On the effect of inband signaling and realistic channel knowledge on dynamic OFDM-FDMA systems

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***Abstract*: Dynamically assigning subcarriers of OFDM systems to multiple different terminals in a cell has been shown to be beneficial in terms of different transmission metrics. However, the success of such a scheme depends on the ability of the access point to inform terminals of their newest subcarrier assignments as well as on the accuracy of the channel state information used to generate new assignments. It is not clear whether the overhead required to implement these two system abilities consumes all of the potential performance increase possible by dynamically assigning subcarriers.**

In this paper, a specific MAC structure is selected enabling the operation of a dynamic OFDM system. Then, we study the question of the required overhead. A static assignment variant serves as a comparison scheme. We investigate the performance difference of these two schemes for various scenarios where at first signaling and then realistic channel knowledge is added to the system model. The results in terms of average throughput and goodput per terminal are obtained for a varying number of terminals in the cell as well as for a varying transmit power. We find that the performance is not only decreased for the dynamic scheme but also for the static one, such that the overall ratio favors the dynamic rather than the static scheme *especially* in realistic system environments.

1. Introduction

Recently, theoretical studies have proven that dynamically assigning subcarriers of **O**rthogonal **F**requency **D**ivision **M**ultiplexing (*OFDM*) systems can be advantageous for the downlink of a single cell in terms of several transmission metrics, e.g. required power or achieved throughput [8–11]. These approaches all exploit the combination of two aspects regarding wireless channels in multi-user communication scenarios: Primarily, the attenuation for one subcarrier is statistically independent among a set of different terminals. In addition to that, the attenuation of subcarriers changes over time and frequency as a consequence of terminal mobility and the multi-path propagation environment. Thus, also regarding a single terminal, the attenuation varies from subcarrier to subcarrier; dynamically assigning "good" subcarriers to terminals promises to improve performance.

When evaluating this potential of dynamic OFDM-FDMA systems, most studies are based on two common, simplifying assumptions. First, it is assumed that at the access point prior to the computation of subcarrier assignments all subcarrier states to each terminal are known. Second, it is assumed that after the generation of assignments wireless terminals somehow "know" which subcarriers they have been assigned by the dynamic algorithm. In some studies the authors mention an existing out-of-band signaling system, but no investigation has been conducted highlighting the cost of such a signaling system. Interestingly, in reality the success of dynamically assigning subcarriers to terminals is directly related to the provided channel knowledge of the access point and to a working signaling system.

It is obvious that fulfilling these two requirements costs system performance. An important question is if this "administrative" overhead required for dynamic schemes might eliminate all the performance advantages that these schemes achieve compared to schemes which do not assign subcarriers dynamically, like static FDMA schemes or TDMA schemes. In this study we investigate this question.

In order to do so we constrain ourselves to a simple **M**edium **A**ccess **C**ontrol (*MAC*) protocol, described in Section 3, which provides a timing structure for channel state acquisition, signaling the assignment information and transmitting data either in downlink or uplink direction. Thus we assume an inband signaling system. As dynamic assignment algorithm we choose a heuristic one described in Section 2 which generates near-optimal assignments in a short amount of time. Based on this, we then study the behavior of the dynamic algorithm and the behavior of a static comparison scheme for different parameter sets of the transmission scenario in Section 4. Finally, we conclude the paper in Section 5.

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2. System Model

We consider a single cell of a wireless system. Any data transmission within this cell is managed by an access point. There are J wireless terminals located within this cell. For data transmission a radio frequency band of bandwidth B is available. The transmission scheme used in the cell is OFDM, which splits the bandwidth into S subcarriers. Due to the orthogonality of the subcarriers the used symbol length per subcarrier and the frequency spacing of two adjacent subcarriers are related by $T_s = \frac{1}{\Delta f}$. We only consider the downlink data transmission direction.

The terminals move constantly within the cell, which has a radius of R, with a certain maximum speed $v_{\max}$. Therefore, the attenuation of the subcarriers varies constantly due to path loss, shadowing and fading. The attenuation differs for multiple subcarriers regarding the same terminal; also the attenuation of the same subcarrier varies regarding different terminals. At time t the matrix $\mathbf{A}(t) = (a_{j,s}(t))$ describes the attenuation values of all S subcarriers regarding all J terminals. Given the attenuation $a_{j,s}(t)$, the **S**ignal to **N**oise **R**atio (*SNR*) $x_{j,s}(t)$ of subcarrier s with respect to terminal j results as given by Equation 1 where $P_{\mathrm{tx},s}(t)$ denotes the transmission power for subcarrier s at time t and $n^2(t)$ denotes the noise power.

$$x_s(t) = \frac{a^2_{\mathrm{j,s}}(t)}{n^2(t)} \cdot P_{\mathrm{tx,s}}(t) \tag{1}$$

To exploit the varying nature of subcarrier states, in the downlink the system employs dynamic **F**requency **D**ivision **M**ultiplexing (*FDM*) for data transmission. Due to this, multiple downlink transmissions of data can be supported simultaneously by assigning multiple terminals different sets of subcarriers. Prior to each downlink transmission the access point can dynamically allocate and assign subcarriers to terminals, based on information of all subcarrier states regarding each terminal. Then, still prior to the downlink transmission itself, the assignments of subcarriers have to be signaled to the terminals. Both the acquisition of channel knowledge and the signaling of assignments are discussed in detail in Section 3 where the **M**edium **A**ccess **C**ontrol (*MAC*) frame, enabling these functions, is described. As dynamic assignment algorithm we choose here the nearly optimal **a**dvanced **D**ynamic **A**lgorithm (*aDA*) introduced in [3].

In order to transmit data on each subcarrier, adaptive modulation is used with the following modulation types: BPSK, QPSK, 16-QAM, 64-QAM and 256-QAM. During one downlink transmission the subcarrier assignments as well as the modulation types are not changed. Out of the available modulation types the system always chooses the one with the highest throughput that still provides a symbol error rate lower than P_{s}; the choice is based on the individual subcarrier's SNR. Transmission power is equally distributed over all subcarriers, we do not assume a power control system here. For forward error control we use block codes, due to their easy handling in simulations.

Each terminal in the cell receives a stream of packets from a source outside of the cell. These packets arrive at the access point and are queued separately for each terminal until they are transmitted to the respective terminal. For simplicity we assume that the access point has always data to transmit to the terminals, therefore the queues are never empty.

3. Channel Knowledge and Signaling System

Successfully assigning subcarriers to wireless terminals, depending on the subcarrier states for each terminal, requires of course that the access point has sufficient knowledge of these states. If the subcarriers can be assumed to be reciprocal in terms of attenuation, then the access point might obtain the required knowledge by observing the attenuation during uplink transmissions. But since this is not the case in general, an alternative is to obtain this knowledge explicitly via the uplink transmissions themselves: The terminals measure the attenuation of each subcarrier during the previous downlink transmission and transmit these measured values to the access point in the following uplink transmission.

Once the access point generated the assignments based on this channel knowledge, the wireless terminals have to be informed prior to the downlink transmission itself which subcarriers are assigned to them. In addition, since we consider a system with adaptive modulation, the used modulation type also has to be signaled to the terminals.

In the following we present and discuss a framing structure that enables such a system to acquire channel knowledge as well as to signal assignments realistically: by paying a price in terms of system performance. This structure is then used for the further study.

3.1. General Frame Structure

We divide time into a continuous stream of frames. Denote the length of one frame by T_{f}. For each frame, the access point computes the subcarrier assignments for this frame (using channel knowledge acquired in the previous frame), signals these assignments to the terminals, conducts the actual downlink data transmission, and, at the end of the uplink, receives channel information from each terminal to be used for the next frame's channel assignments.

Figure 1 shows the basic elements of a frame. A frame starts with a phase during which signaling information is sent to the terminals. This takes a time of T_{sig}. Then follows a downlink phase, which lasts for T_{d}. The last element of a frame is the uplink phase, which has a length of T_{u}.

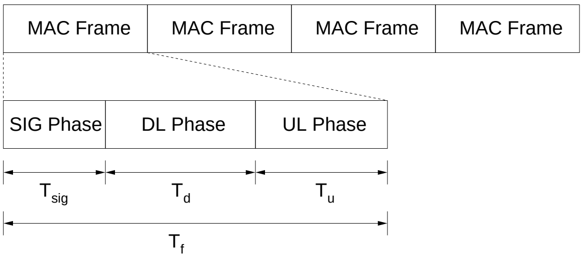

Fig. 1. Elements of a frame

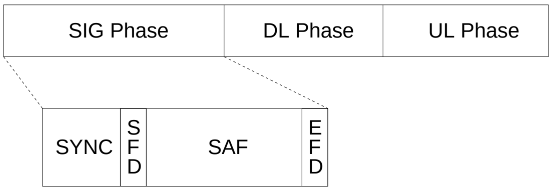

Fig. 2. Elements of the signaling field

3.2. Inband Signaling System

Instead of considering a separate control channel, we suggest the usage of an *inband* signaling system. The signaling information is therefore conveyed using the system bandwidth which is also used to transmit payload. The advantage of such a method is that it does not require additional bandwidth. The downside of this *inband* signaling is that a certain time has to be reserved for transmitting the signaling information, which therefore reduces the system's performance.

The signaling field within each frame consists again of multiple elements, shown in Figure 2. At the beginning of the signaling field, a synchronization field is transmitted, analog to the one used in IEEE 802.11a [4] with a length of 12 symbols (signal acquisition, synchronization and training of the receiver). Then, a start frame delimiter is transmitted to indicate the start of the signaling information. Next, the **S**ubcarrier **A**ssignment **F**ield (*SAF*) is transmitted completely, which holds all assignments and also includes error coding. Finally, an end frame delimiter is sent, which is the last element of the signaling field. The signaling field is shown in Figure 2.

The transmission of the signaling information within this field is done as broadcast. Every terminal in the cell receives this information, even if a terminal will not receive data during this frame and therefore will not be assigned a subcarrier. The signaling field is always transmitted with the same modulation type (BPSK) and is sent via all available S subcarriers.

The signaling information itself is transmitted with a fixed structure (Figure 3). For each frame all S subcarriers are assigned a wireless terminal and a modulation type. This results in a pair of numbers which have to be transmitted for each subcarrier: the terminal's address that has been assigned this subcarrier and the modulation type to be used for downlink transmission. This information is transmitted pairwise for each subcarrier, then follows a CRC code for error detection. This complete field is also protected by a strong error correction code.

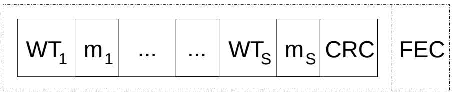

Fig. 3. Structure of the SAF

By broadcasting this information during the signaling phase, all terminals receive all assignments. The advantage of this method is that it gives full flexibility to the assignment algorithm within the access point. The structure of the signaling field does not change, even if only a few terminals are assigned subcarriers. This is not the case if the signaling information is not broadcasted but rather transmitted individually ("piggybacking" the signaling information for example). Then, terminals are excluded from the system whenever they do not receive a subcarrier for a frame. As a consequence these terminals would have to go through the admission process again.

If the signaling information is received completely and it is correct, the terminals only process the data received on their specific subcarriers during the following downlink phase, all other data, although received, is ignored. If the signaling information is not received correctly, all received data during the downlink phase is discarded and during the following uplink phase this is indicated by the terminal. Then, the data transmission is repeated during the next frame.

3.3. Acquisition of Channel Knowledge

In an ideal case a system would have the following properties: While the attenuation of subcarriers does not change for the time span of one frame, the access point would "know" about these subcarrier states in advance of each frame. Obviously, this can not be the case in reality. First, the attenuation of subcarriers changes constantly during one frame, depending on the fading rate [1, 7]. Second, subcarrier states cannot be known in advance.

One approach for a working system in reality could be like this: During the signaling or downlink phase of frame x each wireless terminal measures the attenuation of all subcarriers. In the following uplink phase this information is then conveyed to the access point. The complete subcarrier state information is then available at the access point at the end of frame x. Note that it reflects the subcarrier states as they were at the end of the downlink phase of this frame (in the most optimistic case). This information is now used as an estimate of the subcarrier states for the next frame $x + 1$. So the access point generates new assignments based on these estimates, signals these assignments to the terminals and

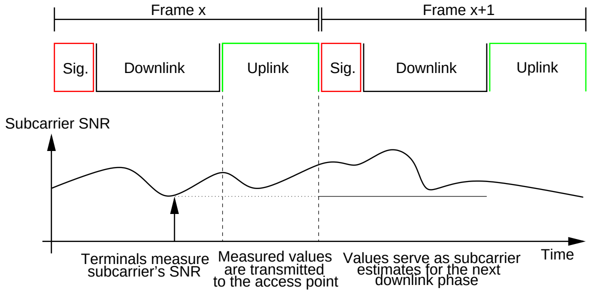

Fig. 4. Process of acquiring subcarrier gain knowledge

then starts the downlink phase. Figure 4 illustrates this process.

The quality of this estimate depends of course on the fading rate of the subcarriers. Note that we do not assume any sophisticated estimation techniques to be present at the access point. The subcarrier state information is obtained at the end of the downlink phase of frame x, and is used as estimate until the end of the downlink phase of frame $x + 1$. Therefore, T_f should be short enough so that matrix $\mathbf{A}(t)$ and matrix $\mathbf{A}(t + T_\mathrm{f})$ do not differ significantly. Since the speed of objects within the propagation environment directly influences the fading process of the subcarriers [7], which is characterized by the coherence time, the length of a frame should be significantly lower than this value.

4. Performance Study

The focus of this study is to highlight the performance of dynamic OFDM-FDM systems considering realistic costs for signaling and channel knowledge acquisition. In this section we first discuss our metrics and comparison schemes, then we introduce the chosen scenario and at last present our results.

4.1. Comparison Schemes and Metrics

We consider two primary metrics in this study. The first one is the average throughput per wireless terminal in bits per second. The second metric is the average goodput per wireless terminal in packets per second. Both metrics consider the data received at the terminals. For the throughput this received data amount is always similar to the transmitted data amount at the access point. However, for the goodput this is not true in general. Here the amount of successfully transmitted packets per terminal is relevant which depends in principle on the length of the packets considered as well as on the used forward error correction code.

We investigate the behavior of the dynamic OFDM-FDM system in three different *scenarios*. In the first one we consider the *ideal scenario*: signaling does not cost bandwidth, is not subject to transmission errors and the access point has perfect knowledge of the subcarrier states in advance. For the second scenario we assume the signaling system to be present as shown in Section 3.2 but the access point has still perfect channel knowledge. This one is called the *half-realistic* scenario. Finally, in the third one, the *realistic scenario*, the access point generates assignments based on outdated channel information and assignments have to be signaled through the discussed inband signaling system.

For all three cases the performance in terms of throughput and goodput of the dynamic OFDM-FDM system is obtained and compared to the performance of a static scheme which only employs adaptive modulation. In the static scheme each terminal receives the same set of subcarriers during all downlink phases. However, adaptive modulation is still applied for data transmission on these subcarrier sets. Therefore, the static scheme also depends on signaling as well as channel knowledge acquisition, but the impact of dynamically assigning subcarriers is taken out of the system.

The performance of both schemes, the dynamic as well as the static one, are obtained for the three different scenarios. Then, for both metrics the ratio between the dynamic and static system setup is computed and considered as the figure of merit in the following. This ratio precisely expresses the gain or loss in performance one has to expect if the dynamic scheme is applied instead of a static one for the corresponding scenario.

4.2. Simulation Scenario

We consider the following simulation scenario. We choose a system with a bandwidth equivalent to IEEE 802.11a [4, 6], thus the available bandwidth is $B = 16.25\ \mathrm{MHz}$, which is split into 52 subcarriers, each with a bandwidth of $312.5\ \mathrm{kHz}$, from which $S = 48$ subcarriers are available for data transmission. Corresponding to this, each OFDM symbol has a length of $T_s = 4\ \mu\mathrm{s}$, from which $T_g = 0.8\ \mu\mathrm{s}$ belong to the guard interval. As center frequency we choose a channel from the U-NII lower band, located at 5.2 GHz.

The subcarrier states change constantly due to the movement of the terminals and the multi-path propagation environment. Wireless terminals move within the cell with a random velocity, the maximum speed is given by $v_\mathrm{max} = 1\ \mathrm{m/s}$. The considered cell has a radius of $R = 100\ \mathrm{m}$. The effects influencing the subcarrier attenuation states are path loss, shadowing and fading. Path loss is determined by the formula $\frac{P_0}{P_\mathrm{tx}} = K \cdot \frac{1}{d^\alpha}$, where $\frac{P_0}{P_\mathrm{tx}}$ denotes the ratio between received and transmitted power, d denotes the distance between transmitter and receiver, K denotes the reference loss for the distance unit d is measured in and α is the path loss exponent. We parameterize the reference loss with $10\ \log(K) = 46.7\ \mathrm{dB}$ and the path loss exponent with $\alpha = 2.4$. The shadowing is assumed to be log-normal distributed with a standard deviation of $\sigma = 5.8\ \mathrm{dB}$

and a mean of 0 dB while no correlational behavior was incorporated in the model. For the fading the power spectral density is chosen to have a Jakes-like shape [1] with a Doppler frequency depending on $v_{\max}$. The multipath propagation environment is characterized by a delay spread of $\Delta\sigma = 0.15\mu\mathrm{s}$ with an exponential power delay profile according to the large open space model of ETSI C [5]. An example environment corresponding to such a setting would be a large airport or exposition hall.

We set the frame length to $T_{\mathrm{f}} = 2$ ms which corresponds to the frame length of HIPERLAN/2 systems [2]. The uplink is not considered any further; the time reserved for T_{u} equals 1 ms, which leaves a time span of 1 ms for the downlink and signaling phase. We consider a maximum of $J = 48$ terminals to be within the cell. Since five modulation types have to be considered in the signaling also, a total of $\lceil \log_2 48 \rceil + \lceil \log_2 5 \rceil = 6 + 3 = 9$ bits has to be transmitted as pure signaling information per subcarrier. Together with a 12 Bit CRC code and a strong BCH code, the length of the signaling field results finally in 498 bits. Using all subcarriers for conveying this information with a BPSK modulation type results in the usage of 11 OFDM symbols for the transmission. Considering the frame delimiters and the synchronization field yields the usage of 19 OFDM symbols or a time length of $T_{\mathrm{sig}} = 0.076;\mathrm{ms}$ for the complete initial phase. The remaining 0.924 ms are spent on the downlink phase.

If a bit error occurs within the signaling data and can not be corrected by FEC, the terminal has to discard all data transmitted to it during the following downlink phase. Fortunately it still stays synchronized and can indicate the loss of the data during the uplink phase while also passing the measured attenuation values of the subcarriers to the access point (assuming that each terminal has a slot during the uplink phase). Then, it simply waits for the next frame to continue the reception of data.

For illustration purposes, each terminal is allocated the same amount of subcarriers, which always corresponds to the ratio $\frac{S}{J}$. The noise power is assumed to equal -117 dBm per subcarrier. Initially the transmit power is set to -7 dBm per subcarrier, according to the maximal allowed transmit power in the U-NII lower band. From the attenuation values of each subcarrier, an instantaneous **S**ignal to **N**oise **R**atio (*SNR*) is obtained. After the assignment of subcarriers a modulation type is chosen to be employed during the downlink phase. As maximum acceptable symbol error probability we choose the value 10^{-2}. Depending on the SNR of the subcarrier, the modulation type with the highest rate is chosen that still has a symbol error probability lower than 10^{-2}. These decisions (subcarrier and modulation) are then signaled to each terminal, after which the downlink phase starts. The data transmitted in the downlink phase is grouped into packets with a size of 1 kByte. Error coding in form of BCH block codes protects the transmission of data in the downlink. For this a $(711, 631, 17)$ code has been chosen, which has been selected according to the maximum symbol error probability and a target bit error probability of 10^{-5}.

4.3. Results

All results are obtained via simulation: We simulated the movement of all wireless terminals within the cell for 300 s. Every 2 ms a sample for each subcarrier attenuation was generated regarding each wireless terminal. Therefore, for each terminal and each subcarrier 150000 SNR values were generated and evaluated afterwards.

First we present results where the number of wireless terminals in the cell varies between 2 and 48. In Figure 5 the absolute average throughput is shown for a varying number of terminals in the cell in case of the ideal scenario for the dynamic and static schemes. The higher the number of terminals is, the lower is the throughput per terminal. Between the static and dynamic scheme is a varying gap which increases for a higher number of terminals in the cell. Note that this general behavior is the same for the remaining absolute throughput and goodput curve pairs for all scenarios. Consequently, we only discuss the ratios between each curve pair in the following.

Figure 6 shows the ratio of the dynamic versus the static scheme for all three scenarios. In general, the throughput ratio increases for a higher number of terminals in the system due to an increase in diversity that can only be exploited by the dynamic mechanisms.Compared to the ratio of the ideal scenario, the other two ratios have a slightly smaller ratio, reduced by 0.04. This offset is clearly due to the additional signaling cost that is taken into account for these scenarios. Furthermore, the half-realistic scenario and the realistic scenario do not differ in the ratios. Therefore, using actual or slightly outdated channel knowledge does not change the throughput performance of the schemes. Note that by using outdated channel knowledge the statistics of the channel do not change, therefore throughput should indeed not change, in contrast to goodput.

In Figure 7 the ratios are given for the goodput. Comparing this with the behavior of the throughput ratios the general behavior is the same: The higher the number of terminals in the cell, the higher is the ratio. However, while for the throughput ratio the ideal scenario has the highest ratio, in the case of the goodput ratio the realistic scenario does achieve the highest ratio. Therefore, in this case the dynamic scheme outperforms the static scheme even more. Note that in terms of absolute goodput (not shown here) the dynamic scheme in the realistic scenario evidently has a lower goodput than in the ideal scenario (differing by at most 30%). But also the goodput of the static scheme is reduced

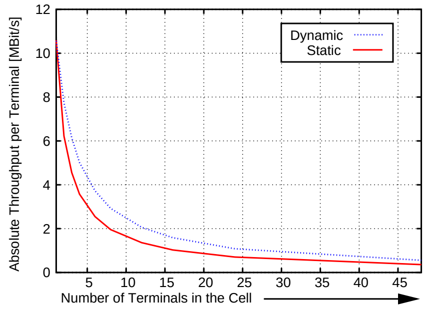

Fig. 5. Average absolute throughput in the case of the ideal scenario for a varying number of terminals in the cell

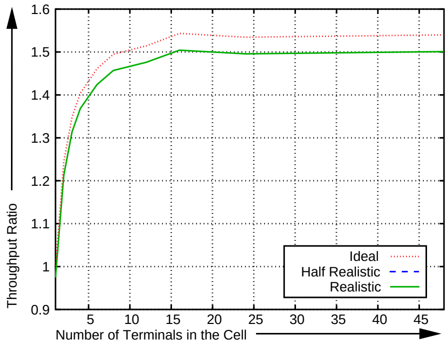

Fig. 6. Average throughput ratio for a varying number of terminals in the cell

for the realistic scenario compared to the ideal scenario. Since the goodput of the static scheme suffers *more* from the condition of using realistic channel knowledge than the goodput of the dynamic scheme, the ratio between dynamic and static increases stronger than in the case of the ideal scenario. This justifies the claim that dynamic schemes actually outperform static schemes, especially when realistic system assumptions are taken into account.

Next we varied the transmission power in the cell where the number of wireless terminals was fixed at $J = 16$. The power (per subcarrier) was varied between $-16\ \mathrm{dBm}$ and $3\ \mathrm{dBm}$ in steps of $1\ \mathrm{dBm}$.

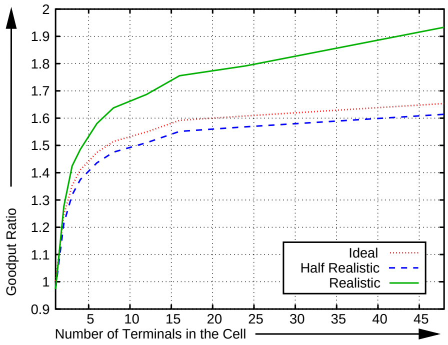

Fig. 7. Average goodput ratio for a varying number of terminals in the cell

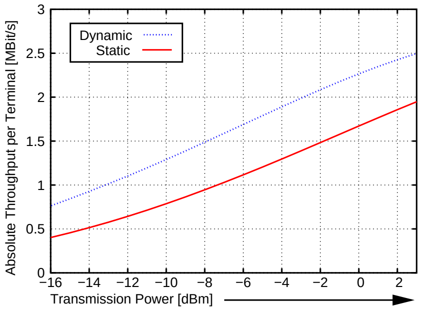

Fig. 8. Average absolute throughput behavior in the case of the ideal scenario for a varying transmit power

In Figure 8 the absolute throughput per terminal for the static and dynamic scheme is shown in case of the ideal scenario. The higher the transmission power, the higher is the throughput for both schemes while the dynamic scheme outperforms the static one. Again this general behavior also applies to all other curve pairs of the scenarios as well as to the absolute goodput behavior, such that we only discuss the ratios next.

In Figure 9 the throughput ratios are given. Clearly, the higher the transmit power per subcarrier, the lower is the throughput ratio. Note that for a higher transmission power the subcarrier states are better in general. Therefore a dynamic algorithm will achieve a lower throughput advantage over the static scheme, since choosing subcarriers with a state well above the average becomes less and less likely (all subcarriers are in a better and better state due to the higher transmit power). Again there is a difference between the ideal scenario's ratio and the ones of the half-realistic and realistic scenario ratios, caused by the required signaling. This already has been observed when varying number of terminals. The half-realistic and realistic scenario have again the same ratio.

In Figure 10 the goodput ratio is given. Here again the goodput ratios have the same behavior as the throughput ratios (decreasing ratio for an increasing transmit power). In this case it can be seen that for a quite low transmit power the realistic scenario ratio is significantly higher than the ratios of the ideal and the half-realistic scenarios. The higher the transmit power is, though, the more do all three ratios become equal.

5. Conclusions and Future Work

This paper studied the question whether or not it pays off to dynamically assign subcarriers in an OFDM system when the requirements of a realistic system structure – costs for signaling and outdated channel knowledge – are taken into account. We answer this question in the affirmative, both for throughput and goodput.

In terms of throughput we find that considering realistic channel knowledge does not change the throughput behavior of the static or dynamic schemes at all. However, by introducing the signaling system, the throughput

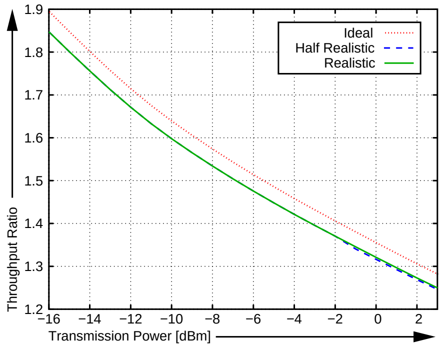

Fig. 9. Average throughput ratio for a varying transmit power per subcarrier in the cell

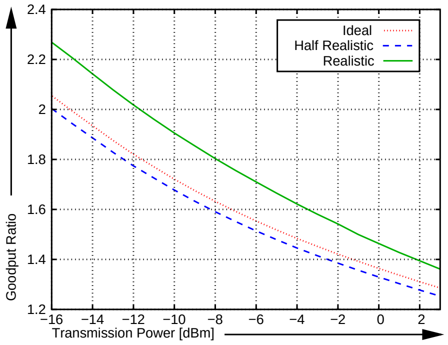

Fig. 10. Average goodput ratio for a varying transmit power per subcarrier in the cell

of the dynamic set up is slightly more reduced (versus the ideal scenario's values) while the one of the static scheme is not so much reduced. This performance reduction is moderate, though.

In terms of goodput the picture changes. While the performance decreasing influence of the signaling system is still present, we actually find that the benefit of using dynamic subcarrier assignments is significantly increased if realistic channel knowledge is taken into consideration. In this case the performance of the static scheme with adaptive modulation is decreased quite strongly (compared to the performance of the same scheme with ideal channel knowledge) while for the dynamic scheme the performance decrease is not as strong. Hence, the ratio of both schemes increases and therefore it pays off more, in terms of goodput, if subcarriers are managed dynamically. This effect becomes significant for a high number of terminals in the cell as well as for a low transmit power. For a low number of terminals or a high transmit power the difference between ideal scenario and real scenario vanishes while the dynamic scheme stills outperforms the static one slightly.

As further work we intend to investigate the ratio between both schemes for other variations of the system model. First of all we are interested in the behavior of the system if the speed of the terminals in the cell increases. In this case the subcarrier states change their behavior faster. Using a frame length of 2 ms, the outdated channel information should become more and more inaccurate when used as channel estimation for the next downlink phase. We are interested in the detailed relationship between varying the speed, using different frame lengths and considering the behavior for the static or dynamic subcarrier allocation schemes. Also, we are interested in the system behavior if the delay spread is varied in the system.

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