OFDM-UWB PHYSICAL LAYER EMULATION FOR EVENT-BASED MAC SIMULATION

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ABSTRACT

Simulation is one possibility to assess the performance of new medium access protocols for wireless communications. While the new algorithms are usually implemented in a very realistic way, the physical layer is emulated as a simple model. Often, this simplification is invalid in complex scenarios, where interference and non line of sight conditions degrade the signal quality.

A complete physical layer implementation including the error correction, modulation, channel equalization and different channel pulse responses is not feasible in a layer two simulator. Hence, its characteristic is mapped onto a computational efficient stochastical model.

The presented method differs from other error models in the way it is enriched with data to compute the packet error rates: The physical layer under examination, the WiMedia OFDM ultra wideband physical layer, is simulated in a detailed physical simulator and the error rates are derived then using an error analysis.

I. INTRODUCTION

One of the most applied methods for the evaluation of new Medium Access Control (MAC) protocols for wireless radio access is an event-based "Monte-Carlo" simulation. Although many different simulators exist, the approaches are very similar to each other: First, the algorithm for the medium access which is under consideration is implemented and parameterized. Then, the simulator generates a multitude of MAC entities which provide to the higher layers the usual services like a (reliable) packet transmission. The user's behavior is simulated by a random-number feed traffic generator which uses these services.

All generated MAC entities communicate to each other via the provided Physical Layer (PHY) services. In a MAC simulator, the real functionality of the PHY like error-correcting coding, modulation and transmission errors that occur because of collisions is abstracted by a combined PHY and channel model.

Before any model can be used in a simulation, it must be parameterized; i. e. the different probability values must be set. This is usually done by a mathematical model for the error packet error rates, e. g. in [1], or by a statistical analysis of a trace obtained from a real network.

In this paper, we concentrate on two equally important subjects: First, we enhance an existing error model for the simulation of an Ultra Wideband (UWB) indoor communication. Secondly, we present a novel way to parameterize this model, so that it reflects the complex behavior of a real UWB system without the need for a real world experiment. Although it is specially tailored to emulate an UWB channel together with the current PHY implementation from the WiMedia Alliance [2], the method can be generalized to any wireless medium access technology.

II. THE UWB INDOOR CHANNEL MODEL

The design and characteristics of any wireless network are rooted in the special features of the underlying channel, i. e. the pulse response. Although the modeling of the UWB channel is a fairly recent field, many proposed models exist (e. g. in [3]). The WiMedia PHY is designed to perform in the following UWB channel model, a detailed description can be found in [4].

A characteristic feature of the UWB indoor channel are the time-of-arrival statistics of the multipath components: Due to the very fine resolution and the large bandwidth of UWB waveforms, multipath results from reflections can be individually resolved at the receiver. This model uses the Saleh-Valenzuela approach [5] where the multipath components are aligned in clusters. It models the distribution of the interarrival times of each clusters and the rays in each cluster as well as the average power of both. Furthermore, fading of the amplitudes is emulated by a log-normal random variable.

To distinguish substantial different channel conditions, the Channel Models (CMs) 1 to 4 are defined by different values for the parameters of the probability distributions. They can be mapped to a scenario with Line Of Sight (LOS) or non Line Of Sight (non-LOS) conditions and different distances from the transmitter to the receiver. The model parameters are available in [4]. Using these parameters, a stochastic process can be configured whose output is a typical pulse response for the chosen scenario type. 100 typical pulse responses for each scenario parameter set are also published to enable a comparison between different UWB PHY techniques.

In a simulation, each of the mentioned pulse responses can be used to design a filter which is applied to the transmitted signal. Additionally, white noise can be added to the signal to emulate interference from other transmissions and background noise.

III. WIMEDIA UWB PHYSICAL LAYER

The WiMedia UWB Physical Layer (PHY) for a Wireless Personal Area Network (WPAN) is specified in [2]. It utilizes the

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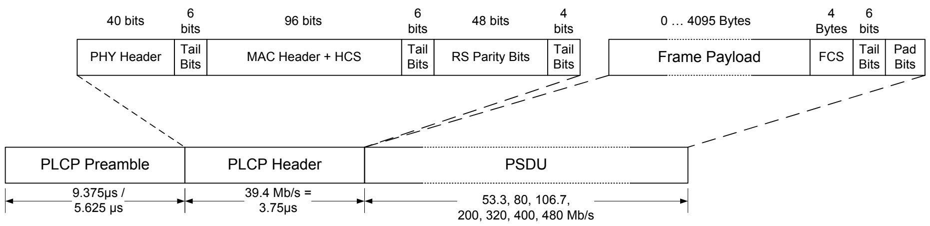

Figure 1: WiMedia PHY frame format.

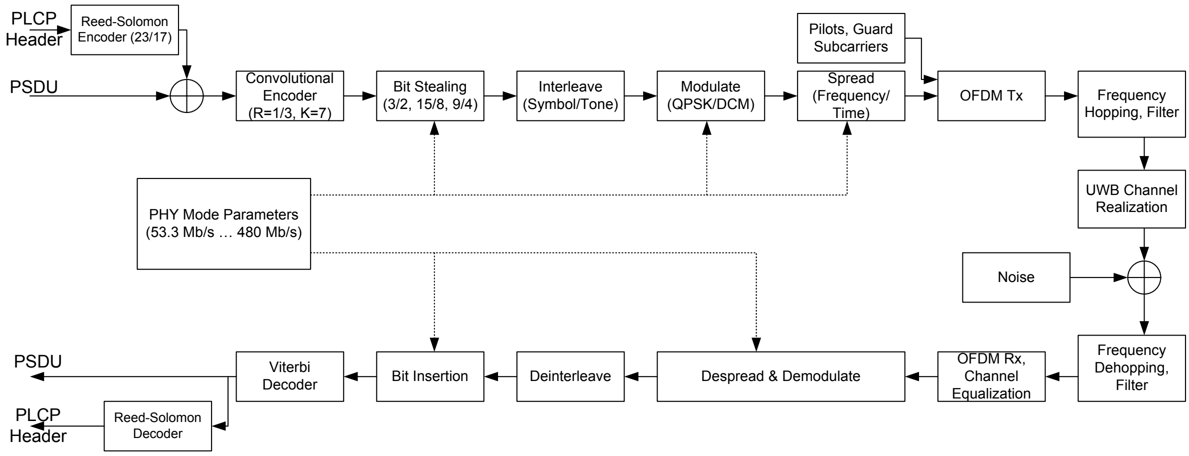

Figure 2: WiMedia PHY transmitter and receiver chain.

unlicensed 3100 - 10600 MHz frequency band to transmit data at the rates 53.3, 80, 106.7, 160, 200, 320, 400 and 480 Mb/s. The spectrum is divided into 14 bands, each with a bandwidth of 528 MHz. The first 12 bands are then grouped into 4 band groups consisting of 3 bands, the last two bands form a fifth group.

Information is transmitted with a Multiband OFDM (MB-OFDM) scheme; Each band is split into 110 sub-carriers (100 data carriers and 10 guard carriers).

A PHY frame consists of three parts, which can be seen Figure 1: The Physical Layer Convergence Protocol (PLCP) preamble (used for timing synchronization, carrier-offset recovery and channel estimation), the PLCP header and the Protocol Service Data Unit (PSDU). To receive a packet correctly, a station has to be synchronized to the frame with the help of the preamble and decode the PLCP header and the PSDU. The relationship of the data rate versus the Packet Error Rate (PER) depends on the success of the error protection schemes used for these two parts. We summarize the different settings for the error protection as the "PHY Mode".

Each PHY mode consists of a parameter set which influences

- The code rate of the Forward Error Correction (FEC) code, determined by the setting of the puncturing mask after the convolutional encoder.
- If an outer Reed-Solomon (R-S) code is used, which is the case for the 39.4 Mb/s mode.
- The modulation type, either Quarternary Phase Shift Keying (QPSK) or Dual Carrier Modulation (DCM); the latter one consists of two parallel 16-Quadrature Amplitude Modulation (QAM) with different bit mappings.
- If the complex symbols are spread using Time Domain Spreading (TDS) or a combination of Frequency Domain Spreading (FDS) and TDS.

Additionally, in all modes the bits are interleaved over six consecutive Orthogonal Frequency Division Multiplexing (OFDM) symbols and permutated across the data subcarriers to exploit the frequency diversity of UWB. The corresponding transmitter and receiver chain where the different error protections are linked to each other is displayed in Figure 2.

More details on the error protection schemes can be obtained from the specification itself, [2], and several other publications that have been produced during the standardization process.

IV. An Error Model for the WiMedia UWB PHY

The error model we present and discuss in the following is based on an error model for a narrow-band OFDM based wireless network described in [1]. We adapt the design decisions which are chosen to emulate the error characteristic of an OFDM transmission, but add elements to incorporate the special features of the UWB channel and the chosen FEC scheme.

With the same reasoning as applied in [1], we argument that when employing local area networks with high data rates (and thus very small symbol durations) in indoor environments, the propagations characteristics can be described as a slowly fading channel, which is stationary for symbol duration. What is not (semi-)stationary are the interferences caused by neighboring radio transmissions from other nodes; depending on the power of those transmissions the reception of the original signal can be disturbed severely.

Therefore, the current Signal to Interference plus Noise Ratio (SINR) level as sensed by the receiver is an important element in the error model. It is calculated for every individual transmission, called a burst, in the following way: The average power of each burst is calculated as

$$P_{\mathrm{Rx}}\,[\mathrm{dBm}] = P_{\mathrm{Tx}}\,[\mathrm{dBm}] - \underbrace{20 \cdot \log_{10}\left(\frac{4\pi d_0}{\lambda}\right)}_{\text{free space path loss at distance } d_0} \underbrace{- 10 \cdot \gamma \log_{10}\left(\frac{d}{d_0}\right)}_{\text{Path loss at distance } d} - X_\sigma - W \quad (1)$$

where

- P_{Tx} is the transmission power.
- d_0, d denote the reference distance and distance between transmitter and receiver; d_0 is set to 1 m.
- λ expresses the mean wavelength; frequency dependant path loss is assumed to be negligible.
- γ is the path loss exponent, set to 2 for LOS and 3.5 for non-LOS conditions.
- X_σ models a log-normal distributed shadowing loss with zero mean and standard deviation σ.
- W models attenuation due to a wall if there is one in the direct path.

For each incoming burst, all other simultaneous bursts are regarded as interference. The cumulative interference power in the SINR is computed as the maximum sum of the simultaneous interfering bursts, even if not all interferers contribute during the complete reception interval. Figure 3 shows exemplary how the maximum interference is calculated for the burst number 2 if bursts 1 and 3 arrive overlapping. After a burst has finished (i. e. the transmission has finished), the SINR can be computed. For each moment, only one burst can be received; therefore, only the burst with the highest received power in comparison with all other bursts during its duration is considered.

This "winning" burst is further processed like indicated in Figure 4: First, a generated random number indicates if an transmission error in the preamble part occurred which cannot be corrected by the used FEC. The error probability p_{err} depends on the applicable CM (as presented in section II.) and the previously computed SINR. If this test succeeds, a similar one is done for the PSDU part of the burst. Additional to the CM and the SINR, the PSDU size and the used PHY Mode influence the probability of an frame error. After the success of this second test, the burst is regarded as successfully received.

To implement this two tests, an error probability analysis has to be performed which considers the given parameters, result-

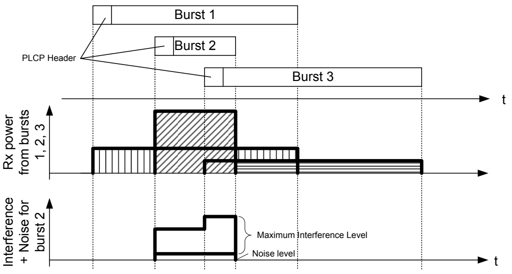

Figure 3: An exemplary SINR calculation for three concurrent transmissions.

ing in the following function:

$$\mathrm{SINR} \times \mathrm{PSDU\ Size} \times \mathrm{PHY\ Mode} \times \mathrm{CM} \rightarrow p_{err} \quad (2)$$
$$\mathbb{R} \times \{0 \ldots 4095\} \times \{0 \ldots 8\} \times \{1 \ldots 4\} \mapsto [0; 1] \quad (3)$$

V. Error Probability Analysis

The quality of the PER model heavily influences the quality and the significance of the generated results. On the one hand, this quality is influenced by the complexity and the applicability of the model, it provides the dimensions by which the current channel quality is determined. On the other hand, care during the parameterization of the model by an error probability analysis is equally important. In the literature, two ways are described to perform an error analysis with the aim to parameterize an error model: Either a mathematical approximation of the Bit Error Rate (BER) or the PER is used to compute the probabilities for different SINR, e. g. in [1]. This approach results in a very general approximation but fails to model special characteristics due to their complexity. Or a trace file, obtained from a real network trace, is analyzed using statistical methods and the model parameters are fit to the resulting data (e. g. [6]). While this method captures all influences of the PHY and the channel, a generalization of the result to other scenarios is hardly possible and thus the risk to overfit the MAC algorithm to one specific scenario exist. Furthermore, it is very hard to generate the network traces with the newest hardware as the real products might be very expensive or even not obtainable.

Therefore, we choose a different method: An implementation of the transmitter and receiver chain of the WiMedia Multiband OFDM Alliance (MBOA) PHY, as displayed in Figure 2 is simulated using Matlab's Simulink package [7] for event-based simulation. In this way, all special characteristics of the PHY can be captured without a cost intensive real implementation. Furthermore, it is possible to implement the channel as one of the mentioned 100 reference pulse responses mentioned in section II. to evaluate the sensitivity of the PHY to different propagation environments.

We enhanced the free available Simulink implementation of the 200 Mb/s WiMedia PHY mode from [8] to support all standardized modes from 39.4 to 480 Mb/s by adding

- Outer R-S encoding for the 39.4 Mb/s mode
- Puncturing schemes for 1/2, 1/3 and 3/4 coding rates
- Frequency-Domain Spreading

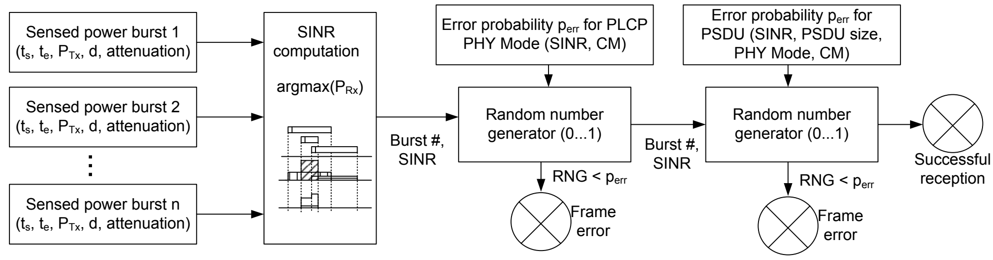

Figure 4: The stepwise error model for the UWB PHY emulation.

- Dual Carrier Modulation (DCM), including phase/amplitude channel equalization in the receiver

In the simulator, the transmitter is feed by a Bernoulli Binary Generator; bit errors are detected by comparing the random input with the output from the receiver after the FEC by the Viterbi decoder (or the R-S decoder, respectively). Although a simple computation of the BER using the two streams is possible, it cannot be used to obtain the PER to parameterize the model presented in section IV. as this approach would assume that the produced bit errors are independent. In [9] it is explained why this is not the case for a Viterbi decoder (even with an outer R-S decoder): Bit errors happen by excursions of the decoder from the correct path in the code trellis structure, and appear therefore as bursts. A complete error statistic is therefore defined by three parameters: The error burst length distribution, the distribution of the length of error-free periods (defined as "gaps") and the error distribution inside a burst.

To evaluate the PER, the first and the last distribution is not needed: a single bit error after the application of the FEC renders the whole frame erroneous and the frame is dropped. Therefore, it suffices to measure the distribution of the gap length to compute the PER. As shown in [10] and [9] the geometric distribution can be used to model for the gap lengths. Hence, the PER can be computed as

$$p_{err}(l,\overline{g}) = 1-(1-q)^{(l-(K-1))} \qquad \forall l \geq K-1 \tag{4}$$

where l denotes the packet size in bits, $q = (\overline{g}-K+2)^{-1}$, K the constraint length of the convolutional code (7 for the WiMedia PHY) and $\overline{g}$ the average gap length. Consequently, the only evaluation parameter for the simulator is the average gap length $\overline{g}$ which has to be estimated for a preset SINR, PHY mode and CM.

A. Simulation Credibility

Like any other evaluation parameter from a simulation, $\overline{g}$ is only an approximation of the "real" value; the confidence in $\overline{g}$ is defined by its α-confidence interval $[\overline{g}-c_{\alpha,\overline{g}};\overline{g}+c_{\alpha,\overline{g}}]$. To assess the impact of this error on p_{err}, an approximate mapping of this interval using the first-order Taylor series expansion of $p_{err}(l,\overline{g})$ at the point $\overline{g}$ can be used. In this way, the size of the α-confidence interval of p_{err} can be estimated as

$$c_{\alpha,p_{err}} \approx \frac{\partial p_{err}(l,\overline{g})}{\partial \overline{g}}(\overline{g})\cdot(\overline{g}+c_{\alpha,\overline{g}})$$

$$\approx \frac{l}{\overline{g}^2}\cdot c_{\alpha,\overline{g}} \tag{5}$$

A stopping criterion for the simulation is a confidence interval which is "small" enough for a large α, i. e. $c_{\alpha,\overline{g}} \leq \overline{g}\cdot r$, $r \ll 1$. $c_{\alpha,p_{err}}$ can then be simplified to approximately $(r\cdot l)/\overline{g}$. To archive a $c_{\alpha,p_{err}}$ of 0.01 for reasonable PERs below 0.1 at the largest frame length of 4095 B, it suffices to set $r = 0.1$. α is set to 0.95 in all simulations.

Furthermore, it is important to assess when to stop the simulation run if a high SINR is simulated. To solve the problem that the number of samples (gaps) in this case does not suffice for a reliable estimation of $\overline{g}$, the simulation is stopped after 10^9 bits are transmitted; $\overline{g}$ is set to 10^9. In this way, $p_{err} \approx 0$ and $c_{0.95,p_{err}} \approx 0$.

VI. Results

A first result of the simulator can be seen in Figure 5: It displays the distribution of the average gap lengths $\overline{g}$ for the 100 channel response answers of CM1 as a Cumulative Distribution Function (CDF). The varied parameters for the 5 curves are the PHY mode (106.3 Mb/s or 320 Mb/s), the SINR (3 dB and 5 dB for the low rate) and (12 dB, 15 dB and 18 dB for the high rate). The CDF shows that, especially with a sufficient high SINR, the spread among the different channel response results is very high.

To parameterize the described error model, a representative channel pulse response has to be selected among the 100 different ones. As the error model is intended to reflect the average case, the pulse response with the lowest average deviation from the median of the 100 $\overline{g}$ is selected; the average deviation is computed for the two PHY modes with the two/three SINR settings as displayed in Figure 5.

Figure 6 shows the average gap lengths for the average channel response of CM1, including the 95% confidence interval. The cutoff of the graph at 10^9 is a result of the limited simulating time, restricting the maximum gap length to this value.

The graphs demonstrate how the requirement for a high SINR rises for the faster transmission rates. While the performance of the 400 Mb/s is still acceptable (reaching error-freeness at 26 dB), the 3/4 coding rate of the 480 Mb/s mode makes a transmission very sensitive to interference. This situation is worsened in the case of the average channel response of CM3, which is shown in Figure 7: While the robust PHY modes up to

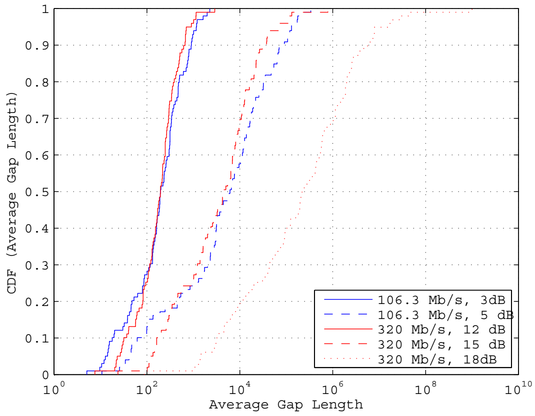

Figure 5: CDFs of the average gap lengths $\overline{g}$ for the 100 channel response answers of CM1.

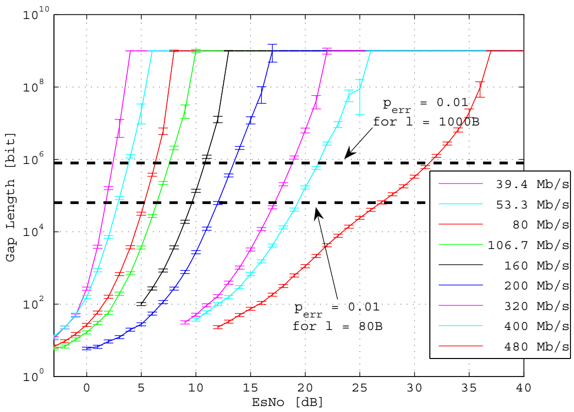

Figure 6: Average gap lengths for the average channel response of CM 1.

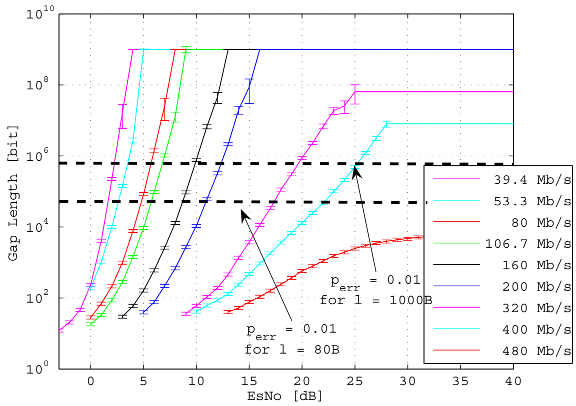

Figure 7: Average gap lengths for the average channel response of CM 3.

200 Mb/s can take advantage from their TDS and FDS operation and compensate the bad channel, the high-rate modes are unable to provide a sufficient gap length (and PER) even for very high SINR. Hence, they are not usable in the indoor non-LOS conditions modelled by CM3.

VII. Conclusion

Although special care was taken to represent the real life conditions of UWB transmissions as accurately as possible, the approach cannot reflect all error characteristics. Most of the compromises are related to the computational efficency, which is especially important for a MAC simulator. However, the model takes into account all relevant effects like the LOS/non-LOS conditions, attenuation, interference, frame lengths, modulation and coding schemes. The presented scheme allows a realistic simulation of the limitations of wireless networks due to neighboring interferers and different channel conditions

The channel models have been implemented in our Specification and Description Language (SDL) based simulation environment Wireless Access Radio Protocol 2 (WARP2). In our further work, we are planning to evaluate the current WiMedia MAC protocol including future extensions enabling mesh networks.

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