LOW-COMPLEXITY MIMO CHANNEL SIMULATION BY REDUCING THE NUMBER OF PATHS

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ABSTRACT

The simulation of frequency-selective multiple-input multiple-output (MIMO) channels is computationally expensive. Especially on a real-time simulation platform the number of paths that can be realized is limited by the available processing power. This paper presents a new algorithm, that reduces the number of paths in the channel impulse responses while preserving the original power delay profile (PDP) of the channel. The new path-reduction algorithm can be applied to synthetically generated channels as well as measured channels.

The performance of the algorithm is evaluated for scenario F of the I-Metra channel model as well as for a channel measured in the suburban village of Weikendorf near Vienna by comparing the PDPs of the original channel and the reduced path number channel. Further, bit error rate evaluations with a MIMO WiMAX link-level simulator are carried out and compared. The simulation results show that the reduced path number channels show close performance to the original channels.

1. INTRODUCTION

The design and optimization of modern radio communication systems requires realistic models of the radio propagation channel. However, the simulation of frequency-selective multiple-input multiple-output (MIMO) channels is computationally expensive. Since computational resources are always limited, methods for reducing channel model complexity while retaining the original model-accuracy are of great interest for communication engineers.

For most communication systems, “standardized” channel models exist. For example the I-Metra channel models [1] are used for the MIMO WLAN IEEE 802.11n standard as well as for the WiMAX IEEE 802.16 standard. Such “standardized” channel models are often defined by power delay profiles (PDPs) that specify the energy at a given path delay. Usually, these path delays are not multiples of the system sampling rate. Therefore, resampling of either the transmit and receive signals or the channel impulse responses is required. The resampling of the impulse response has the advantage of lower complexity but results in leaking of a single tap energy to multiple taps. This direct consequence of the interpolation results in a highly increased number of taps requiring a lot of additional computational power.

When using measured channel impulse responses for system evaluation purposes the problem is very similar. Channel sounders usually yield channel impulse responses with many taps. A fast and low complexity implementation therefore also requires an algorithm allowing to reduce the number of channel taps without or with minor performance degradation.

Related Work

In [2] we used a simple sinc-interpolation to resample impulse responses and selected the n strongest paths for simulation. It was shown that the use of eight paths is sufficient to model the I-Metra scenarios U, A, B, C, and D accurately. Scenarios E and F have a much larger delay spread and could not be modeled accurately. Both scenarios showed an abberation of about 1 dB at an SNR of 10 dB in the bit error rate (BER) simulations carried out with a WLAN 802.11n simulator.

In [3] the problem of simulating geometry based channel models with low complexity is treated. The authors use discrete prolate spheroidal (DPS) sequences to derive a subspace representation of the channel, that is independent of the number of propagation paths. In this work, the emphasis is on stochastic channel models and measured data.

The authors of [4] analyze several alternative methods to the sinc-interpolation to convert reference tapped delay line models to the sampling rate of the system. However, the problem of reducing the number of paths is not addressed.

The paper [5] presents three different algorithms to reduce the number of paths in measured channels. Their methods se-

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lect a subset of the paths of the original impulse response under the constraint of some optimization criterion. However, this method does not conserve the energy in the channel and thus leads to performance degradations in the BER simulations.

Contributions
We present a new algorithm that reduces the required number of taps of a given, arbitrary impulse response. In contrast to the methods presented in [5] our algorithm preserves energy at specific delay regions of the impulse response. Our method therefore does not require a new power normalization after the path number reduction. We apply our algorithm to synthetic (i. e., computer generated) and measured channel impulse responses. The performance evaluation of the path reduced channel model is accomplished in two steps. At first, the resulting power delay profiles are compared. Secondly, we use the path reduced channel model in an IEEE 802.16-2004 [6] compliant WiMAX simulator and compare the uncoded bit error ratio.

2. ALGORITHM

Given an impulse response $h(\tau)$ sampled with sampling time T_i, the following algorithm resamples $h(kT_\text{i})$ to the channel simulator's sampling time T_o and reduces the number of paths to N_tap.

1. Resample the impulse response to the channel simulator sampling time T_o using a sinc interpolation filter with a length of $2K+1$:

$$h(mT_\text{o}) = \frac{T_\text{o}}{T_\text{i}} \sum_{k=-K}^{K} h(kT_\text{i})\text{sinc}\left(\frac{\pi}{T_\text{i}}(mT_\text{o} - kT_\text{i})\right). \tag{1}$$

The particular scaling factor $\frac{T_\text{o}}{T_\text{i}}$ is required for preserving the energy of the impulse response when changing the sample rate.

2. Sum all tap values at negative time indices and add them to the tap $h(0)$:

$$h(0) = \sum_{m\leq 0} h(mT_\text{o}) \tag{2}$$

This step ensures that the resulting impulse response remains causal.

3. Construct the set $\mathcal{M}$ of all indices m, where the resampled impulse response is not zero, i.e. $h(mT_\text{o}) \neq 0$.

4. Find the index m_min of the tap with the smallest energy unequal to zero:

$$m_\text{min} = \arg\min_{m\in\mathcal{M}} |h(mT_\text{o})|^2. \tag{3}$$

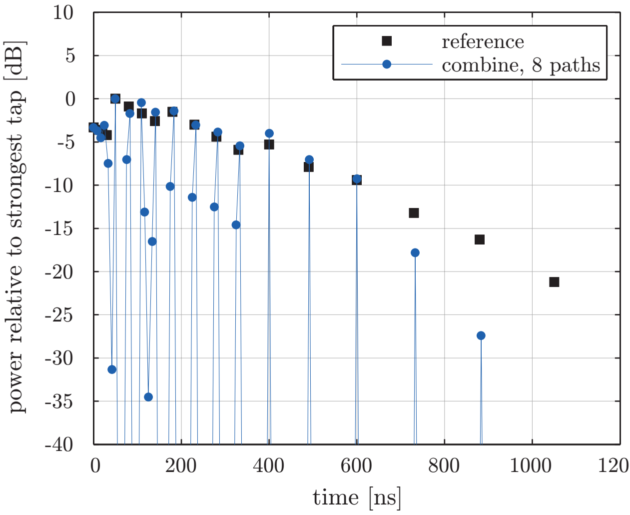

Fig. 1. Power delay profile of the I-Metra F model ("original") and the reduced channel model using eight paths.

5. Find nearest neighbor m_nb of m_min in $\mathcal{M}$. If two nearest neighbors exist, choose the one with smaller tap energy.

$$m_\text{nb} = \arg\min_{m\in\mathcal{M}} |m_\text{nb} - m_\text{min}|. \tag{4}$$

6. Add and update tap values accordingly:

$$\begin{aligned} h(m_\text{nb}T_\text{o}) &:= h(m_\text{nb}T_\text{o}) + h(m_\text{min}T_\text{o}), && (5)\\ h(m_\text{min}T_\text{o}) &= 0. && (6)\end{aligned}$$

7. Go to step 3. if $|\mathcal{M}| > N_\text{tap}$, where N_tap is the desired, maximum number of taps in the final impulse response.

3. SYNTHETIC CHANNEL

In this section, we apply the algorithm presented in Section 2 to the I-Metra channel model scenario F. The PDPs of the I-Metra channel models are specified at a sampling rate of 100 MHz. The ARC SmartSim channel emulator [2]—which uses these impulse responses for real-time channel emulation to test WLAN and WiMAX hardware—employs a sampling rate of 120 MHz. After resampling the 18 multipath components of the I-Metra scenario F from 100 to 120 MHz, we observe $2K+N$ paths, where $2K+1$ is the length of the sinc interpolation filter and N is the maximum delay of the channel in samples. Especially when performing real-time emulation of MIMO channels, more multipliers are required than currently available in FPGAs.

3.1. Power Delay Profile

In Fig. 1 the PDP of the original I-Metra scenario F is compared to the PDP of the path number reduced model. Here we reduced the total number of paths that are available in

	Mean Delay	RMS Delay Spread
reference (100 MHz)	145.5 ns	149.8 ns
sinc interpolation (120 MHz)	145.6 ns	150.2 ns
largest, 8 paths (120 MHz)	112.9 ns	107.9 ns
combine, 8 paths (120 MHz)	145.8 ns	135.4 ns

Table 1. Mean Delay and RMS Delay Spread of I-Metra scenario F.

Physical layer	256 carrier OFDM
Modulation	4-QAM
Bandwidth	20 MHz
Cyclic Prefix	1/8 = 1390 ns
Maximum Delay of Channel	1050 ns

Table 2. WiMAX simulation parameters for I-Metra channel model F.

every impulse response to eight. Note that the power delay profile of the eight path model shows energy at more than eight delays. This is explained by the averaging over impulse responses when calculating the PDP. Due to this effect, the original PDP and the PDP of the path number reduced model show a good matching and only at large delays an abberation is observed.

Table 1 shows the mean delay and the RMS delay spread for different path reduction algorithms. The *reference* values here are given by the original model at a channel model sampling rate of 100 MHz. A sinc interpolation to 120 MHz leaves the mean delay and the RMS delay spread and the mean delay almost unchanged. After path reduction, the mean delay and the RMS delay spread are much better reproduced by our new path reduction method (*combine*) than with the sinc8 method of [2] (here denoted as *largest* method).

3.2. WiMAX Simulations

Since synthetic channel models are often used in system simulations, the complexity reduced channel models should accurately reflect the BER of the transmission system. We therefore also investigated the influence of the new path number reduction method on the bit error ratio of an IEEE 802.16-2004 compliant WiMAX transmission. We used the simulation parameters summarized in Table 2.

The uncoded bit error ratio for I-Metra channel model F is shown in Fig. 2 and a close-up of the SNR range between 4 and 6 dB in Fig. 3. In these simulations we transmit at two antennas (Alamouti space-time coded) and receive at two antennas (maximum ratio combining). The spatial correlation matrices defined in the I-Metra models are included in the channel model. The *reference* curve in the figures was obtained by resampling the transmit signal to the original sampling rate of the I-Metra channel models of 100 MHz. All other curves were obtained at a channel model sampling rate of 120 MHz corresponding to the ARC SmartSim channel emulator sampling rate. The path reduction algorithm was applied to all impulse responses of the individual MIMO links. In Fig. 3 we can see that the new path reduction method (*combine*) with four paths almost achieves the *reference* performance with an loss of only 0.15 dB. Compared to other path reduction methods, like in [2], where the path reduction is achieved by simply taking the largest n paths (we will reference this as the *largest* method in the following), the new method shows much better performance in terms of complexity and accuracy. The *largest* method shows an abberation of more than 0.5 dB when eight or even sixteen paths are used for the channel simulation.

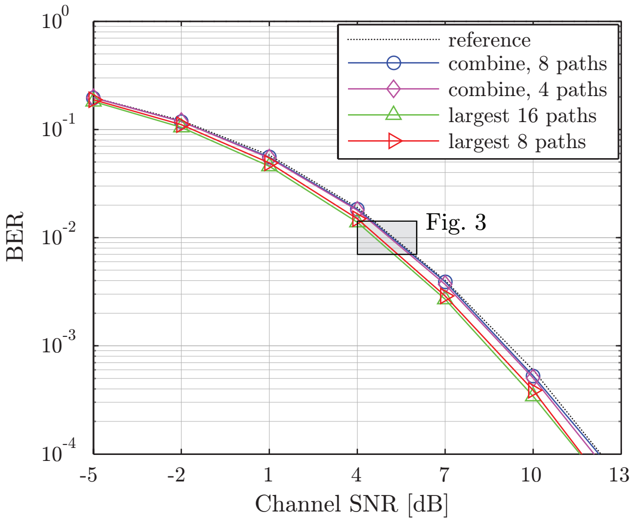

Fig. 2. BER simulation results of I-Metra model F.

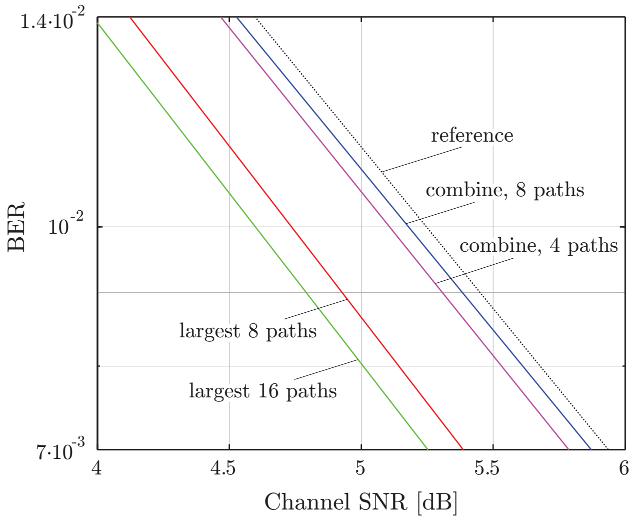

Fig. 3. BER simulation results of I-Metra model F.

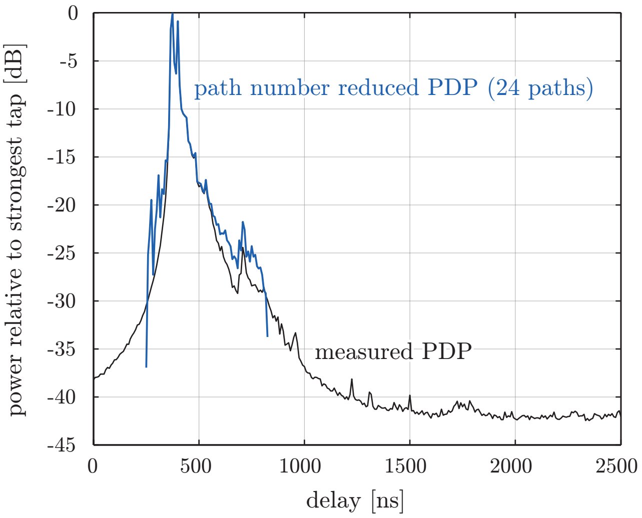

Fig. 4. Power delay profile of the measured impulse responses and the path number reduced impulse responses.

	Mean Delay	RMS Delay Spread
original, 384 paths	408 ns	142 ns
threshold, 71 paths	399 ns	50 ns
combine, 24 paths	401 ns	59 ns

Table 3. Delay Spreads of measured impulse responses.

4. MEASURED CHANNEL

In this section we describe the application of the path reduction algorithm to measured channel sounder data.

The measurement data used for the numerical experiments in this paper were recorded during a measurement run in Weikendorf, a suburban area in a small town approximately 50 km north of Vienna, Austria, in autumn 2001 [7, 8]. The sounder operated at a center frequency of 2000 MHz with an output power of 2 Watt and a transmitted signal bandwidth of 120 MHz. The transmitter emitted a periodically repeated signal composed of 384 subcarriers in the band 1940–2060 MHz. The repetition period was 3.2 microseconds. The transmitter was the mobile station and the receiver was at a fixed location.

4.1. Power Delay Profile

For the evaluation of the path reduction algorithm we chose the first 1000 impulse responses of a particular measurement (number 47). This corresponds to the first 21 seconds of the measurement route. In this time, the scenario and thus the PDP of the channel does not change significantly due large scale fading. The PDP shown in Fig. 4 was obtained by averaging over the impulse responses between the first transmit antenna and the first receive antenna.

The channel sounder delivers channel impulse responses of length 384, far too much for real-time channel emulation. An application of measured impulse responses in a real-time channel emulator therefore requires a massive reduction of the path number. If our algorithm is applied directly to the measured data, we observe after the path reduction several artificial paths. These paths are generated by combining taps that contain only measurement noise energy but no path energy. This problem can be solved by taking only 99 % of the overall energy contained in the power delay profile. The taps containing the remaining 1 % of the overall energy are discarded. By applying this threshold, the number of taps in the measured impulse responses are reduced from 384 to 71, still to much for real-time channel emulation. We reduce the number of taps further by applying steps 3. to 7. of our path combining algorithm described in Section 2. The resulting power delay profile, illustrated in Fig. 4, shows a very good match for a range of about 25 dB and a good match for another 5 dB. Here we used a maximum number of 24 paths in every impulse response. Depending on the desired accuracy and/or complexity the number of paths can be adjusted accordingly.

Table 3 shows that the path reduction algorithm also reproduces mean and RMS delay spread of the channel model accurately (threshold here refers to the PDP of the impulse responses after applying the 99% energy threshold). The RMS delay spread of the original PDP is much larger because of the many noise taps at large delays.

4.2. WiMAX Simulations

One major application of the path number reduction method is the emulation of measured channel impulse responses for real-time verification of wireless transmission systems. In this section we present the BER simulation results for the WiMAX OFDM physical layer that are obtained using the original and the reduced path number channel impulse responses.

In the BER simulations we used the same parameters as for the evaluation of the I-Metra scenario F model (Table 2). The cyclic prefix of 1/8 (= 1390 ns) was chosen appropriately to avoid intersymbol interference since the maximum delay spread of the measured impulse response is 830 ns (after the previously mentioned preprocessing). The simulations were carried out for a transmission system with a single antenna on both link ends. Fig. 5 shows the simulated uncoded BER for six different implementations of the measured impulse responses. The ‘99 % energy’ curve corresponds to a channel model where only the previously described threshold is applied to the measured impulse responses. This curve can be seen as a reference for all other, lower complexity implementations with reduced path number. The curves labeled with *combine* correspond to our new path reduction method and the curves labeled with *largest* correspond to the path reduction method where simply the n largest paths are taken for the channel simulation. All curves in Fig. 5 look very similar, but when we look at a close-up of the SNR range

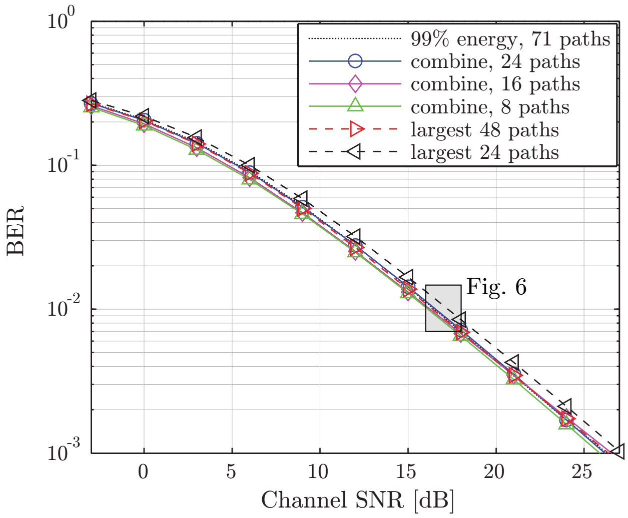

Fig. 5. BER simulation results with the measured channel impulse responses.

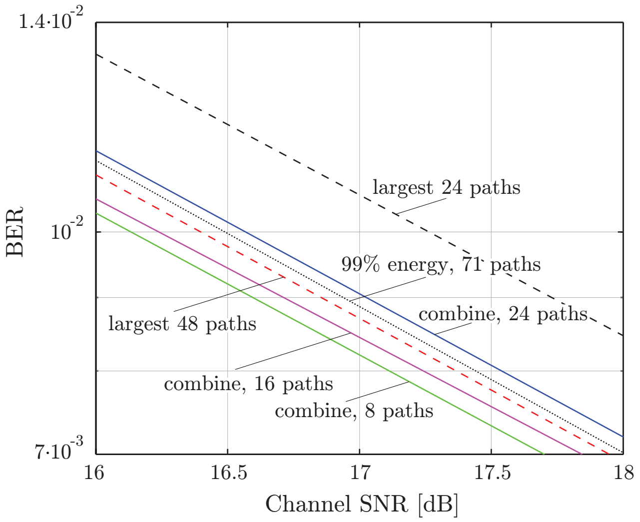

Fig. 6. BER simulation results with the measured channel impulse responses.

from 16 to 18 dB in Fig. 6 we can make the following observations. The *combine* method with 24 paths works very well, also does the *largest* method with 48 paths, at the cost of twice the path number. The *combine* method gets worse if we reduce the number of paths. However, if we use eight paths for the channel simulation and the *combine* method we still have an abberation of only 0.4 dB. The *largest* method, on the other hand, shows with 24 paths already a shift in the BER curve of 0.8 dB.

5. RESULTS AND CONCLUSIONS

We presented an algorithm that allows to reducing the number of paths of a channel model enabling low complexity channel emulation with high accuracy. We applied the algorithm to impulse responses generated according to the I-Metra channel model scenario ”F” and to measured impulse responses. The power delay profiles of the path number reduced channel show a much better matching with the original power delay profiles than a maximum energy approach, where simply the largest paths are considered. Also BER simulations of a 802.16-2004 WiMAX system with OFDM physical layer show that the path number reduced channels give a performance close (<0.2 dB) to the original channel model.

6. REFERENCES

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