

Channel State Aware Protocol Framework for Loaded Wireless Multicarrier Systems

Abstract-- To overcome the scarcity in wireless spectrum, multicarrier modulation has been proposed for broadband wireless communications. When the channel varies slowly in time, as is the case for applications with low terminal mobility, adaptive loading greatly improves the system performance. Yet, the resulting link quality still exhibits significant fluctuations and is not adequate for most applications. Therefore, higher layers of the protocol stack have to be made adaptive to cope with and combat these variations. All such adaptive protocols critically rely on channel state awareness. Thus far, this coupling between the protocol layers has only been investigated for single carrier systems, and the extension to complex real systems such as multicarrier ones is yet unexplored. In this paper, we derive a framework that provides channel state information in a loaded multicarrier system. In fact, we prove that a single parameter is sufficient to fully predict the system performance and to provide all the state information needed. We illustrate this both for link layer adaptation and channel-state dependent scheduling, improving the worst-case throughput by more than 50% and virtually eliminating connection losses.

Index terms-- multicarrier, channel state awareness

I. INTRODUCTION

A. Wireless Multicarrier Systems

Multi-media applications are getting more and more prevalent, but typically still depend heavily on a wired connection. The past few years a drive towards untethered access has emerged which critically relies on broadband wireless communications [1][2]. However, the wireless spectrum is a limited resource necessitating highly spectrally efficient modulation schemes. One increasingly popular solution is the use of **Orthogonal Frequency Division Multiplexing (OFDM)** [2][3]. It has been standardized for Digital Audio Broadcast (DAB) and Digital Video Broadcast (DVB). Recently, OFDM was also adopted in the 802.11a [4] and HYPERLAN II [23] standards for Wireless Local Area Networks (WLAN). Flarion has proposed its variant, called Flash OFDM, for 3G systems [5] and CISCO is considering vectored OFDM for digital microwave communications [6].

In a basic OFDM system, the used frequency band is subdivided in a large set of narrow subbands, or subcarriers, which are spaced very closely together. Each such subband carries an independent, low-rate data stream. Because of the large number of such subbands, the aggregate data rate is high. The tight inter-carrier spacing is made possible by moving the multiplexing functionality in the digital domain using a Fast Fourier Transform (FFT) [3]. Besides the resulting high spectral efficiency, its immunity to intersymbol interference is another important benefit of OFDM [1].

The Signal to Noise Ratio (SNR) is not the same on each of the subcarriers, due to frequency selective fading and interference [22][24][25]. It has been recognized that optimizing the power and data rate on each of the subcarriers based on the local SNR greatly improves the system performance, provided that variations in time can be tracked efficiently [2]. Techniques that exploit this observation are known as “**adaptive bit loading**” (in the remainder, we will also refer to them as “adaptive loading”, “bit loading” or simply “loading”) [22][24][25]. Such adaptive loading is not yet included in current standards, but comes as an almost natural extension [24] and has received considerable attention in the research community.

B. Channel State Awareness

The past few years, researchers have realized that optimizing the physical layer by itself does not provide an adequate system solution. Instead, other layers of the protocol stack need to be equipped with awareness of the wireless channel. In a straightforward scheme, the link layer can decide to defer transmission when the quality of the wireless link is below a certain threshold [7]. Other techniques adapt the retransmission policy or the error control to the current state of the channel [8][9]. Also adapting the length of the link layer frames to the varying channel conditions improves the overall performance in terms of throughput or energy consumption [10]. In wireless point-to-multipoint scenarios, the notion of channel state dependent scheduling takes the quality of the links to the different receivers into account [11]. Wireless fair queuing strategies provide methods for compensating for deferred transmissions due to bad links [12][13].

All these techniques require **channel state information** to migrate upwards through the protocol stack. This in effect eliminates the independence between protocol layers and introduces **interaction between lower and higher**

layers. Existing methods to steer the adaptation, include measuring the bit error rate, signal to noise ratio or other performance metrics. Another approach that was taken is to map the physical layer to a simplified channel model, such as a two-state Markov chain [9][10][11][12]. In this case, the appropriate information that is communicated to the higher layers is the current Markov state.

We will show that, even with the performance improvements of adaptive loading, higher layers in OFDM systems still need to be made aware of the state of the physical layer, such that they can adapt to changes in channel conditions. However, the channel characterization schemes that were used for single carrier systems are not well suited for loaded multicarrier systems. First of all, they would have to be performed on each subcarrier separately, resulting in unnecessary (as we will show in this paper) complexity and overhead. Second, it is unclear how these characterizations from the different subcarriers should be combined to result in an adequate representation of the aggregate channel state. The goal of this paper is therefore to provide a compact, efficient and accurate channel state representation for a loaded multicarrier system.

C. Our Contributions

In this paper, we analyze the behavior of a loaded OFDM system and prove that it essentially corresponds to that of a **virtual single carrier system**. In fact, a **single parameter** is able to capture all the relevant information that is required for any higher layer that does not modify the loading itself. Our model is valid when a user is assigned all subcarriers or only a subset of them (as in multi-user OFDM [25]). Also it captures the most general cases where the subcarriers can suffer from correlated or uncorrelated fading, noise and interference [22][24].

The crucial implications of our model towards channel state awareness are two-fold. First of all, in a measurement-based approach, we can **treat the system as a black box** and ignore the fact that it is composed of individual subcarriers. Secondly, we can **estimate this single parameter directly** and use it as a description of the channel state. We will show that this option is preferable, as it is calculated solely based on the output of the loading algorithm. In addition, all metrics of a measurement-based approach could be derived promptly and accurately from this parameter, and as such render measuring these metrics unnecessary.

Our single parameter description is therefore able to provide input to channel aware protocols, such as scheduling algorithms or link layer adaptation, in a much more efficient and accurate fashion than any extension of existing techniques.

II. MULTICARRIER SYSTEM

A. Basic System

A simplified view of a multicarrier system is shown in figure 1. This representation does not correspond directly to the physical implementation, but illustrates the conceptual idea behind a multicarrier system, which is all we require here.

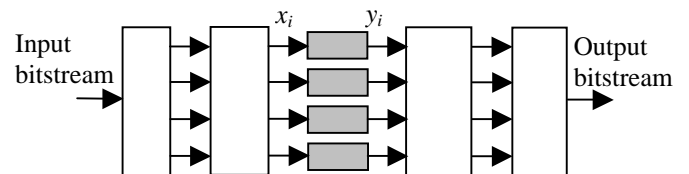


Figure 1: Multicarrier system

To transmit at a high aggregate data rate, an input bitstream is split up into N parallel streams. Each stream, which has a lower data rate, is transmitted in a separate frequency band. These frequency bands are very narrow and spaced extremely close together. In each band, the bits are modulated onto a subcarrier and mapped to transmit symbols x_i [3]. In this notation, i is the subcarrier index. The collection of the symbols on N subcarriers is called an OFDM symbol.

Each of the N frequency bands occupies part of the wireless channel, represented by the shaded boxes. In a typical OFDM system, the part of the channel that corresponds to a particular subcarrier, experiences flat fading and can therefore be represented as in figure 2, for perfect carrier phase estimation [14][15]. Here, α_i is the channel gain factor, which depends on the path loss, shadowing effects and multi-path fading. The noise and interference are denoted by n_i and I_i respectively. Our analysis is valid irrespective of the statistics of these channel parameters $\{\alpha_i n_i I_i\}$ and whether or not they are correlated between subcarriers.

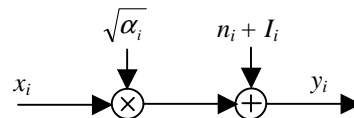


Figure 2: Model for the i^{th} subchannel in a multicarrier system

It is possible that a particular user does not utilize all N subcarriers. As part of a multi-access scheme, subcarriers might be divided between the users [25]. Without loss of generality, we reindex the subcarriers such that the first M are the ones assigned to user under consideration.

B. Performance Expressions

Each subcarrier is modulated independently and, in principle, any modulation scheme can be used. In practice, Quadrature Amplitude Modulation (QAM) is picked in the vast majority of the cases due its excellent behavior and ease of implementation. However, the subsequent analysis and our resulting model are valid for other modulation schemes as well by virtue of a similar derivation. Equations (1)-(2) express the performance of QAM in terms of Symbol Error Rate (SER) as a function of the received SNR for each subcarrier i [14]. It is strictly speaking an approximation, but it is valid for all practical values of SER [14]. We nevertheless refer to it as *approx1*. In these equations, b_i represents the number of bits per symbol, which is called the QAM constellation size. In practical systems, this has to be an integer number. The parameter K_i depends on the number of possible QAM constellation points, as given by (2).

$$SER_i = K_i \cdot Q \left(\sqrt{3 \cdot \frac{SNR_i}{2^{b_i} - 1}} \right) \quad (1)$$

$$K_i = 4 \cdot \left(1 - \frac{1}{2^{b_i/2}} \right) \quad (2)$$

The received SNR on the i^{th} subcarrier is given by (3), where P_i is the transmit power on that subcarrier and β_i is defined in (4) as a function of the channel gain and the noise and interference.

$$SNR_i = \beta_i \cdot P_i \quad (3)$$

$$\beta_i = \frac{\alpha_i}{N_i + I_i} \quad (4)$$

The Bit Error Rate (BER) on the i^{th} subcarrier can be expressed as (5). The only assumption made is that a symbol error results in only one bit error. This is satisfied for all but the largest values of SER, which are not practical system operating points anyway [14]. We refer to this approximation as *approx2*.

$$BER_i = \frac{SER_i}{b_i} \quad (5)$$

In more general terms, we can express b_i as a function of SNR_i [16]:

$$b_i = \log_2 \left(1 + \frac{SNR_i}{\Gamma_i} \right) \quad (6)$$

In this equation, Γ_i is called the gap and measures the SNR loss compared to capacity [16]. It depends on the SER, the coding scheme and the system implementation. In this case of uncoded QAM, it is equal to (7), as can be derived from (1) and (6).

$$\Gamma_i = \frac{\left[Q^{-1} \left(\frac{SER_i}{K_i} \right) \right]^2}{3} = \frac{\left[Q^{-1} \left(\frac{b_i \cdot BER_i}{K_i} \right) \right]^2}{3} \quad (7)$$

C. Adaptive Loading

In the previous subsection, we have presented relationships between the error performance, the channel gain and the transmit power for the i^{th} subcarrier. These relationships are valid for each of the M subcarriers that are assigned to a user.

There is still freedom in assigning P_i and b_i to the individual subcarriers, while taking into account the overall average power and bit rate given by (8) and (9). Typically, one of these is formulated as a constraint, while the other one is optimized for. Adaptive loading algorithms have been designed to optimally perform this assignment.

$$P_{av} = \frac{1}{N} \sum_{i=1}^M P_i \quad (8)$$

$$b_{av} = \frac{1}{N} \sum_{i=1}^M b_i \quad (9)$$

Several loading algorithms have been proposed in literature, which have different tradeoffs of performance versus complexity [16][17][18][19][20][22][25]. All of them recognize that the optimum approach is to assign power and bits in such a way that the performance is the same on each of the subcarriers. This is indeed logical as no subcarrier is more critical than any other in this case, avoiding a bottleneck. Strictly speaking, this would mean that the SER_i is the same (or better yet, the BER_i), but in practice SER_i/K_i or equivalently Γ_i is made constant over the subcarriers.

$$\Gamma_i = \Gamma \Leftrightarrow \frac{SER_i}{K_i} = \frac{SER}{K} \quad (10)$$

It is worthwhile to note that typically some subcarriers are not loaded at all, when it is inefficient for them to carry any information [17]. Those are the ones with the lowest values of α_i . These subcarriers end up with P_i and b_i both

equal to 0. From (2), we see that K_i is equal to zero as well. To simplify our equations, we also define SER_i equal to zero for these carriers, although mathematically it is undefined according to (1).

To be able to assign the number of bits, loading algorithms require knowledge of the SNR on each subcarrier, or equivalently β_i . In practice, channel estimation techniques perform this task [2]. This estimation phase and the loading algorithm itself consume a finite amount of time. Moreover, knowledge about the exact constellation size is needed at the receiver for decoding purposes. Whether the loading algorithm runs at the receiver or at the sender side, this information has to be communicated. The allowable amount of overhead further limits the update rate of the bit loading. OFDM with bit loading therefore makes sense only in those scenarios where the channel time variations are not too fast compared to this update overhead. This is the case for stationary and quasi-stationary applications. At regular intervals, the channel estimation and bit loading need to be updated to avoid excessive performance loss [21]. In the case of a high enough update rate, the channel can be assumed approximately invariant between two updates. When the channel varies too fast, it is impossible to implement adaptive bit loading. Although such multicarrier systems exist, in this paper we explicitly focus on the performance of systems with adaptive loading. This automatically implies that the above conditions are satisfied by assumption.

In addition, in a setting with interfering cells, the bit loading algorithm essentially becomes a distributed assignment problem [22]. What we describe in this paper is the next step after the loading assignment is performed. Once the power and bit are assigned to the subcarriers, either in a link-based or network wide fashion, our model predicts the resulting performance.

III. SINGLE PARAMETER DESCRIPTION

A. Derivation

Although expressions for the performance on each of the subcarriers separately are well known, no existing work has provided a simple expression of the overall performance of a loaded multicarrier system. In this subsection, we analytically derive such an expression and the physical interpretation is treated in the next subsection. We can substitute (3) in (8) to express the average transmit power P_{av} as:

$$P_{av} = \frac{1}{N} \sum_{i=1}^M P_i \quad (11)$$

$$= \frac{1}{N} \cdot \sum_{i=1}^M \frac{SNR_i}{\beta_i} \quad (12)$$

Note that subcarriers that are not loaded have P_i (and thus SNR_i) and b_i equal to 0. Together with (6), (12) becomes:

$$P_{av} = \frac{1}{N} \cdot \sum_{i=1}^M \frac{\Gamma_i}{\beta_i} \cdot (2^{b_i} - 1) \quad (13)$$

Since loading algorithms all satisfy (10), we get:

$$P_{av} = \frac{\Gamma}{N} \cdot \sum_{i=1}^M \frac{(2^{b_i} - 1)}{\beta_i} \quad (14)$$

To simplify this expression, we define a new parameter δ as:

$$\delta = \frac{2^{b_{av}} - 1}{\frac{1}{N} \cdot \sum_{i=1}^M \frac{2^{b_i} - 1}{\beta_i}} \quad (15)$$

By directly substituting δ in (14), we can rewrite it as:

$$P_{av} = \Gamma \cdot \frac{(2^{b_{av}} - 1)}{\delta} \quad (16)$$

Note that rewriting (14) to (15)-(16) is simply an algebraic substitution. No assumptions or simplifications are made. We reorder this expression, such that b_{av} for the overall loaded system is given by (17).

$$b_{av} = \log_2 \left(1 + \frac{P_{av} \cdot \delta}{\Gamma} \right) \quad (17)$$

Because of (10), and in analogy with (7), we can express Γ as (18).

$$\Gamma = \frac{\left[Q^{-1} \left(\frac{SER}{K} \right) \right]^2}{3} \quad (18)$$

Consequently, (17) and (18) are combined to yield (19).

$$\frac{SER}{K} = Q \left(\sqrt{3 \cdot \frac{\delta \cdot P_{av}}{2^{b_{av}} - 1}} \right) \quad (19)$$

In addition, the total number of bit errors in an OFDM symbol is given by (20), assuming as before that a symbol error causes exactly one bit error. In this expression, BER is the average bit error rate of the entire OFDM symbol.

$$\begin{aligned} BER \cdot (b_{av} \cdot N) &= \sum_{i=1}^M BER_i \cdot b_i \\ &= \sum_{i=1}^M \frac{SER_i}{K_i} \cdot K_i \end{aligned} \quad (20)$$

Note again that the unloaded subcarriers have no contribution to this sum. Since $I_i = I$, we can further manipulate this equation based on (10):

$$BER \cdot (b_{av} \cdot N) = \frac{SER}{K} \cdot \sum_{i=1}^M K_i \quad (21)$$

By combining (19) and (21), we get:

$$BER = \frac{1}{b_{av} \cdot N} \cdot \left(\sum_{i=1}^M K_i \right) \cdot Q \left(\sqrt{3 \cdot \frac{\delta \cdot P_{av}}{2^{b_{av}} - 1}} \right) \quad (22)$$

Or alternatively, the overall bit error rate is given by:

$$BER = \frac{K}{b_{av}} \cdot Q \left(\sqrt{3 \cdot \frac{\delta \cdot P_{av}}{2^{b_{av}} - 1}} \right) \quad (23)$$

$$K = \frac{1}{N} \cdot \sum_{i=1}^M K_i \quad (24)$$

The two expressions above, together with (15) describe the behavior of the loaded multicarrier system analytically. We will refer to this as our **level-1 model**. It only uses *approx1* and *approx2*. Equation (23) suggests that the BER is uniform, which is not exactly true. Since only the gap is same for the various subcarriers, the BER_i is not exactly equal. Nevertheless, the differences are small, and virtually insignificant at the system operating points of interest. As a result, the overall BER, given by (23), can be considered as being uniform for practical purposes. We have verified this statement through extensive simulations.

In addition, it is well recognized that the impact of K in expressions such as (1) and (23) is minor [14]. We propose to replace K by K' defined as in (25). This approximate expression is obtained by replacing b_i in (2) by b_{av} . This not only simplifies calculations, but also ties much better into the physical interpretation of our model, which we will discuss in the next subsection. We refer to this as our **level-2 model**. Note that in this case, the entire system behavior is condensed into the single parameter δ , as K' does not depend on the loading or channel anymore.

$$K' \stackrel{\Delta}{=} 4 \cdot \left(1 - \frac{1}{2^{b_{av}/2}} \right) \quad (25)$$

To validate our model and the subsequent adaptation strategies, we have resorted to extensive and detailed simulations. As we explained before and is apparent from the above derivation, our model is valid irrespective of the specific channel, interference, or subcarrier assignment to the different users. Due to space limitations, all simulations in this paper are for a specific, but common type of OFDM system: the user is assigned all carriers ($N = M$), the channel gain factors correspond to uncorrelated (unless noted otherwise) Rayleigh fading, there is no interference, and the noise is additive white Gaussian with average power P_n [14]. However, we have verified that our entire analysis remains valid for other channel statistics, multiuser OFDM [25], and inter-cell or other interference. Furthermore, we selected the loading algorithm proposed in [20], which is a modification of the Hughes-Hartoghs algorithm [17]. It assigns the bits and power to each subcarrier such that the power is minimized for a given data rate specification (i.e. b_{av} is specified as a constraint). Again, the validity of our approach does not assume a particular algorithm, and we chose this one solely for illustration purposes.

Figure 3 illustrates the accuracy of the analytical model we derived in this subsection. The curves for our level-1 and level-2 model are generated in the following way. After bit loading, δ is calculated from (15) based on the bit assignments and channel estimation. The BER curve is obtained directly from (23). On the other hand, the 'bit true' curve is completely based on bit-true simulations of the loaded system without any approximations. In these simulations, the multicarrier system has $N = 100$ and the target bit rate is specified as $b_{av} = 4$ bits/symbol. As a reference, the curve for an unloaded multicarrier system over the same channel is shown, together with the performance of an AWGN channel.

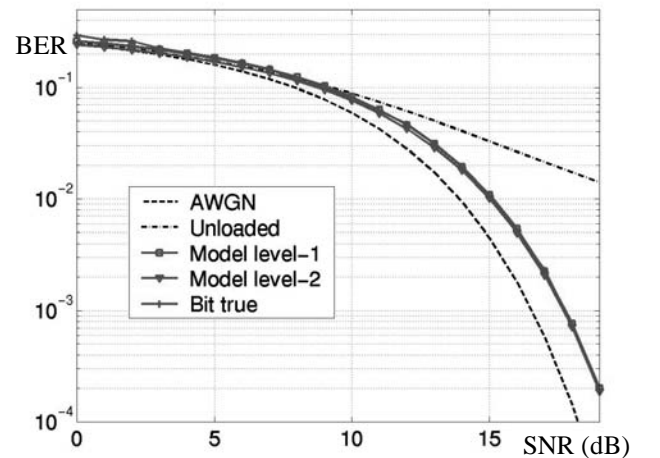


Figure 3: Performance assesment of our model

It is clear that adaptive loading indeed greatly improves the system performance compared to the unloaded case. Our level-1 model behaves as expected. The small discrepancy at high BER is due to *approx1* and *approx2*. We also observe that our level-2 model is very accurate, despite the arbitrary definition of K . We build further upon this level-2 model in the remainder of this paper.

B. Interpretation

We have shown that the performance of the loaded multicarrier system can be nicely predicted with our level-2 model. We only need to calculate one parameter δ , which depends on knowledge of the bit assignments b_i and of β_i (which are needed for the loading algorithm in the first place). **This parameter δ is independent of the transmit power, and therefore characterizes the entire BER-SNR curve in just one number.**

From (23), we see that the behavior of the loaded multicarrier system is equivalent to that of a single carrier system, where the SNR is given by δP_{av} . It completely expresses the BER performance as a function of the transmit power and target bit rate. The specifics of the N parallel subcarriers and the bit loading are hidden inside the parameter δ . Since δ does not depend on the transmit power, it is also clear that for a particular wireless channel there is a fixed power penalty compared to the AWGN channel with the same P_{av} and b_{av} . This can be verified from figure 3. The original unloaded multicarrier system does not have that property, as is apparent from that same figure 3. Adaptive loading therefore in effect ‘whitens’ the channel.

As we have discussed before, bit loading only makes sense in scenarios where the channel varies slowly enough, such that the channel gains remain virtually constant between updates. As a consequence, our model has a practically constant δ between two loading updates.

C. Applicability

Higher layers can thus consider the loaded OFDM system as a black box and all procedures to measure performance metrics can be borrowed from single carrier systems with only minor modifications. For example, only the overall BER needs to be estimated, instead of on each subcarrier separately. However, obtaining an accurate estimation requires sufficiently long time averaging. This introduces extra latency, which can in term reduce the accuracy as the channel varies in time.

On the other hand, our results also show that we can perfectly predict the BER analytically using (23) if we know the value of δ . Once the loading algorithm has been executed, δ can be calculated immediately. This parameter is only a function of b_i and α_i , the outputs and inputs of this

algorithm respectively. As a result, no additional estimation phase is required, and therefore no extra latency is introduced. Overall, this approach is more accurate than estimating the BER directly. Note that parameter δ remains valid between loading updates, as long as it is updated together with the loading. As we will show next, this ensures that it tracks the channel time variations over longer time time-scales.

IV. CHANNEL STATE AWARE TECHNIQUES

In this section, we illustrate the usefulness of our single parameter description in providing channel state information. As examples, we focus on frame length adaptation and scheduling, but these benefits extend to other link, network, transport and application layer protocols.

A. Channel State Dependent Scheduling

For our discussion on channel state dependent scheduling, we consider the setup of figure 4. Transmitter A, which could be a basestation in a wireless LAN for example, has two possible wireless receivers B and C. As part of the medium access, A has to decide when it transmits to each of its receivers, a problem that is known as packet scheduling. We choose a scheme where the transmissions to different users are separated in time. The model we discussed in the previous subsection is also useful if the subcarriers are divided between the users as in multi-user OFDM [25].

It has been recognized that due to the time-varying wireless channel, the scheduling should take into account the channel state [11]. When the transmission quality turns bad, the channel state dependent scheduling defers scheduled transmissions until the next good period. Clearly, it is critical to be able to monitor the channel state. Existing research has mostly assumed a simple channel model, such as a 2-state Markov chain, which is inadequate for multicarrier systems [11][12].

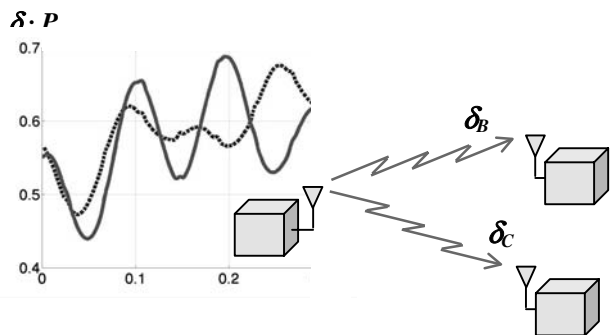


Figure 4: Scheduling in a broadcast system

We propose the following new approach:

1. *A* periodically sends out training symbols. The two receivers estimate the channel response and locally perform the bit loading. With this knowledge, they also calculate their instantaneous value of δ .
2. *B* and *C* send their value of δ back to *A*.
3. As δ_B and δ_C completely describe the BER performance, the scheduling algorithm running in *A* decides who will be the recipient of the next transmission (let us assume it is *B*) and broadcasts this information.
4. *B* sends the information on the bit loading to *A*.
5. *A* sends the data to *B* using the specified bit loading.

Note that the receivers that are not scheduled only need to send their value of δ to *A* and not the full information on the bit loading. This saves on protocol overhead.

In figure 4, we have also illustrated how the δ might vary over time in a practical system. These curves are for a time varying channel for a Doppler shift of 25 Hz, based on Jakes model [15]. The other simulation settings are listed in Table I. The fading on the subcarriers is chosen to be uncorrelated. For the selected update rate, the bit loading and δ are updated every 5000 symbols and remain approximately constant during these intervals. Over time spans of tenths of seconds, variations are dictated by the Doppler rate. Figure 4 illustrates this phenomenon with simulated profiles of δ for both *B* and *C*. As the channels between these two receivers are independent [15], so are the δ profiles.

Table I: Simulation settings

N	100 (uncorrelated)	f_{Doppler}	25 Hz
b_{av}	4 bits/symbol	f_{update}	3200 Hz
P_{av}/P_n	20 dB	R_s	16 Mbaud

B. Link Layer Frame Length Adaptation

As mentioned before, the loaded multicarrier system basically offers the services of a physical layer in the OSI model. In order to send data over a wireless channel, the bits need to be grouped into link layer frames and scheduled for transmission. The size of these frames needs to be optimized for the characteristics of the underlying channel. Higher layer packets, like IP datagrams, typically are fragmented and reassembled to fit into the link layer frames.

It has been recognized that operating with a fixed frame length over an inherently variable wireless channel is inefficient [10]. Instead, this frame length can be made adaptive based on the momentary channel condition.

Frame length adaptation inherently exploits the tradeoff between overhead and loss rate. In our discussion here, each frame has a cyclic redundancy check (CRC) to determine when it contains errors. Since there is no correction capability in this case, a single bit error leads to the entire frame to be dropped. Smaller frames have therefore a higher change of making it through. Each frame, however, contains a fixed header overhead, such that in relative terms this overhead increases with decreasing frame length.

We denote the length of the frame's data field and header field by L and H respectively. With these definitions, the frame error rate (FER) can be expressed as:

$$FER = 1 - (1 - BER)^{L+H} \quad (26)$$

For practical values of BER, equation (27) provides a tight approximation.

$$FER \approx (L + H) \cdot BER \quad (27)$$

The measure of interest here is called the 'goodput', which is the actual data rate offered to the higher layers [10]. It therefore takes into account the fact that header overhead and the erroneous transmissions do not constitute actual data. Equation (28) expresses the goodput T in terms of bits per second, as a product of three terms. The first one is the total number of frames per second (R_s is the total symbol rate on the channel), the second one is the fraction of good frames and the third one is the number of useful bits per good frame.

$$T = \left(\frac{R_s \cdot b_{\text{av}}}{L + H} \right) \cdot (1 - FER) \cdot L \quad (28)$$

Or after substituting (27) in the above expression:

$$T = R_s \cdot b_{\text{av}} \cdot L \cdot \left(\frac{1}{L + H} - BER \right) \quad (29)$$

The data field size L_{opt} that maximizes this T and the corresponding optimal goodput T_{opt} are given by (30) and (31) respectively.

$$L_{\text{opt}} = H \cdot \left(\frac{1}{\sqrt{H \cdot BER}} - 1 \right) \quad (30)$$

$$T_{opt} = R_s \cdot b_{av} \cdot \left(1 - \sqrt{H \cdot BER}\right)^2 \quad (31)$$

The above expressions are valid for any single carrier system. Since we have shown in section III that a loaded multicarrier system can be modeled as a virtual single carrier one, these expressions remain valid.

For our analysis, we decouple the link layer and physical layer adaptation. This means that the adaptive loading is not aware of any frame length adaptation. More precisely, the value of b_{av} is kept constant and the loading algorithm only reacts to changes in the channel. From (15), it is clear that the value of δ varies accordingly.

We investigate a point-to-point link over a time varying wireless channel. The actual bit loading and frame length adaptation algorithm can run at either the sender or the receiver and the resulting assignments need to be communicated to the other side [2]. Each time the adaptive loading is updated, δ is calculated as well. With this knowledge, the BER can be estimated using (23) and plugged into (30) to generate L_{opt} .

Figure 5 depicts the profile of δ that resulted from one of our simulation runs. The settings for the channel are again those of Table I. Figure 6 illustrates how L_{opt} is adapted over time. The possible values of L_{opt} are quantized to multiples of 32 bits. The header size H is set equal to 32 bits.

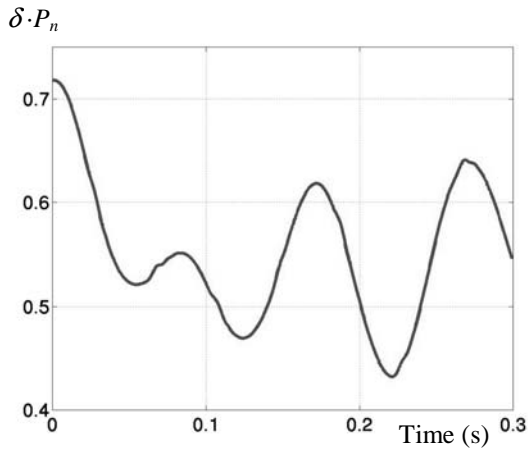


Figure 5: Time varying channel

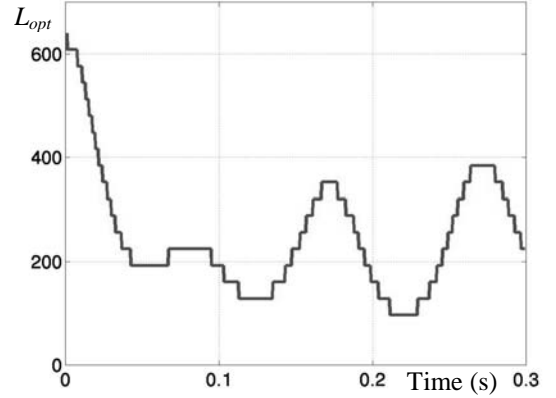


Figure 6: Adaptive frame length

The normalized throughput is shown in figure 7. For comparison, we have also added the throughput in the case a fixed frame length of 416 bits would have been chosen. It is clear that without frame length adaptation, severe throughput variations still occur despite the adaptive loading. The main benefit of frame length adaptation is smoothing out these dips.

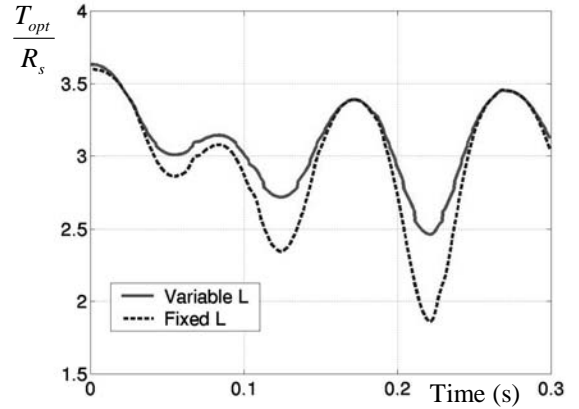


Figure 7: Throughput variation

Our results illustrate that the adaptation can be based on the single parameter δ . In practice, adapting the frame length does not have to involve evaluating expressions (23) and (30). Instead, we can implement the following procedure:

1. Calculate δ from (15), preferably in the log-domain

2. A table is stored that maps values of δP_{av} into the appropriate L_{opt} . A table look-up therefore suffices here.

Finally, we extend our analysis towards more quantitative results. To this end, the performance improvements of frame length adaptation in an OFDM system are averaged over 5,000 simulation runs. In this case, we have chosen a channel that exhibits correlated Rayleigh fading and additive white Gaussian noise. The channel has an exponential power delay profile with an RMS delay spread τ_{RMS} of 0.5 μ s [2]. This results in a correlation bandwidth of about 2 subcarriers [14]. The other settings are again the same as before.

Figure 8 shows the cumulative distribution of the BER as obtained from (23). We have verified through bit true simulations that this curve is indeed accurate. The distribution of the optimal packet is presented in figure 9. Again, we wish to compare the performance to that of a system with a fixed frame size of 416 bits. The resulting normalized throughput is given in figure 10. It is clear that frame length adaptation **almost completely eliminates the severe drops in throughput** performance. In fact, the 1 percentile worst case improves from 0.7 bits/symbol to 1.2 bits/symbol, while the 5 percentile increases from 1.5 bits/symbol to 2.3 bits/symbol.

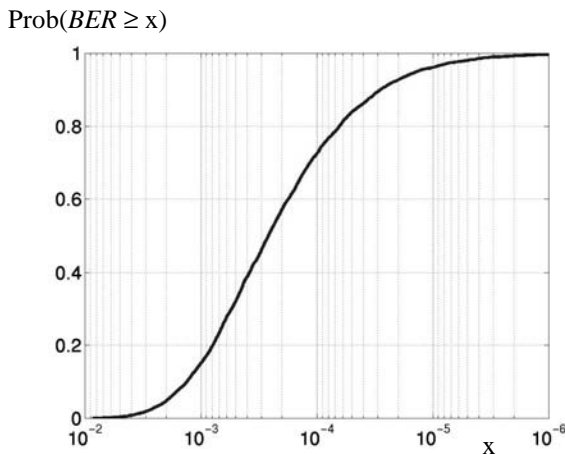


Figure 8: Cumulative distribution of the BER

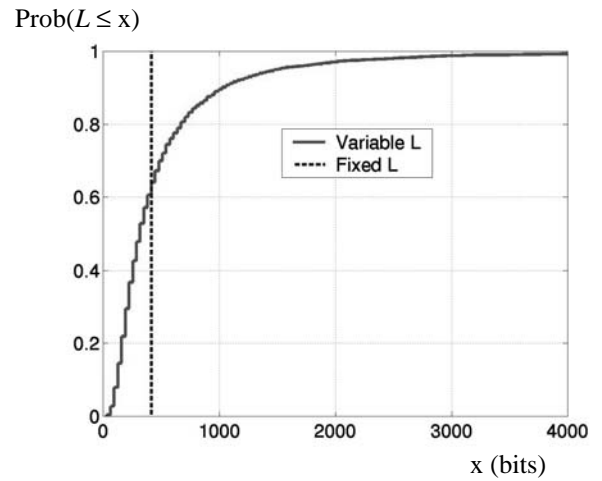


Figure 9: Cumulative distribution of the frame size

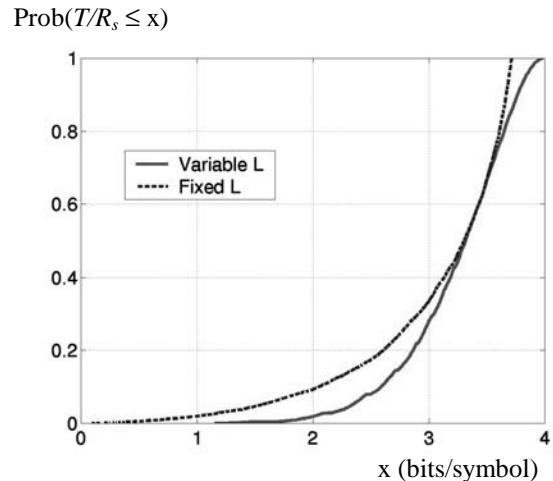


Figure 10: Cumulative distribution of the throughput

Indeed, the worst-case throughput is often the critical performance metric, rather than the average value. The upper layers essentially perceive a very small throughput value as a loss in connectivity. This can have several detrimental effects, such as loss of transmit state and need for re-initialization. For example, in this case, the occurrence of a throughput below 1 bits/symbol is eliminated using frame length adaptation, compared to a probability of 1.9% otherwise. For a threshold of 2 bits/symbol, the probability decreases from 9.3% to 1.8%.

V. CONCLUSIONS

When channel variations are slow enough such that they can be tracked efficiently, OFDM systems greatly benefit from adaptive bit loading. We have proven that the performance of such a loaded multicarrier system can be predicted with a single parameter that is independent of the SNR. This model is valid for whether or not the noise and fading are correlated or uncorrelated between subcarriers, and whether or not interference is present.

We have also shown how we can calculate this parameter based on the inputs and output of the loading algorithm. As a result, we have to our disposition a very compact description of the state of the physical layer that can be calculated on the fly. To improve the overall system performance, higher layer protocols need to be channel aware. Our compact description of the channel state is a valuable component in this interaction between higher and lower layers. We have illustrated its usefulness in channel state dependent scheduling and in steering link layer frame length adaptation.

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