

# Adaptive loading strategy for a high speed OFDM-based WLAN

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## Abstract

Wireless LANs based on OFDM are limited in their performance by the dips in the frequency spectrum of the indoor multi-path channel. To simulate performance, we first derive a simplified channel model from a ray-tracing analysis of the indoor channel. The performance of OFDM-based WLANs can be augmented by adaptive loading of the subcarriers, which has shown to be very valuable for DMT modems on wired media (for example in ADSL). In this paper, we investigate the application of adaptive loading to a 100 Mbit/s OFDM-based wireless LAN. From the different adaptive loading algorithms, the Fischer et al. algorithm is selected because it offers computational advantages for similar performance. This algorithm is then integrated in a complete system by implementing a channel and noise power estimation. Simulations show that the proposed adaptive loading strategy improves the system performance considerably (6 dB gain for a BER=10<sup>-2</sup>). Moreover, the simulations confirm that the simplified channel model is a reliable description of the indoor channel.

## 1 Introduction

Wireless LANs show the clear advantages over their wired counterparts that they reduce the initial wiring effort and allow much more flexibility. However, to become really competitive with traditional LANs, they require higher data rates than what they currently offer, and thus a very efficient usage of the available capacity is needed. For the topology of such a WLAN we envision a star-configuration consisting of relatively large cells, e.g. a corridor in an office environment. In order to limit propagation losses for such a topology, the target frequency bands should not be very high (probably in the 2-3 GHz or 5-6 GHz bands). As a modulation technique for the WLAN, we chose OFDM (Orthogonal Frequency Division Multiplexing), because of its ability to mitigate ISI by introducing a cyclic prefix, its promising multiple-access possibilities and its flexibility. A prototype OFDM-modem ASIC is under development at IMEC at the moment [1]. The simulations presented in this paper are based on the concept of this OFDM-modem. Applying adaptive loading on top of OFDM-modulation is one means to increase the capacity usage of the WLAN and mitigate the effects of Rayleigh fading. This paper presents such a system and analyzes its performance.

The organization of this paper is as follows. The second section proposes an indoor channel model following a

geographical approach based on ray-tracing. Therefrom, we derive time and frequency domain responses for a typical office environment. A corresponding simplified channel model is deduced for simulation efficiency. Section 3 describes several adaptive loading algorithms, which are evaluated in terms of their performance, implementation complexity and practical implications. The Fisher et al. algorithm [6] is selected over the alternatives. Section 4 describes the integration of the selected algorithm in a complete system, by implementing a practical channel and noise power estimation which provide the input for the adaptive loading. Simulation results are given for the different steps in the algorithm, and the resulting BER-performance is compared with the results without adaptive loading. Finally, section 5 summarizes the most important conclusions and gives a view on the future work.

## 2 Channel model

It is of primordial importance to first dispose of a reliable model for the wireless indoor channel, in order to be able to give a realistic estimate of the system's performance, based on simulation results. Especially when investigating adaptive loading, the results are heavily dependent on the specific channel characteristics, and a reliable model for the channel response is a necessity. The following aspects are important for the indoor propagation modeling approach:

- on the one hand, the indoor channel should be modeled as close to the actual propagation phenomena as possible,
- on the other hand, it is not necessary to obtain an exact channel response which takes all geometrical details and propagation effects into account.

Taking into account the above considerations, a ray-tracing technique on a 'higher' level (only modeling of the walls and not of different obstacles) was considered to be the best approach for a sufficiently accurate (yet time-consuming) model of the channel

A typical corridor in an office environment is taken as the geometrical input for the ray-tracing algorithm. This input corresponds with the topology we propose for a WLAN. Figure 1 shows a typical output of the implemented algorithm and displays the different propagating waves. We take multi-path components into account up to a certain threshold for the power loss (which was 30dB lower than the power of the first ray for the presented example). The transmitter (T) is located in

the middle of the corridor, while the receiver (R) is situated in one of the office rooms. Solid lines display the walls, while all dotted lines represent propagation paths.

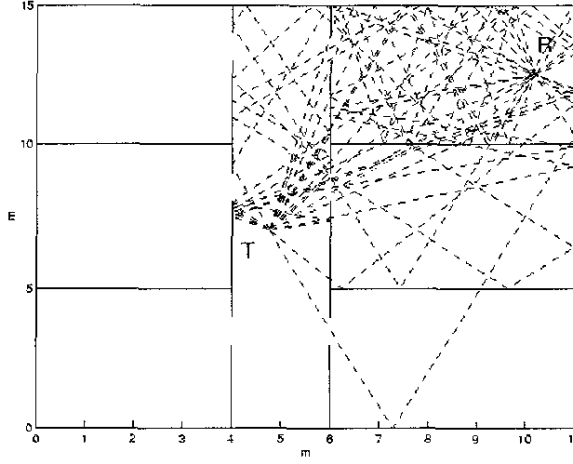


**Figure 1:** Typical ray-tracing output

The above picture shows that a lot of reflections take place in the indoor environment and consequently a large number of multi-path components arrive in the receiver. The channel impulse response in the time domain will clearly consist of a number of discrete pulses. The resulting power delay profile is given in figure 2.

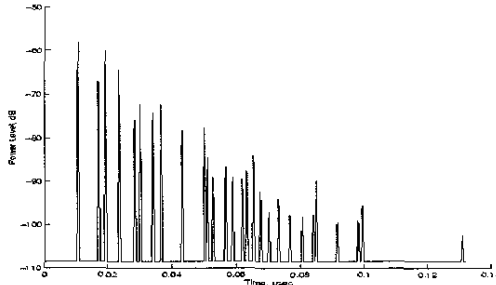


**Figure 2:** Power delay profile

Simulation results show that the delay spread in this environment varies between 10 and 40 ns. The delay differences between subsequent multi-path components are in the order of 0.1 ns. From the simulation result, the channel transfer function in the frequency domain was calculated by simply taking the FFT transform. The result is presented in figure 3. This frequency response shows a very good agreement with measurement data in a similar environment [2]. It is clear that the indoor propagation channel is frequency selective, with a coherence bandwidth in the order of 5 to 25 MHz. From this observation, we can conclude that using a flat fading model is not reliable for the envisaged bit rate of 100 Mbps, and it should be possible to improve the system's performance by exploiting frequency diversity. Dips in the spectrum of up to 30 dB are perceived, meaning that

the transmission in these frequency bands will be degraded dramatically.

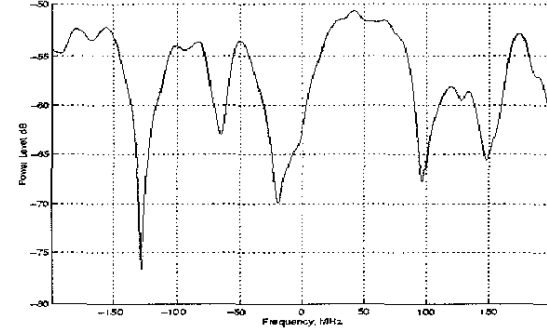


**Figure 3:** Frequency response

The ray-tracing results also confirm that the channel responses for receivers (or transmitters) separated over distances of at least  $\lambda/2$ , are completely uncorrelated.  $\lambda/2$  is 6 cm for a frequency of 2.4 GHz which means that this constraint is met in all practical multi-user situations. This result is important in the view of applying adaptive loading in a multiple user situation, as we plan to do in a next step.

From the analysis of the indoor propagation channel, a simplified channel model was deduced which can generate equivalent power delay profiles (and thus also channel transfer functions) without going through the rather extensive ray-tracing step. The time domain response  $h(t)$  is approximated by a sum of impulses with random phases and with amplitudes that are on the average exponentially decaying. The exact mathematical expression is given by:

$$h(t) = \sum_{i=1}^M A_i \delta(t - i\Delta\tau) e^{j\phi_i} \quad (1)$$

$$\text{with,} \quad A_i = \exp(-a \cdot i \cdot \Delta\tau) \cdot (1 + \rho_i) \quad (2)$$

$$\rho_i = v \cdot s_i \text{ and } s_i = \text{uniformly distributed } [-1 \dots 1]$$

$$\phi_i = \text{uniformly distributed } [0 \dots 2\pi]$$

where  $a = 1/\sigma_{RMS}$  with  $\sigma_{RMS}$  the delay spread on the channel,  $v$  is a parameter for the variation on the amplitudes of the multi-path components,  $\Delta\tau$  gives the resolution between different multi-path components, and  $T_m = M \cdot \Delta\tau$  is taken to be 4 times the delay spread. Specific values and typical ranges for the parameters of the model are derived from the geometrical analysis, giving the following results:

$$\sigma_{RMS} \sim 10 \dots 40 \text{ ns} \quad (3)$$

$$v \sim 0 \dots 1 \quad (4)$$

$$\Delta\tau \sim 0.1 \dots 5 \text{ ns} \quad (5)$$

Channel responses generated by this simplified model, show a very good correspondence with the results from the ray-tracing algorithm, as will be shown further in section 4.

### 3 Adaptive loading algorithms

Generally speaking, about 1% of the carriers have an attenuation that is 20dB below the average and about 0.1% of the carriers attenuate 30 dB below the average. Since transmission over this carriers is severely degraded ( $BER \approx 0.5$  for the 30dB dips at moderate SNR), these carriers determine the performance, which can be achieved with OFDM. Therefore, adaptively loading the carriers seems an interesting means for increasing the capacity usage on the channel. By measuring the channel and identifying dips and peaks in the spectrum, the transmission can be optimized. In particular, adaptive loading adjusts the number of bits assigned to a specific carrier, to the SNR of this carrier. Capacity can be achieved by distributing the energy according to the waterfilling distribution [9]. However, this distribution is difficult to compute and assumes infinite granularity in constellation size. Different practical (but sub-optimal) adaptive loading algorithms have been proposed in the ADSL-context.

The Hughes-Hartogs [3,4] algorithm allocates bits one by one, each time selecting that carrier for which transmission of an additional bit can be done with the smallest additional transmit power for a requested BER. Unfortunately, this strategy is too complex for a practical implementation in the envisaged high speed WLAN, since it asks for comprehensive sorting. The algorithmic complexity for Hughes-Hartogs is proportional to  $O(R_{\text{total}} \times N_c)$ , with  $R_{\text{total}}$  the total number of bits to be assigned and  $N_c$  the number of carriers.

A second loading algorithm, proposed by Chow et al. [5], focuses on a rate distribution according to the capacity of the subchannels. The bits are assigned as follows:

$$R_i = \log_2 \left\{ 1 + \frac{S_i}{N_i \cdot (\Gamma + \gamma_{\text{margin}})} \right\} \quad (7)$$

where  $S_i$  is the signal power,  $N_i$  the equivalent noise power and  $R_i$  the transmission rate of carrier  $i$ . The algorithm is based on the 'gap approximation'. The noise margin  $\gamma_{\text{margin}}$  is determined iteratively to make sure that the total bitrate equals the targeted bitrate. The SNR gap  $\Gamma$  is a constant which estimates the difference between channel capacity and the actual capacity usage by the transmission scheme. The complete transmission system is characterized by this single parameter. This algorithm does not rely on comprehensive sorting and is therefore computationally less expensive than the Hughes-Hartogs algorithm. The worst case algorithmic complexity here is only proportional to  $O(I \times N_c + 2N_c)$ , where  $I$  equals the maximum number of iteration steps which is allowed.

While the algorithm of Chow et al. tries to maximize the usage that is made of the channel capacity, in our practical case, we try to transmit at a given data rate (determined by the application) with a minimal achievable bit error rate. This reasoning forms the basis of the algorithm that was proposed by Fischer et al [6].

Rate and power are distributed over the different carriers in order to minimize the BER at a constant total bitrate  $R_T$  and transmit power. The bits in this algorithm are assigned according to the formula shown in (8).

$$R_i = \frac{R_T}{D} + \frac{1}{D} \cdot \log_2 \left( \frac{\prod_{i=1}^D N_i}{N_i^D} \right) \quad (8)$$

This bit assignment is done iteratively since  $R_i$  as calculated by (8) may become negative and those carriers have to be excluded.  $D$  equals the number of carriers that are still included in a specific iteration. The algorithm iterates until the target rate is reached and all rates of the remaining channels are positive. The worst case algorithmic complexity is comparable to the previous algorithm, but the computations required for the Fischer strategy are a lot simpler. Computationally, it is the least expensive, making it especially suitable for high-speed data transmission. Furthermore, the performance of this algorithm is shown in [6] to be superior or at least equivalent to the other ones in terms of achievable BER. The Fischer et al. algorithm was therefore chosen as being the most appropriate for the high speed WLAN case.

#### 4 An adaptive loading system for WLAN

In order to investigate the effect of adaptive loading on the performance of a high speed WLAN, we simulated the algorithm of Fischer et al. for both the ray-tracing and the simplified channel model. All simulations are based on an OFDM modem, which uses 256 carriers and a 8 bit cyclic prefix for coping with ISI and ICI.

The first step that is required in any loading technique, is an estimation of the noise powers and the attenuations on all carriers. We accomplish this by sending a BPSK-modulated PN-sequence 4 times over the channel. Both the attenuation and the noise power estimation are based on these reference symbols. Let  $r(i)$  be the signal received on the  $i$ -th carrier. Formula (9) gives the output of the OFDM demodulator (i.e. the FFT), provided the length of the guard interval was chosen to be longer than the delay spread of the channel:

$$r(i) = PN(i) \cdot H(i) + N(i) \quad (9)$$

where  $H(i)$  stands for the complex channel attenuation factor (i.e. the FFT of the channel impulse response  $h(t)$ ) and  $N(i)$  stands for the complex additive white Gaussian noise on carrier  $i$  with noise power  $N_0(i)$  on carrier  $i$ . We take the average of the channel estimations obtained for each PN-sequence. This reduces the noise power of the estimation for each carrier by a factor 4. We deduce the channel attenuation estimation  $\hat{H}$  from:

$$\hat{H}(i) = \text{avg}\{r(i) \cdot PN(i)\} \quad (10)$$

$$= H(i) + \text{avg}\{N(i) \cdot PN(i)\} \quad (11)$$

Here,  $\text{avg}\{.\}$  means taking the average over the 4 PN-sequences that were sent. Figure 2 shows the spectrum of

a channel generated by the simplified model of section 2, together with the unfiltered channel estimation.

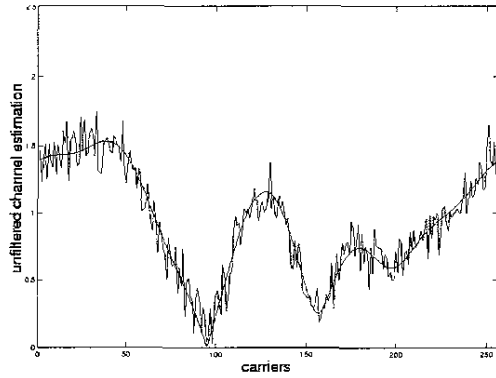


**Figure 4:** Unfiltered channel estimation

To further diminish the estimation noise power and obtain a better estimation  $\hat{H}_f$ , we apply a lowpass filter to the channel estimation. Following a property of the FFT for finite time signals, the spectrum of  $H(i)$  is equal to  $h(-t) + n(-t)$ , which only has signal components up to  $T_m$ . The rest of the spectrum of  $H(i)$  (up to  $NT$ ) only contains noise contributions and can be filtered away. This decreases, in the case of an ideal filter, the noise power of the carrier attenuation estimation by a factor  $T_m/NT$ . However, a simple lowpass filter, based on the mean filter, was used for reasons of complexity. Figure 5 shows a typical result for the filtered channel estimation.

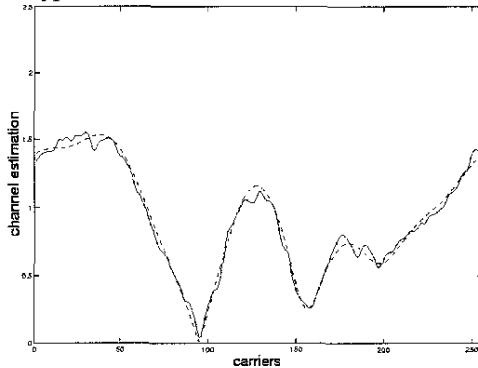


**Figure 5:** Filtered channel estimation

Figure 6 shows the performance of the different steps in the estimation in terms of MSE. The final (filtered and averaged) attenuation estimation achieves a MSE of  $10^{-2}$  for 6dB of  $E_b/N_0$ . A further reduction of MSE is possible by using better filtering at the expense of complexity. Alternative channel estimation strategies are also possible [7][8].

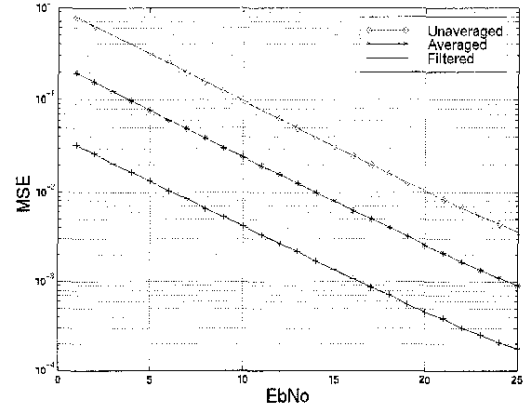


**Figure 6:** Performance of the estimators

The noise power estimation  $\tilde{N}$  is obtained in a similar manner

$$\tilde{N}(i) = \text{avg} \{ |r(i) - \tilde{H}_f(i) \cdot PN(i)|^2 \}, \quad (11)$$

Using these noise power and attenuation estimations, the bits are assigned in first instance with infinite granularity to the carriers using the Fischer et al. algorithm. In the next step, the assigned number of bits is quantized to an even integer. Only even integers are allowed in order to balance the BER on the I and Q components. The third part of the algorithm adapts the bitassignment in order to make sure that  $R_{\text{total}}$  equals the targeted bitrate. Finally, the power of each carrier is adjusted so that all carriers yield the same BER. The bit assignment for the channel estimation in figure 5 is shown in figure 6.

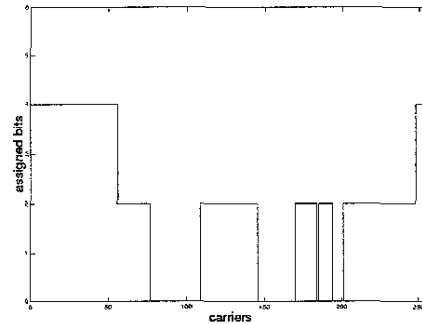


**Figure 6:** Bit assignment

This figure indicates that the dips in the spectrum are not carrying any bits while more bits are transmitted on the carriers with low attenuation. Furthermore, the order of the constellation on the good carriers is low (QPSK or 16-QAM) compared to the order in ADSL, since in general the  $E_b/N_0$  is relatively low for the indoor channel.

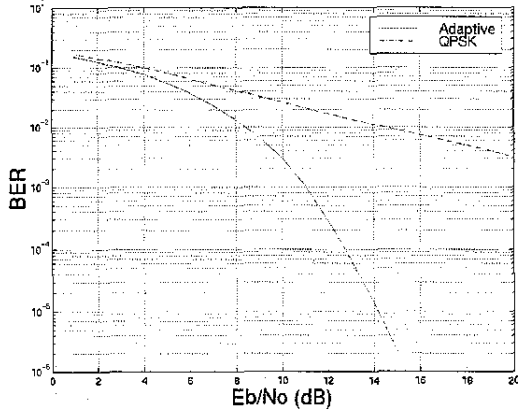


Figure 7: Performance for ray-tracing model

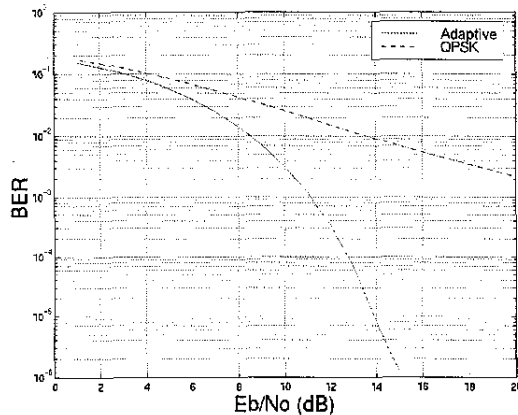


Figure 8: Performance for simulation model

Figure 7 compares the BER for adaptive loading and for plain QPSK on all the carriers for the ray-tracing channel model when the data rate is 100Mbps and a cyclic prefix of 8 bits is used. A 6 dB gain is observed for  $\text{BER} = 10^{-2}$ . Figure 8 shows the BER for the simplified simulation channel model. As can be concluded from these two figures, the difference between the simplified channel model and the ray-tracing model is minimal. From the figures, it is clear that a substantial advantage can be achieved by adapting the bit allocation to the spectrum of the fading channel. The main benefit arises from the fact that the carriers which form an errorfloor in QPSK, are now avoided. To accomplish this, more bits have to be sent on the peaks but since even on the good carriers the SNR is relatively low, this does not result in high order constellations as in ADSL.

## 5 Conclusions

The simplified statistical model in this study, which was derived from a ray-tracing model, forms an efficient representation of the indoor channel. It was used to simulate the performance of the adaptive loading strategy that we propose for a high speed OFDM-based WLAN. This adaptive loading strategy comprises of a channel

response and noise estimation phase, and uses the Fischer approach [6] to assign the bits to the carriers. Simulations show a 6 dB improvement for a BER of  $10^{-2}$  to the normal OFDM-modem. In other words, adaptive loading is certainly a good method to improve the capacity usage in WLANs.

In our ongoing work, we are analyzing a multi-user situation with Orthogonal Frequency Division Multiple Access (OFDMA). The assignment of the carriers to the different users adds an extra degree of freedom. The optimum solution is based on multi-user waterfilling. However, complexity issues may necessitate the development of heuristics for this optimization problem. Preliminary results confirm the expectation that in a multi-user situation, we can benefit from the fact that the channels of the different users are uncorrelated. The advantages of adaptively assigning bits and carriers will increase with the number of users. Thus, the usage of the total network capacity can be greatly improved in comparison to the single user case.

## 6 References

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