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Throughput Study for a Dynamic OFDM-FDMA System with Inband Signaling

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***Abstract*— OFDM-FDMA systems provide the flexibility to support simultaneous downlink data transmissions to different terminals. By dynamically assigning different sets of subcarriers to different terminals, they also have the potential to react to fast changing attenuation states of wireless channels. It has been shown that hence dynamic OFDM-FDMA systems can improve various transmission metrics such as throughput or required power.**

However, these dynamic systems require a signaling mechanism informing each terminal prior to the data transmission itself which subcarriers they have been assigned. In this paper, we study the dependency between overhead caused by the signaling system and number of subcarriers used in the system for a varying number of terminals in the cell. We find that in terms of resulting throughput per terminal there exists an optimal number of subcarriers into which the bandwidth should be split. This optimal number depends on the setting (especially, terminal number) and provides, if used, a significant performance increase compared to using a fixed number of subcarriers[1].

I. Introduction

Recently, the concept of dynamic **O**rthogonal **F**requency **D**ivision **M**ultiplexing (*OFDM*) – **F**requency **D**ivision **M**ultiple **A**ccess (*FDMA*) systems has been shown to be quite beneficial in terms of various performance metrics for a multi-user, wireless communication system. In OFDM systems the provided system bandwidth is split into multiple narrowband communication channels called subcarriers. Accordingly, instead of conveying the data serially through a *single* channel the data is split and then transmitted in parallel over *multiple* channels. This leads to robust transmission in frequency-selective channels as well as to a higher spectral efficiency compared to traditional FDMA systems.

It is well known that the attenuation of wireless channels changes over time and frequency [1]. If the OFDM system has been carefully designed, the frequency-selective behavior experienced over the complete communication channel translates into a varying attenuation from subcarrier to subcarrier at any given time instance. Per subcarrier the attenuation is nearly constant, resulting in a flat fading behavior per subcarrier (where adjacent subcarriers are correlated though). Also, in a multiuser scenario, subcarriers of different wireless terminals behave statistically independent such that the attenuation of each subcarrier varies from terminal to terminal.

A dynamic OFDM-FDMA system exploits these attenuation variations. Out of the complete set of subcarriers an algorithm periodically generates disjoint subsets of subcarriers which are then assigned to different terminals intending to receive or transmit data. The subcarrier assignments are

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generated periodically with an interval during which the subcarrier states have changed significantly (for example according to the coherence time). In addition to assigning the subcarriers, the dynamic algorithm can also assign different transmit powers to subcarriers and decide about the used modulation/coding scheme to be employed per subcarrier. Various different schemes [2–5] have been shown to improve system metrics such as consumed power or throughput on the downlink compared to static FDMA schemes or TDMA schemes.

However, these advantages are related to three distinct problems, currently under research. First, the access point has to acquire periodically all subcarrier attenuation states in order to generate meaningful subsets to be assigned. Second, after the full matrix of channel attenuations is available the access point has to generate the assignments, which is a complex task in general but must not consume much time since the wireless channel changes constantly. Third, after these subsets have been generated, each terminal has to be informed *prior* to the data transmission which subcarriers it may receive or transmit data on.

In this work we focus on the third aspect. We choose a certain, rather simple dynamic assignment approach and study the performance loss due to signaling based on a pure overhead-oriented signaling model for the downlink of a single cell. Certain key parameters influencing the impact of the signaling overhead are investigated such as the behavior in throughput regarding different numbers of subcarriers and different terminal numbers.

The remainder of this paper is organized as follows. The system model for this study is presented in Section II. Next we present the signaling model considered in Section III. In Section IV we present the result of this study, finally we conclude the paper in Section V.

II. System Model

We assume J wireless terminals to be located within a cell. Any data transmission within the cell is managed by the access point. We only consider the downlink transmission direction. The provided bandwidth B is split into S subcarriers where the spacing between the subcarriers ΔS is a multiple of $\frac{1}{T_s}$ with T_s being the data symbol duration per subcarrier. In addition to the data symbols of all subcarriers the OFDM symbol consists also of a a guard interval of duration T_g to prevent **I**nter**s**ymbol **I**nterference (*ISI*) . The guard interval depends on the delay spread $\Delta\sigma$ expected to encounter in the propagation environment, in general the guard interval should exceed the delay spread ($T_\mathrm{g} > \Delta\sigma$). Therefore the total OFDM symbol has a duration of $T_s + T_g$.

Every T_f milliseconds an algorithm at the access point generates new assignments based on existing, current subcarrier attenuation knowledge provided. As dynamic algorithm we pick the one presented in [6]. This algorithm assigns each terminal a set of subcarriers which is optimal in terms of the attenuation values experienced (each terminal receives a set of subcarriers which have a minimal attenuation). The size of the set per terminal has to be chosen prior to executing the algorithm. For illustration purposes each terminal is assigned the same number of subcarriers. We chose this optimal algorithm because very good heuristics exist for this kind of assignment problem allowing the generation of the assignments within a few hundred μs while the performance loss is tolerable (around 5%). Due to complexity reasons per subcarrier the same transmission power is employed, no power adaption is taken into account in the assignment algorithm. However, we consider an adaptive modulation scheme to be employed. Five different constellations are used: BPSK, QPSK, 16-QAM, 64-QAM and 256-QAM. The access point chooses per subcarrier always the modulation type which yields the highest amount of data conveyable per downlink phase while still providing a symbol error probability lower than $P_s = 10^{-2}$.

The subcarrier attenuation states 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 $v_{\max}$.

As performance metric we consider the average throughput per wireless terminal in the cell. Each terminal has a separate queue at the access point which always holds data. This data arrives from sources outside of the cell.

III. Signaling Model

We assume an *inband* signaling system. Prior to each downlink phase the newly generated assignments are conveyed through the available bandwidth of the system to the terminals. In this study, we do not intend to discuss a more specific design of the signaling system, rather we present a simple, lower bound overhead model for the signaling cost. After the assignments have been generated the access point has to indicate to each terminal which subcarriers and which modulation types have been assigned to whom. This information is – most likely – broadcasted. If the signaling information were not broadcasted but transmitted explicitly per terminal, a terminal could easily loose synchronization to the assignments (through a bit error in the signaling part) and would have to wait until the next admission control phase. Also, if a particular terminal is not part of the assigned set of terminals (i.e. it is not active for this time instance) they immediately loose synchronization. These problems do not occur if the complete signaling information is broadcasted prior to each downlink phase.

Furthermore, the question arises how the signaling information is going to be represented in the system. One option is to transmit, for each terminal, the assigned subcarrier identification codes and the corresponding modulation types. Such a scheme would have the drawback that delimiters are needed in the signaling bit stream to indicate the end of the assignments for terminal x and the beginning of the assignments of terminal $x + 1$. Also, since more terminals might be associated to the access point than actually are active for the next downlink phase, this scheme would require to indicate the wireless terminal's identity prior to each assignment information. A different representation of the signaling data is to transmit for each subcarrier the assigned terminal identification code and then the assigned modulation type. This way, the system is highly flexible and does not require any additional information to be conveyed.

From this discussion we can directly derive the bit overhead caused by dynamically assigning the subcarriers in an OFDM-FDMA system. The bit rate D_{Sig} needed to represent this information per downlink phase is given in Equation 1: 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, M is the number of modulation types used) for each of the S subcarriers has to be represented.

$$D_{\mathrm{Sig}} = \frac{S \cdot (\lceil \log_2(J) \rceil + \lceil \log_2 M \rceil)}{T_f} \qquad (1)$$

Note that this is a strict overhead model. It considers the amount of bits required to represent the signaling information only. No coding requirements or other frame- and system aspects have been taken into consideration. We only consider the minimal amount of data required to represent the assignments correctly assuming a broadcast of the signaling information. In this model the signaling cost therefore depends on the number of subcarriers S, on the number of terminals in the cell J, on the number of used modulation types M, and on the length of the time the assignments are valid T_f.

IV. Performance Evaluation

From the different parameters the signaling cost depends on (subcarrier number S, terminal number J, number of modulation types M and length of a time frame T_f) we studied the behavior of the cost for a varying number of terminals in the system while also varying the number of subcarriers. For each setting (consisting of number of terminals and subcarrier number) we first obtained the average throughput per terminal in the cell achieved by the dynamic algorithm without signaling – denoted as *ideal throughput* – and subtracted then the rate required for signaling, resulting in the *real throughput*. The results were obtained via simulation.

Varying the number of subcarriers in the system for a given total bandwidth achieves an interesting effect. The more subcarriers the bandwidth is split into, the longer is the data symbol duration per subcarrier (T_s). However, the duration of the guard interval T_g stays the same since the delay spread of the propagation environment does not change. Therefore, the ratio between time spent to transmit a data symbol and time spent to prevent ISI per subcarrier, $\frac{T_s}{T_g}$, increases with an increasing number of subcarriers per bandwidth. This leads to an overall increase in throughput per terminal since more and more time is spent on data transmission than on ISI prevention. From the throughput perspective, a higher number of subcarriers in the system is thus desirable. However, the higher the number of subcarriers, the higher is the signaling cost according to Equation 1. The investigation of this tradeoff is the contribution of this study.

For the simulation the following settings were chosen. The cell radius was set to $50\ \mathrm{m}$. The system bandwidth was $B = 16.25\ \mathrm{MHz}$, the guard interval length was fixed at $T_g = 0.8\ \mu\mathrm{s}$, the length of a frame was set to $T_f = 2\ \mathrm{ms}$, while a downlink phase had half the length. The maximum speed of the terminals was set to $v_{\max} = 1\ \mathrm{m/s}$ while 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. The carrier frequency of the system was $f_c = 5.2\ \mathrm{GHz}$. Most of these values equal the IEEE 802.11a standard [7].

Figure 1 shows the result for $J = 16$ wireless terminals in the cell where the number of subcarriers is varied. As discussed above, the ideal throughput does increase with the number of subcarriers. But due to the linear increase of the signaling cost, the resulting real throughput increases at first but then decreases again. At $S_{\mathrm{opt}} = 80$ subcarriers the real throughput has a maximum value while the performance is lower for a smaller and larger number of subcarriers.

This behavior of the real throughput is not only related to this specific setting, we find that for any setting of wireless terminals an optimal number of subcarriers can be found, maximizing the real throughput. In Figure 2 the performance behavior is shown for $J = 8$ wireless terminals in the cell. Comparing this to the case with $J = 16$ terminals in the cell we find that the maximum value for the real throughput increases and is now at $S_{\mathrm{opt}} = 160$. This is due to the fact that with less terminals in the cell the signaling cost is lower and therefore the increase in signaling cost for a varying number of subcarriers is lower leading to a higher number of subcarriers at the maximum.

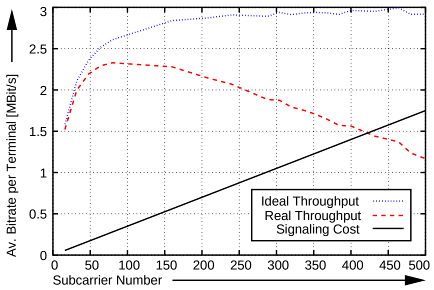

Fig. 1. Ideal and real throughput for a varying number of subcarriers S with $J = 16$ terminals in the cell

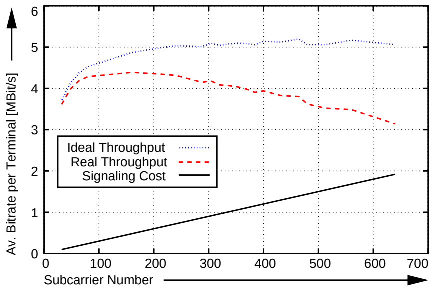

Fig. 2. Ideal and real throughput for a varying number of subcarriers S with $J = 8$ terminals in the cell

In Figure 3 these optimal numbers of subcarriers are shown for different numbers of terminals. In addition to this the figure also shows a curve representing the throughput gain achieved by applying the optimal number of subcarriers to the system versus applying a fixed number of subcarriers to the system. As fixed number we chose $S = 48$ subcarriers, equivalent to IEEE 802.11a. Both the optimum number of subcarriers and the throughput advantage decrease with an increasing number of terminals in the cell. Note that this throughput advantage is not related to a static FDMA system, it actually considers a fully dynamic OFDM-FDMA system with varying subcarriers numbers versus a dynamic system with a fixed number of subcarriers.

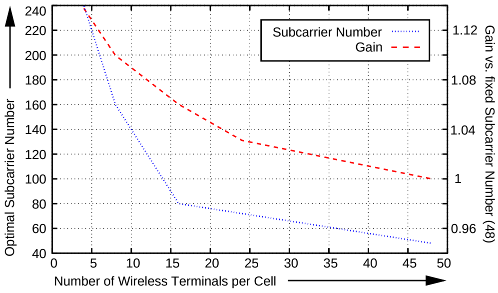

Fig. 3. Optimal number of subcarriers for a varying number of wireless terminals. Also given: Gain achieved by using the optimal number of subcarriers for each terminal setting versus using a fixed number of subcarrier ($S = 48$)

V. Conclusions

We studied the behavior of a dynamic OFDM-FDMA system considering an inband signaling system with a pure overhead model. The model is capable of representing a minimal data cost in order to represent the newly generated assignments by a dynamic algorithm in OFDM–FDMA. From this model it is apparent that the signaling cost depends on the number of subcarriers of the system, the number of terminals in the cell, the length of a frame and the number of used modulation types.

We show that for a varying number of terminals in the cell there exists an optimum number of subcarriers which maximizes the overall achieved throughput per terminal. The larger the number of terminals is, the lower is this optimum number. Comparing the optimal throughput of the corresponding number of subcarriers with the throughput achieved when using a fixed number of subcarriers in the system, each terminal benefits by up to 15%. The larger the number of terminals in the cell is, the lower is this benefit. This suggests to vary the number of subcarriers into which the overall bandwidth is split, depending on the number of terminals which are actually active in the downlink. In this context it is quite beneficial to find that the optimal number of subcarriers decreases the higher the number of terminals is since with a lower number of subcarriers the computation time for the generation of the assignments decreases.

As further steps we intend to investigate means in reducing the impact of the signaling cost. One solution is to include the signaling cost in the optimization problem (penalizing the change of a subcarrier assignment by a certain cost factor). Especially regarding the correlational behavior of subcarrier states this is a promising solution. Also, we actually consider to include more "protocol" aspects into the signaling model such as coding cost and frame delimiter costs. As it turns out this seems to yield a different class of optimization problem where the complexity of the yet quite simple problem increases significantly.

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