment synchronization of this terminal. Although transmission errors can also occur in the case of the fixed size signaling field model, it is more robust to errors. However, there might be schemes which can mitigate this loss of assignment synchronization, such as transmitting during the following signaling phase all subcarrier assignments for this specific terminal.

As further fields of investigation we consider multiple areas. First of all, we will investigate the performance behavior of both approaches for further parameter variations of the model. For a given speed it is quite obvious that there will exist an optimum time length of the frames (T_{f}) since this influences the signaling cost as well as the strength of the correlation in time. It is possible that this optimum length will differ for the two approaches and therefore the performance difference at these different frame lengths is of interest.

Second, these approaches are pure overhead models so far. They do not represent the fact that in a broadcast scenario a fixed modulation type with a certain rate is employed. Also these models do not consider the impact of error correction codes applied to protect the signaling information from transmission errors. Furthermore blocks the signaling information in a broadcast model OFDM symbols, not bits. Therefore a more realistic optimization approach will try to minimize the number of OFDM symbols required to signal the new assignments rather than reducing the pure number of bits (therefore a form of quantization is introduced: Using BPSK and for example 256 subcarriers, one OFDM symbol carries 256 bits, therefore if the variable signaling field approach generates reassignments worth only 100 bits, it can still add some reassignments since the OFDM symbol is already wasted for signaling completely.). Such an optimization approach is going to be more complex but might yield even better performance results.

Third, there exist good heuristics [8] to the optimization problems presented in Equation 1 and Equation 3. Therefore we are interested if the observed impact depending on the choice of signaling model chosen also occurs if these heuristics are employed or, due to their greedy structure, the heuristics react differently to the combination with a signaling scheme.

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