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A study of impact of inband signalling and realistic channel knowledge for an example dynamic OFDM–FDMA system

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SUMMARY

Dynamically assigning sub-carriers of *orthogonal frequency division multiplexing* (OFDM) systems to multiple different terminals in a cell has been shown to be beneficial in terms of different transmission metrics. The success of such a scheme, however depends on the ability of the access point to inform terminals of their newest sub-carrier 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 functions consumes all of the potential performance increase possible by dynamically assigning sub-carriers. In this paper, a specific MAC structure is selected enabling the operation of a dynamic OFDM system, incorporating a signalling scheme for dynamically assigned sub-carriers. Based on this structure, we study the overhead required for a dynamic sub-carrier scheme; a static variant that serves as a comparison case. We investigate the performance difference of these two schemes for various scenarios where at first signalling and then realistic channel knowledge is added to the system model. Average throughput and goodput per terminal serve as figures of merit; the number of terminals in the cell, the transmission power per sub-carrier, the delay spread and the movement speed of the terminals are varied. We find that a realistic overhead model decreases the performance of both static and dynamic schemes such that the overall ratio favours in all cases except for higher speeds the dynamic rather than the static scheme especially in realistic system environments. Copyright © 2005 AEIT.

1. INTRODUCTION

Recently, theoretical studies have proven that dynamically assigning sub-carriers of *orthogonal frequency division multiplexing* (OFDM) systems can be advantageous for the downlink of a single cell in terms of several transmission metrics, for example required power or achieved throughput [1–4]. These approaches all exploit the combination of two aspects regarding wireless channels in multiuser communication scenarios: first, for a given sub-carrier, its attenuation values with respect to different sub-carriers are statistically independent random variables. Second, the attenuation of sub-carriers changes over time and frequency as a consequence of terminal mobility and the multipath propagation environment. Thus, also

regarding a single terminal, the attenuation varies from sub-carrier to sub-carrier; dynamically assigning ‘good’ sub-carriers to terminals promise to improve performance.

When evaluating this potential of dynamic OFDM–FDMA systems, all these studies are based on two common, simplifying assumptions. First, it is assumed that at the access point, prior to the computation of sub-carrier assignments, all sub-carrier attenuations (also referred to as ‘states’) to each terminal are known. Second, it is assumed that after the generation of assignments wireless terminals somehow ‘know’ which sub-carriers they have been assigned by the dynamic algorithm. In some studies, the authors mention an existing out-of-band signalling system, but no investigation has been conducted highlighting the cost of such a signalling system (in effect

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representing an unfair advantage for dynamic systems as a potential performance, disadvantage is not considered). Interestingly, in reality the success of dynamically assigning sub-carriers to terminals is directly related to the provided channel knowledge of the access point and to a working signalling 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 sub-carriers dynamically, like static FDMA schemes or TDMA schemes. In this study, we investigate this question regarding an example system that is set up quite similar to IEEE 802.11a. Especially, we investigate the variation of four different parameters: the number of terminals in the cell, the transmit power per sub-carrier, the delay spread of the propagation environment and the maximum speed of objects in the propagation environment. A preliminary version of this study has been published in Reference [5]. We extend on this work by incorporating the investigation regarding the delay spread variation and the maximum speed variation. In addition, we present more analysis explaining the observed result differences.

In order to study the two aspects decreasing the achieved performance, we constrain ourselves to a simple *medium access control* (MAC) protocol, described in Section 3, which provides a timing structure for channel state acquisition, signalling the assignment information and transmitting data either in downlink or uplink direction. We thus assume an inband signalling 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 behaviour of the dynamic algorithm and the behaviour of a static comparison scheme for different parameter sets of the transmission scenario in Section 4. Finally, we conclude the paper in Section 5.

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 at centre frequency f_c . The transmission scheme used in the cell is OFDM, which splits the bandwidth into S overlapping sub-carriers. In order to avoid inter-carrier interference (ICI) of the overlapping sub-carriers, the used

symbol length per sub-carrier and the frequency spacing of any two adjacent sub-carriers have to be chosen carefully, the relation is given by the equation $T_s = (1/\Delta f)$. 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 sub-carriers varies constantly due to path loss, shadowing and fading. The attenuation differs for multiple sub-carriers regarding the same terminal; also the attenuation of the same sub-carrier varies regarding different terminals. The matrix $\mathbf{A}(t) = (a_{j,s}(t))$ describes the attenuation values of all S sub-carriers regarding all J terminals. Given the attenuation $a_{j,s}(t)$, the signal to noise ratio (SNR) $x_{j,s}(t)$ of sub-carrier s with respect to terminal j is given by Equation 1, where $P_{\text{tx},s}(t)$ denotes the transmission power for sub-carrier s at time t and $n^2(t)$ denotes the noise power.

$$x_s(t) = \frac{a_{j,s}^2(t)}{n^2(t)} \times P_{\text{tx},s}(t) \quad (1)$$

To exploit the varying nature of these sub-carrier states, in the downlink the system employs *dynamic frequency division multiplexing* (FDM) for data transmission. Due to this, multiple downlink transmissions of data can be supported simultaneously by assigning different sets of sub-carriers to different terminals. Prior to each downlink transmission the access point can dynamically allocate (i.e. decide about the number of sub-carriers given to each terminal) and assign (i.e. decide about which sub-carriers are given to each terminal according to the allocation) sub-carriers to terminals, based on information of all sub-carrier states regarding each terminal. Then, still prior to the downlink transmission itself, the assignments of sub-carriers have to be signalled to the terminals. Both, the acquisition of channel knowledge and the signalling of assignments are discussed in detail in Section 3 where MAC layer, enabling these functions, is described.

As dynamic assignment algorithm, we choose here the nearly optimal heuristic one referred to as *advanced dynamic algorithm* (aDA), introduced in Reference [6]. It requires as input the sub-carrier states and the sub-carrier allocations for each terminal. Based upon this input, aDA can generate quite good sub-carrier assignments within 0.5 ms on standard computers. This delay caused by the computational complexity of the algorithm has not been considered any further.[†]

[†]This simplification is justifiable since the computation of allocations and assignments can be pipelined and overlapped with the last half of a MAC frame.

In order to transmit data on each sub-carrier, adaptive modulation is used with the following modulation types: BPSK, QPSK, 16-QAM, 64-QAM and 256-QAM. During one downlink transmission the sub-carrier 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 sub-carrier's SNR. Transmission power is equally distributed over all sub-carriers; we do not assume an adaptive power distribution here due to the additional computational complexity associated with it. 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 SIGNALLING SYSTEM

Successfully assigning sub-carriers to wireless terminals, depending on the sub-carrier states for each terminal, requires of course that the access point has sufficient knowledge of these states. If the sub-carriers 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. 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 sub-carrier 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 which sub-carriers are assigned to them. In addition, since we consider a system with adaptive modulation, the used modulation type also has to be signalled 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.

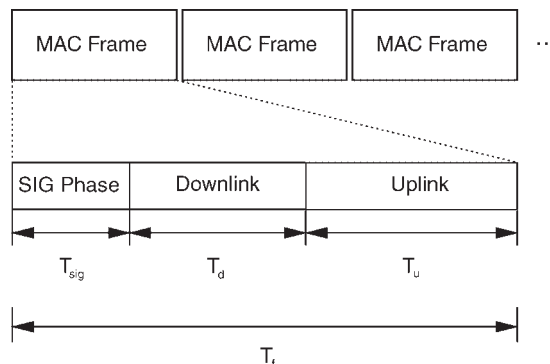


Figure 1. Elements of a frame.

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 sub-carrier 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 signalling 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 .

3.2. Inband signalling system

Instead of considering a separate control channel, we suggest the usage of an inband signalling system. The signalling 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 (and thus allows a fair comparison between static and dynamic schemes, unlike out-of-band signalling approaches). The downside of this *inband* signalling is that a certain time has to be reserved for transmitting the signalling information, which therefore reduces the system's performance.

The signalling field within each frame consists again of multiple elements, shown in Figure 2. At the beginning of the signalling field, a synchronisation field is transmitted, analog to the one used in IEEE 802.11a [7] with a length of 12 symbols (signal acquisition, synchronisation and training of the receiver). Then, a start frame delimiter is transmitted to indicate the start of the signalling information.

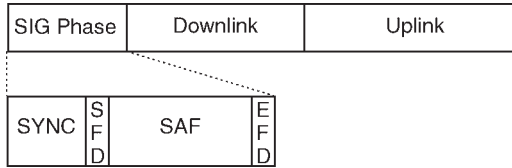


Figure 2. Elements of the signalling field.

Next, the sub-carrier assignment field (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 signalling field. The signalling field is shown in Figure 2.

The transmission of the signalling 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 sub-carrier. The signalling field is always transmitted with the same modulation type (BPSK) and is sent via all available S sub-carriers.

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

By broadcasting this information during the signalling 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 signalling field does not change, even if only a few terminals are assigned sub-carriers. This is not the case if the signalling information is not broadcasted but rather transmitted individually ('piggybacking' the signalling information for example). Then, terminals are excluded from the system whenever they do not receive a sub-carrier for a frame. As a consequence these terminals would have to go through the admission process again.

If the signalling information is received completely and it is correct, the terminals only process the data received on their specific sub-carriers during the following downlink phase, all other data, although received, is ignored. If the

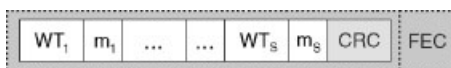


Figure 3. Structure of the Sub-carrier Assignment Field (SAF).

signalling information is not received correctly, all received data during the downlink phase is discarded and during the following uplink phase the loss 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 sub-carriers does not change for the time span of one frame, the access point would 'know' about these sub-carrier states in advance of each frame. Obviously, this cannot be the case in reality. First, the attenuation of sub-carriers changes constantly during one frame, depending on the fading rate [8, 9]. Second, sub-carrier states cannot be known in advance.

One approach for a working system in reality could be like this: during the signalling or downlink phase of frame x each wireless terminal measures the attenuation of all sub-carriers. In the following uplink phase, this information is then conveyed to the access point. The complete sub-carrier state information is then available at the access point at the end of frame x . Note that it reflects the sub-carrier 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 sub-carrier 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 then starts the downlink payload transmission. Figure 4 illustrates this process.

The quality of this estimate depends of course on the fading rate of the sub-carriers. Note that we do not assume any sophisticated estimation techniques to be present at the access point. The sub-carrier 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

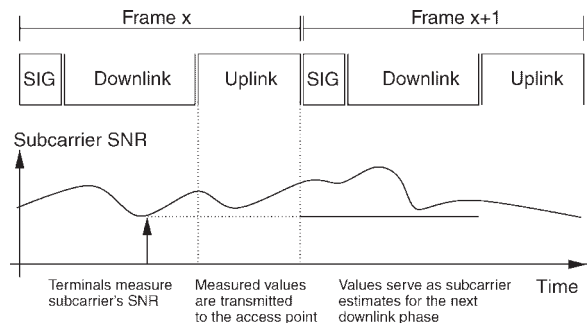


Figure 4. Process of acquiring sub-carrier gain knowledge.

$A(t)$ and matrix $A(t + T_f)$ do not differ significantly. Since the speed of objects within the propagation environment directly influences the fading process of the sub-carriers (together with the centre frequency of the system) [8], which is characterised by the coherence time, the length of a frame should be lower than this value. Even in this case however, the channel estimates will vary from the real values since the coherence time is a statistical measure, which cannot guarantee channel stability over some time span. Note that an estimation error as such does not have to harm the system, only if the next sub-carrier state has been overestimated a certain performance decrease will be observed (resulting in an increase of bit errors).

4. PERFORMANCE STUDY

The focus of this study is to highlight the performance of dynamic OFDM-FDM systems considering realistic costs for signalling 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. For further details on any aspect of this investigation, refer to Reference [10].

4.1. Metrics and comparison schemes

Two primary metrics are chosen 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 equal to the transmitted data amount at the access point. However, for the goodput this is not true in general. Here the amount of successfully received packets per terminal is relevant, which depends on the length of the packets considered as well as on the used forward error correction code.

We investigate the behaviour of the dynamic OFDM-FDM system in three different scenarios. The first one is the ideal scenario: signalling does not cost bandwidth, is not subject to transmission errors and the access point has perfect knowledge of the sub-carrier states in advance of each frame. For the second scenario we assume the signalling system to be present as described in Subsection 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. These assignments then have to be signalled through the discussed inband signalling system.

For all three scenarios, the performance in terms of throughput and goodput of the dynamic OFDM-FDM system is obtained and compared with the performance of a static scheme. In the static scheme, each terminal receives the same set of sub-carriers during all downlink phases. Nevertheless, adaptive modulation is still applied for data transmission on these sub-carrier sets. Therefore, the static scheme also depends on signalling as well as channel knowledge acquisition, but the influence of dynamically assigning sub-carriers 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. Hence, this ratio is the result of investing into a certain additional computational power at the access point and at the terminal.

4.2. Simulation parameterisation

We consider the following simulation scenario. We choose a system with a bandwidth equivalent to IEEE 802.11a [7, 11], thus the available bandwidth is $B = 16.25$ MHz, which is split into 52 sub-carriers, each with a bandwidth of 312.5 kHz, from which $S = 48$ sub-carriers are available for data transmission. Corresponding to this, each OFDM symbol has a length of $T_s = 4 \mu\text{s}$, from which $T_g = 0.8 \mu\text{s}$ belong to the guard interval. As centre frequency, we choose a channel from the U-NII lower band, located at 5.2 GHz.

The sub-carrier states change constantly due to the movement of the terminals and the multipath propagation environment. Wireless terminals move within the cell with a random velocity, initially the maximum speed is given by $v_{\text{max}} = 1$ m/s. The considered cell has a radius of $R = 100$ m. The effects influencing the sub-carrier attenuation states are path loss, shadowing and fading. Path loss is determined by the formula $P_0/P_{\text{tx}} = K \times (1/d^\alpha)$, where (P_0/P_{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 parameterise the reference loss with $10 \log(K) = 46.7$ dB and the path loss exponent with $\alpha = 2.4$. The shadowing is assumed to be log-normal distributed with a standard deviation of $\sigma = 5.8$ dB and a mean of 0 dB while no correlational behaviour was incorporated in the model. For

the fading, the power spectral density is chosen to have a Jakes-like shape [9] with a Doppler frequency depending on v_{\max} . The multipath propagation environment is characterised by a delay spread, initially set to $\Delta\sigma = 0.15 \mu\text{s}$, with an exponential power delay profile according to the large open space model of ETSI C [12]. An example environment corresponding to such a setting would be a large airport or exposition hall.

We set the frame length to $T_f = 2 \text{ ms}$ which corresponds to the frame length of HIPERLAN/2 systems [13]. 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 signalling phase. We consider a maximum of $J = 48$ terminals to be within the cell. Since five modulation types have to be considered in the signalling also, a total of $\lceil \log_2 48 \rceil + \lceil \log_2 5 \rceil = 6 + 3 = 9$ bits has to be transmitted as pure signalling information per sub-carrier. Together with a 12 Bit CRC code and a (498,444,13)-BCH code, the length of the whole signalling field results finally in 498 bits. Using all sub-carriers 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 synchronisation field results in the requirement of 19 OFDM symbols or a time length of $T_{\text{sig}} = 0.076 \text{ ms}$ for the complete initial phase. The remaining 0.924 ms are spent on the downlink phase.

If a bit error occurs within the signalling data and cannot be corrected by FEC, the terminal has to discard all data transmitted to it during the following downlink phase. Then, it has to indicate the loss of the data during the uplink phase while also passing the measured attenuation values of the sub-carriers to the access point (assuming that each terminal has a slot during the uplink phase). Therefore, it simply waits for the next frame to continue the reception of data.

For illustration purposes, each terminal is allocated the same amount of sub-carriers, which corresponds to the ratio S/J . We only consider cases where S/J results in an integer number. If not, the number of sub-carrier could be distributed unequally such that over a larger time span (multiple frame times) all terminals receive the same number of sub-carriers. Such a scheme would yield the data points in the case of 20 or 5 terminals in the cell. However, in a running system also different policies could be implemented using an allocation algorithm, which determines the amount of sub-carriers each terminal receives, for example according to the amount of data queued for each terminal at the access point [14].

The noise power is assumed to equal -117 dBm per sub-carrier. Initially the transmit power is set to -7 dBm per sub-carrier, according to the maximal allowed transmit power in the U-NII lower band. From the attenuation values of each sub-carrier, an instantaneous SNR is obtained. After the assignment of sub-carriers 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 sub-carrier, the modulation type with the highest rate is chosen that still has a symbol error probability lower than 10^{-2} . These decisions (sub-carrier and modulation) are then signalled 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. During this time span, the terminals moved in the cell following a rather simple movement pattern [10]. Every 2 ms samples for each sub-carrier attenuation were generated regarding each wireless terminal, providing a significant oversampling (depending on the maximum speed of the terminals) of each sub-carrier during the down-link phase of a frame.

Due to space limitations not all investigated parameters of the study can be presented here. For the complete study and further information refer to Reference [10]. Out of the study, four parameter variations of the presented system setup are going to be presented in the following. First, we varied the number of terminals in the system. Next, we varied the transmit power per sub-carrier. Finally, we varied two parameters influencing the correlational behaviour of the fading: the delay spread and the maximum speed of objects, both related to the propagation environment of the wireless cell.

4.3.1. Variation of the number of terminals. First, we present results where the number of wireless terminals in the cell varies between 1 and 48. The maximum speed was set to $v_{\max} = 1 \text{ m/s}$ while the delay spread was $\Delta\sigma = 0.15 \mu\text{s}$. The transmit power equalled -7 dBm per sub-carrier.

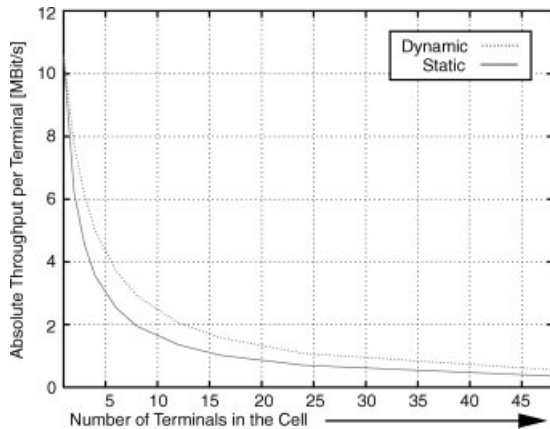


Figure 5. Average absolute throughput in the case of the ideal scenario for a varying number of terminals in the cell.

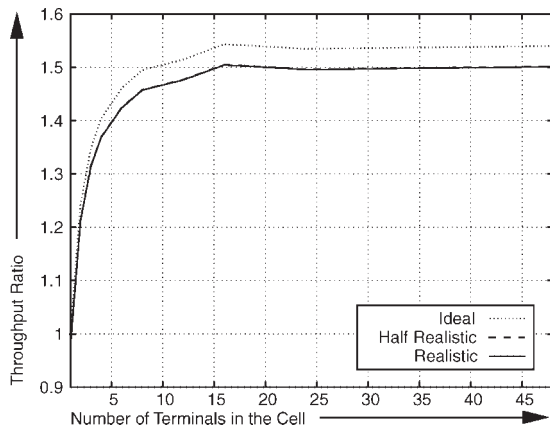


Figure 6. Average throughput ratio for a varying number of terminals in the cell.

In Figure 5, the absolute throughput per terminal is shown for a varying number of terminals in the cell for the ideal scenario (dynamic and static scheme). The higher the number of terminals is, the lower is the throughput per terminal. Between the performance of the static and dynamic scheme is a varying gap. Note that this general behaviour 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

[‡]For all presented absolute plots the 0.95-confidence intervals have been removed, due to their very small size compared to the curve behaviours.

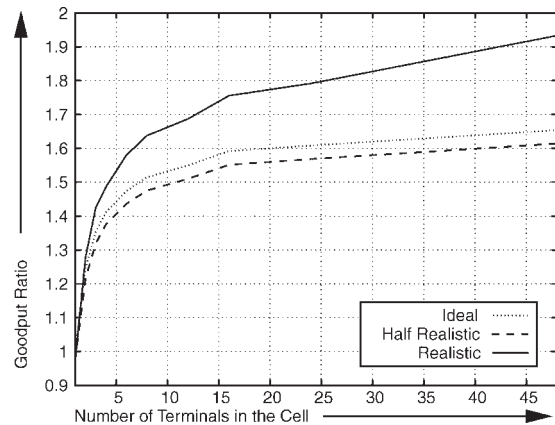


Figure 7. Average goodput ratio for a varying number of terminals in the cell.

system due to an increase in diversity that can only be exploited by the dynamic mechanisms (multiuser diversity). For about 16 or more terminals, dynamic schemes outperform static schemes by about 50%, even when taking signalling cost into account. Compared to the ratio of the ideal scenario, the other two ratios are slightly smaller, reduced absolutely by 0.04. This offset is clearly due to the additional signalling 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 good-put. Comparing this with the behaviour of the throughput ratios the general behaviour is the same: the higher the number of terminals in the cell, the higher is the ratio. However, while for the throughput the ideal scenario has the highest ratio, in the case of the goodput the realistic scenario does achieve the highest ratio. Therefore, in this case, the dynamic scheme outperforms the static scheme even more, almost doubling the goodput in a highly loaded cell. Note that in terms of absolute goodput (not shown here) the dynamic scheme in the realistic scenario evidently has a lower good-put than in the ideal scenario (differing by at most 30%). But also the goodput of the static scheme is reduced 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

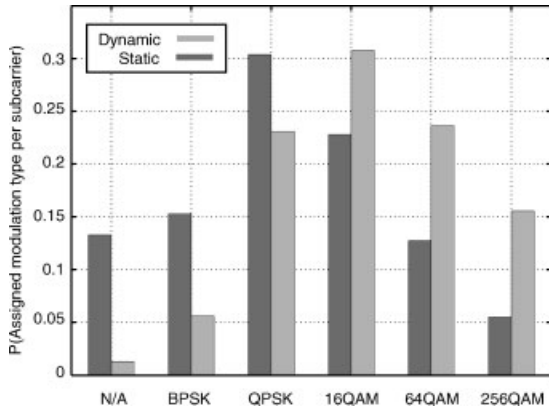


Figure 8. Probability of assigning a sub-carrier with a specific modulation type (average for 16 terminals in the cell, a transmit power of -7 dBm per sub-carrier and low maximum speed within the environment of 1 m/s).

between dynamic and static increases stronger than in the case of the ideal scenario.

Why does the goodput of the static scheme with adaptive modulation suffer more in the case of realistic channel knowledge than the dynamic scheme with adaptive modulation? Two possible reasons were further investigated. One reason could be that the probability of overestimating a certain modulation type is higher in the static case than in the dynamic case. A second reason could be that the average overestimation error for each modulation type is higher for the static scheme than for the dynamic scheme.

Out of these two reasons, the first one has no effect. For all modulation types beside BPSK the probability of an overestimation is higher for the dynamic scheme than the static scheme (figure not shown here). However, the main source of bit errors that cannot be corrected by the error coding is the average overestimation error of the modulation types.

Consider first the probability of scheduling a certain modulation type: according to Figure 8, for 16 terminals in the cell on average the static scheme assigns a sub-carrier with BPSK or with QPSK with a probability of 0.46 while assigning a sub-carrier with a 16-, 64- or 256-QAM modulation type has a probability of 0.41 (in the remaining cases no data is scheduled on the sub-carrier due to a too bad SNR, even for BPSK). In contrast, the dynamic scheme assigns a sub-carrier with BPSK or with QPSK only with a probability of 0.29 while assigning a sub-carrier with a QAM modulation type has a probability of 0.7 (almost never is a sub-carrier scheduled with a very bad SNR). Higher modulation types (the QAM types) are therefore much more often utilised in the case of the

dynamic scheme, lower modulation types (the phase shift keying modulation types) are utilised much more often by the static scheme. This directly explains the difference in the throughput.

Now consider the average overestimation error at a maximum speed of 1 m/s, shown in Figure 19. It is higher for both schemes for lower modulation types. Therefore, a higher number of symbols is erroneous in the case of the static scheme (Figure 19) overall. In addition, a single symbol error has a higher impact on the bit error probability for lower modulation types than for higher ones, if the overestimation is not too high (as long as the SNR is not very low for each modulation type, most symbol errors map into a single bit error, assuming the usage of Gray codes for coding adjacent symbols [8, page 273]).

We conclude from this, that as long as the average estimation error is not too high, the probability of overestimating a certain modulation type does not have a significant impact (as the caused bit errors can be corrected by the BCH codes). In contrast, the average overestimation error together with the probability of scheduling a certain modulation type is the major source for bit errors, which remain in the bit stream after error correction. This leads to the behaviour of the goodput ratio in the realistic case.

4.3.2. Variation of the transmit power. Next, we varied the transmission power in the cell where the number of wireless terminals was fixed at $J=16$. The power (per sub-carrier) was varied between -16 and 3 dBm in steps of 1 dBm. The maximum speed was still set to $v_{\max} = 1$ m/s while the delay spread was set to $\Delta\sigma = 0.15$ μ s.

In Figure 9, the absolute throughput per terminal for the static and dynamic scheme is shown for the ideal scenario. The higher the transmission power, the higher is the throughput for both schemes; the dynamic scheme outperforms the static one. Again this general behaviour also applies to all other curve pairs of the scenarios as well as to the absolute goodput behaviour, such that we only discuss the ratios next.

In Figure 10, the throughput ratios are given for varying transmission power. Clearly, the higher the transmit power per sub-carrier, the smaller is the throughput ratio. Note that for a higher transmission power the average sub-carrier SNR is higher in general. Therefore, a dynamic algorithm will achieve only a smaller throughput advantage over the static scheme, since choosing sub-carriers with a state well above the average becomes less and less likely (all sub-carriers are in a 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

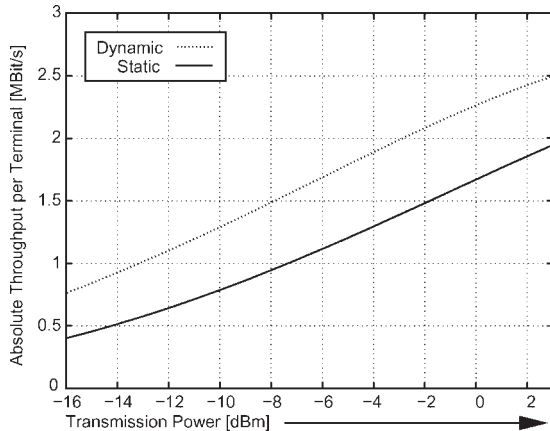


Figure 9. Average absolute throughput behaviour in the case of the ideal scenario for a varying transmit power.

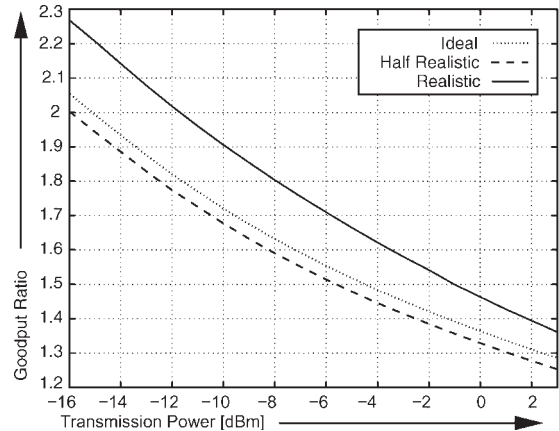


Figure 11. Average goodput ratio for a varying transmit power per sub-carrier in the cell.

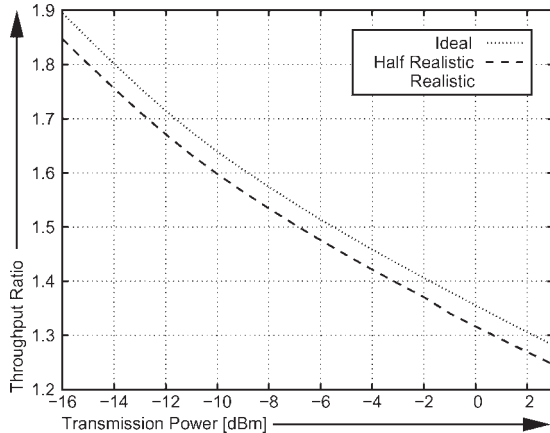


Figure 10. Average throughput ratio for a varying transmit power per sub-carrier in the cell.

and realistic scenario ratios, caused by the required signaling. This has already been observed when varying the number of terminals. The half-realistic and realistic scenario have again the same ratio.

In Figure 11, the goodput ratio is given. Here again the goodput ratios have the same behaviour 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 similar do all three ratios become.

4.3.3. Variation of the delay spread. For any propagation environment the delay spread has a strong impact on the frequency-selectivity of the fading process (experi-

enced in the time domain as ISI). If the delay spread is high, the attenuation due to fading is less correlated for two adjacent sub-carriers. Over the course of all sub-carriers, a high delay spread leads to a higher frequency diversity of the sub-carriers, the variability of the attenuation values per sub-carrier is increased.

In order to study the impact of this higher variability on the system metrics, we varied the delay spread from 0.05 up to 0.3 μs in steps of 0.05 μs . Note that these values are all much smaller than the guard interval of 0.8 μs such that the small change of the delay spread did not lead to any consequences for the intersymbol interference per sub-carrier. However, the variability of the attenuation per terminal over all sub-carriers did change. According to Reference [9], the corresponding coherence bandwidth changed from 3.1 to 0.5 MHz (and therefore was still a lot higher than the bandwidth of each single sub-carrier). For this investigation, the number of terminals in the cell was chosen to be 16, the transmit power equalled -7 dBm per sub-carrier. The maximum speed in the environment was set to $v_{\text{max}} = 1$ m/s.

Figure 12 shows the absolute throughput behaviour for the static and dynamic scheme in the ideal scenario. Clearly, with an increasing delay spread we can observe an increasing throughput for the dynamic scheme while the throughput of the static scheme stays constant. The reason for this is that the dynamic scheme can exploit the increasing frequency diversity caused by the increasing delay spread. In contrast, since the static scheme only applies adaptive modulation but has no means to choose from different sub-carriers, the static scheme does not benefit from an increasing delay spread.

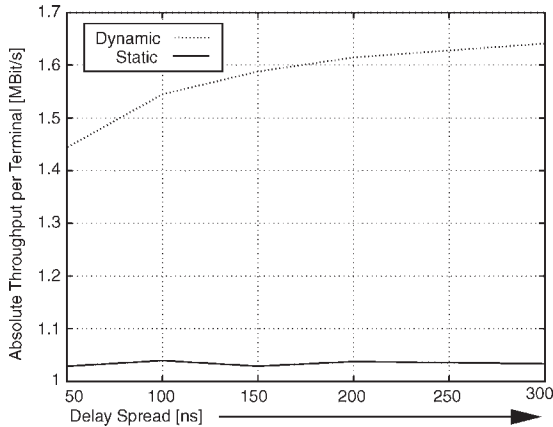


Figure 12. Average absolute throughput behaviour in the case of the ideal scenario for a varying delay spread.

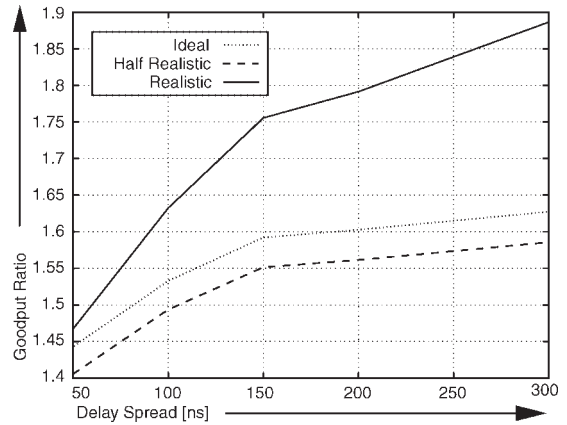


Figure 14. Average goodput ratio for a varying delay spread in the propagation environment of the cell.

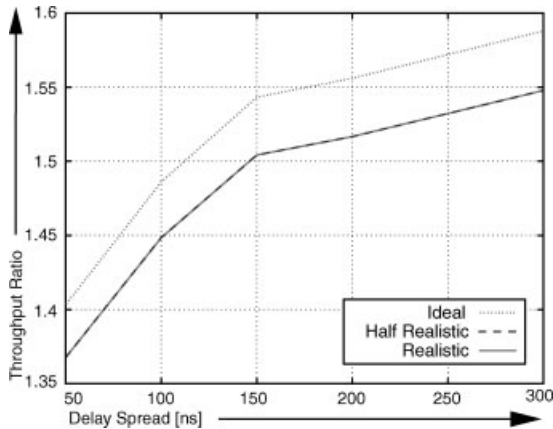


Figure 13. Average throughput ratio for a varying delay spread per sub-carrier in the cell.

Accordingly, the ratio of the throughput, shown in Figure 13, increases roughly from 1.4 for the smallest value of the delay spread, up to 1.6 for the highest value of the delay spread. Including the signalling cost reduces this figure by 0.04 while the usage of realistic channel knowledge has no significant effect on the throughput ratio.

However, the usage of realistic channel knowledge has a significant effect on the goodput ratio, as shown in Figure 14. The qualitative behaviour of the goodput ratio equals the behaviour for the throughput ratio. However, especially in the realistic channel knowledge case, the resulting ratio is significantly higher than in the case with the varying transmit power and the varying number of terminals. The quantitative ratios vary between 1.5 and 1.9 for the goodput. The explanation for this is again the

average estimation error (as shown in Figure 19). The throughput gain of the dynamic scheme is achieved by scheduling higher modulation types more often. These modulation types have a lower average estimation error than the lower ones. Thus, the goodput ratio increases with an increasing delay spread. Note that the absolute goodput decreases for each scheme as realistic channel knowledge is included in the investigation.

4.3.4. Variation of the maximum speed. At last, we present an investigation where the maximum speed of objects within the propagation environment was varied, from $v_{\max} = 1$ up to $v_{\max} = 50$ m/s. Note that a speed of $v_{\max} = 50$ m/s would not match the propagation environment any more, since nothing within a large open space environment would have such a speed. However, since the speed of the objects influences the variability in time of the attenuation of the sub-carriers, this high speed could correspond to a different scenario, where the speed is only increased modestly, but the length of a frame is considerably increased. In this investigation, though, the speed was varied while the frame length was kept constant at $T_f = 2$ ms. Note that the coherence time, resulting from the maximum speed of the propagation environment and the centre frequency of the radio system [9], varies for the chosen values from 12 down to 0.25 ms for the highest speed. Thus, the coherence time of the sub-carriers was longer than the frame length for a speed larger than 6 m/s. The number of wireless terminals was kept constant at 16, while the transmit power equalled -7 dBm per sub-carrier. The delay spread was set to $\Delta\sigma = 0.15$ μ s.

In Figure 15 the absolute throughput behaviour is shown for the ideal scenario in the case of the dynamic and static

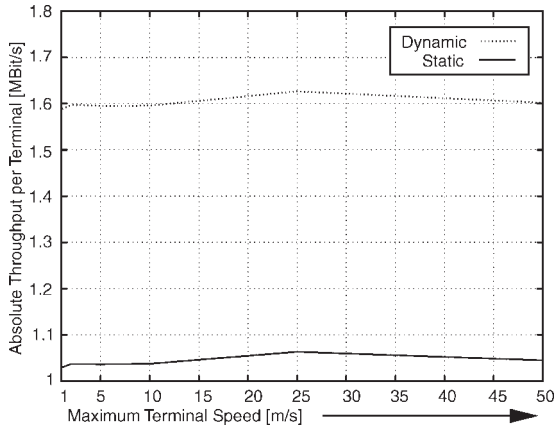


Figure 15. Average absolute throughput behaviour in the case of the ideal scenario for a varying maximum speed.

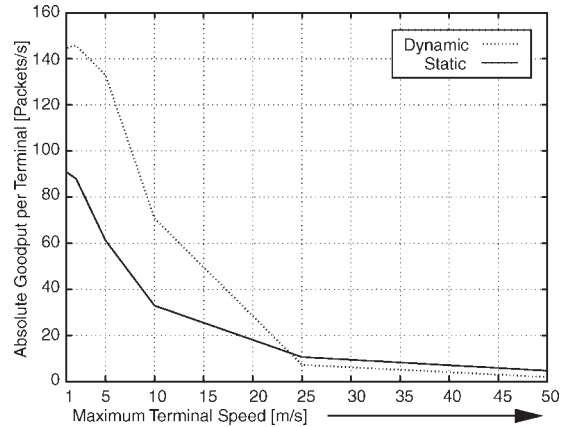


Figure 17. Average absolute goodput behaviour in the case of the ideal scenario for a varying maximum speed.

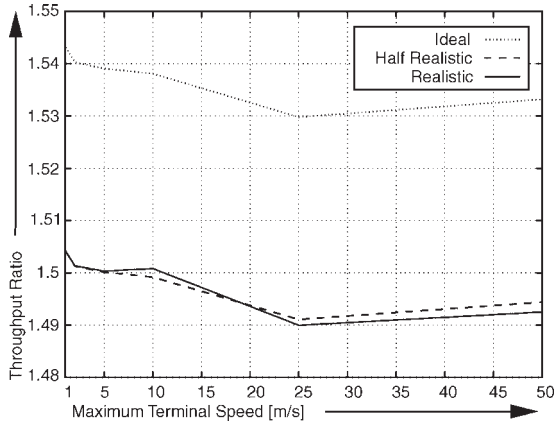


Figure 16. Average throughput ratio for a varying maximum speed in the cell.

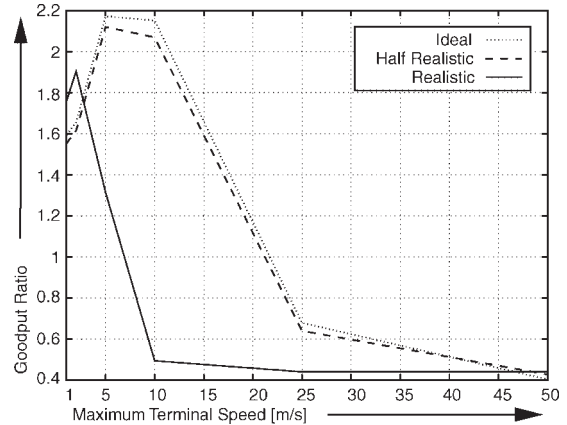


Figure 18. Average goodput ratio for a varying maximum speed in the cell.

scheme. As the speed increases in the system, the average throughput per terminal for both schemes remains the same. Note that with an increasing speed the statistics only change in the time domain. This cannot be exploited by this dynamic scheme; therefore the throughput stays constant (in contrast to the increasing delay spread, where the dynamic scheme was able to exploit the changed statistics in the frequency domain).

In Figure 16, the corresponding ratios are shown for all three scenarios. As it is with the ideal scenario, the ratios stay constant roughly at a value of 1.5 for the other two scenarios. Including realistic channel knowledge leads to no effect for the throughput ratio, including the signalling impact leads to an absolute loss of 0.04 for both ratios.

As we turn now to the results for the goodput, the qualitative and quantitative behaviour does not match the

throughput anymore, in contrast to the previous parameter investigations. In Figure 17 we first show the absolute goodput behaviour for the ideal scenario of the dynamic and static scheme. As the speed increases, the goodput for both schemes drops. Up to a speed of 10 m/s there is still a significant performance difference between the static and dynamic scheme, however for higher speeds the goodput of the dynamic scheme drops below the one of the static scheme. At these speeds the absolute goodput is very low, less than ten packets are correctly received by the terminal on average for both schemes, the packet error rate is therefore unacceptable high (for the dynamic scheme on average 170 packets are transmitted per second, for the static scheme on average 130 packets are transmitted).

Considering the ratio for this scenario, in Figure 18, we observe at first an increase of the ratio up to a maximum

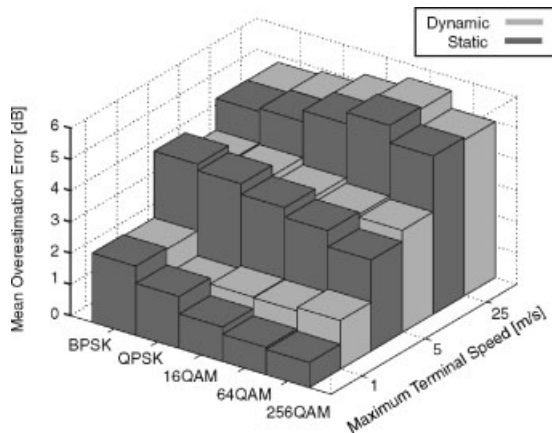


Figure 19. Mean overestimation error (realistic scenario) for each modulation type at three different maximum speeds (1 m/s, 5 m/s and 25 m/s) of the terminals (16 terminals, transmit power of -7 dBm per sub-carrier and a delay spread of $\Delta\sigma = 0.15$ μ s).

ratio point for a speed of 5 m/s, for a higher velocity the ratio drops sharply. Interestingly, at very high speeds the ratio is below 1—the static scheme has a higher goodput than the dynamic scheme. However, at these speed values the absolute goodput is very low (< 10 Pakets/s) in either case anyway.

Switching to realistic channel knowledge leads to a much faster decrease of the ratio. Here, the ratio peaks at a speed of 2 m/s, for a speed higher than 6 m/s the ratio drops below 1 (at 6 m/s the coherence time of the channel is 2 ms). For this speed and higher ones, the absolute goodput (graph not shown here) is very low, resulting again in a very high packet error probability.

This behaviour of the performance ratios can be explained by the average estimation error in case that the channel is overestimated for each modulation type. For low speeds, the estimation error is higher for low modulation types in case of the realistic channel knowledge (Figure 19). If the speed increases now, and thus the variability in time of the channel is increased, this imbalance in the average estimation error is reversed. First of all, for all modulation types the absolute estimation error increases quite a lot from around 1.5 dB on average to 5 dB on average (Figure 19). In addition, the absolute estimation error is now as high for the high modulation types as it is for the low modulation types, which leads to quite a strong performance loss considering the goodput for both schemes. Therefore, a more sophisticated estimation algorithm should reduce the average estimation error with a positive impact for the goodput performance of both schemes.

5. CONCLUSIONS AND FUTURE WORK

This paper studied the question whether or not it pays off to dynamically assign sub-carriers in an OFDM system when the requirements of a realistic system structure—costs for signalling 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 behaviour of the static or dynamic schemes at all. However, by introducing the signalling system, the throughput of the dynamic set up is slightly more reduced (vs. 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 signalling system is still present, we actually find that the benefit of using dynamic sub-carrier assignments is significantly increased if realistic channel knowledge is taken into consideration for low speeds of the terminals. The more realistic assumptions result in a bigger performance loss for the static scheme than for the dynamic one. The resulting improvement over the static scheme is actually larger than with less realistic assumptions, making the case for dynamic sub-carrier assignments even stronger. This effect becomes significant for a high number of terminals in the cell as well as for a low transmit power or for a relatively high delay spread. However, as the speed of the terminals increases, the goodput for both schemes decreases drastically due to severe estimation errors, calling for a more sophisticated channel estimation scheme, if such a system is going to be applied in equivalent propagation environments. This area remains as an issue for future work, together with analytical characterisations of the issues raised in this paper.

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