Hardware Impairments in Millimeter Wave Communications using OFDM and SC-FDE

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***Abstract*—Millimeter wave (mmWave) communications are recognized as a key technology in 5G architecture by achieving highly boosted data rate due to the large available bandwidth. For proper mmWave access design in practical systems, the impact of hardware impairments leading to performance degradations have to be considered adequately. In this extended abstract, we study several hardware aspects such as phase noise and non-linear power amplifiers using their models at mmWave frequency and evaluate the performance in an outdoor urban mmWave scenario. IQ imbalance, analog-to-digital converter and digital-to-analog converter resolution are discussed in the full paper. The respective influence on two air interfaces, namely, orthogonal frequency division multiplexing (OFDM) and single-carrier frequency domain equalization (SC-FDE), are analyzed and compared. It is shown that SC-FDE is much more robust against impairment from non-linear power amplifiers than OFDM under system configuration at mmWave range. Although this less robustness is compensated by channel coding in OFDM systems significantly, SC-FDE with minimum mean square error equalization can still outperform OFDM in some coded cases.**

I. INTRODUCTION

For practical system designs of mmWave access at high frequencies between 3 GHz and 300 GHz, hardware impairments from the RF chains should be considered adequately for complete performance evaluation. In [1], several hardware aspects are described to facilitate 60 GHz simulations intended for wireless personal area networks (WPAN), including phase noise (PN), non-linear power amplifiers (NPA), IQ imbalance, analog-to-digital converter (ADC) and digital-to-analog converter (DAC) resolution. Proper modeling of these imperfections at mmWave range is of special importance and thus is required to study the resulting performance degradation in different channel scenarios. These aspects are investigated in additive white Gaussian noise (AWGN) channels at 60 GHz in [2] with comparison between OFDM and SC-FDE systems. Similar investigations and comparisons are presented in [3] for an indoor WPAN environment. The contribution of this work is, a) we consider an outdoor urban mmWave scenario with a recently proposed 3D channel model [4] and build a sectorized beamforming model [5] on top of it; b) employing this channel model with beamforming, we initiate comparisons between OFDM and SC-FDE transmissions with hardware impairments modeled at mmWave frequency. The corresponding impacts on both air interfaces are studied based on numerical performance evaluations, which give insights into practical system design for outdoor mmWave communications.

II. SYSTEM SETUP AND PARAMETRIZATION

A single-stream mmWave communication system is considered in outdoor urban scenarios using the channel model proposed in [4] at 73 GHz. To compensate the large path-loss at mmWave range, a sectorized beamforming model [5] is employed and built on top of the channel. Specifically, we adopt a beam with a constant gain within a given beamwidth θ, which can be achieved by, e.g., assuming omnidirectional antenna arrays. This beam is steered to point in the direction leading to the highest receive signal to noise ratio (SNR). Note that narrower beam yields less frequency selectivity of the mmWave channel. Without hardware impairments, it is well known that SC-FDE with MMSE equalization outperforms OFDM in uncoded systems whereas OFDM becomes superior to SC-FDE with MMSE when coding is applied [6]. However, due to lower peak to average power ratio (PAPR), SC-FDE with MMSE might be advantageous over OFDM considering hardware impairments, as discussed in this work.

For performance evaluation using link-level simulations, we follow the numerology from the METIS project [7]. Specifically, each data frame employs 2048 subcarriers with 4-QAM and a subcarrier spacing of 720 kHz. The length of cyclic prefix (CP) is set to be $1/8$ of the data frame, which is sufficient to avoid interference from the previous frame when employing beamforming with a $\theta = 7^\circ$ beamwidth in a non-line of sight (NLOS) environment. In coded systems, an LDPC code of rate $R_\mathrm{C} = 0.5$ is used to encode each data frame individually with a maximum of 100 iterations for decoding. The SNR is defined in the sense of $\frac{E_b}{N_0} = 10 \log_{10} \frac{1}{\log_2 M \cdot R_\mathrm{C} \cdot \sigma_n^2}$ in dB to include the impact of modulation alphabet M, code rate R_C and Gaussian noise variance σ_n^2.

III. PERFORMANCE EVALUATION

A. Phase Noise

Oscillators used for signal up-/down conversion yield random deviation of output signal frequency around the carrier, which is depicted by PN. Therefore, both oscillators at the transmitter and receiver can not operate exactly at the same carrier frequency. Here, we adopt a typical one-pole one-zero PN model defined by its power spectral density (PSD) [1], which is given by

$$\mathrm{PSD}(f) = \delta \cdot \frac{1 + (f/f_z)^2}{1 + (f/f_p)^2} \ . \qquad (1)$$

The corner frequencies are set to $f_p = 1$MHz and $f_p = 100$ MHz that accord to the low and high frequency transitions, respectively. δ represents the low frequency noise level.

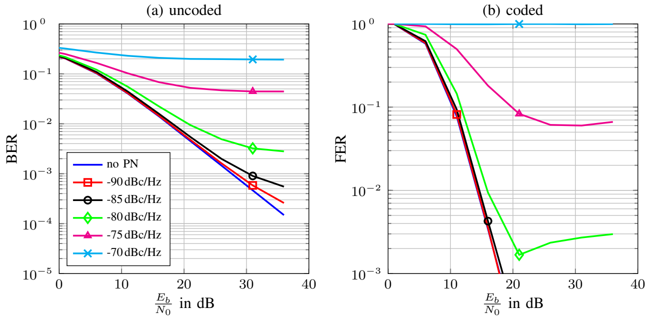

Fig. 1: Performance of OFDM with PN of different δ, (a) for uncoded BER and (b) for coded FER.

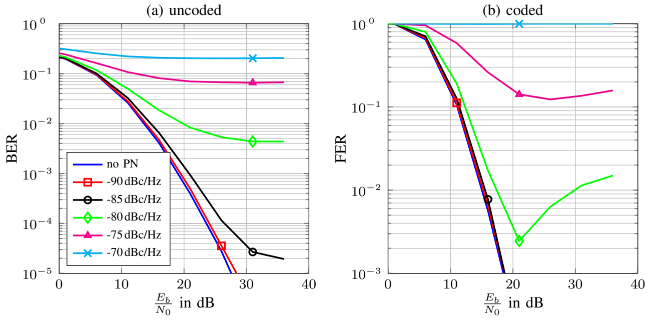

Fig. 2: Performance of SC-FDE with PN of different δ, (a) for uncoded BER and (b) for coded FER.

In Fig. 1 and Fig. 2, both uncoded bit error rate (BER) and coded frame error rate (FER) considering PN with different δ are shown for OFDM and SC-FDE, respectively. In uncoded systems, OFDM is slightly more robust against PN than SC-FDE. Specifically, SC-FDE outperforms OFDM significantly without PN, whereas OFDM becomes even superior with PN of $\delta = -80$dBc/Hz at high SNR. In case of coding, the impairment from PN is mitigated tremendously by channel codes. For example, PN with $\delta = -85$dBc/Hz already approaches the ideal case also at high SNR. Furthermore, OFDM achieves much lower error floor than SC-FDE, e.g., by $\delta = -80$dBc/Hz due to better exploitation of channel frequency selectivity.

B. Non-linear Power Amplifier

In case of linear power amplifiers (LPA), the transmit signals are linearly scaled without distortion. However, only NPA is practically feasible that generally suppresses input signal of large amplitude. For modeling of such non-linear characteristics, the Rapp model is commonly used to describe the input-output signal characteristics of a NPA [1]. To avoid non-linear distortion, the input signal power needs to be backed off to keep the signal within the linear zone at the expense of lower power efficiency. This is especially important for input signals with a high PAPR since the operating point of the power amplifier changes.

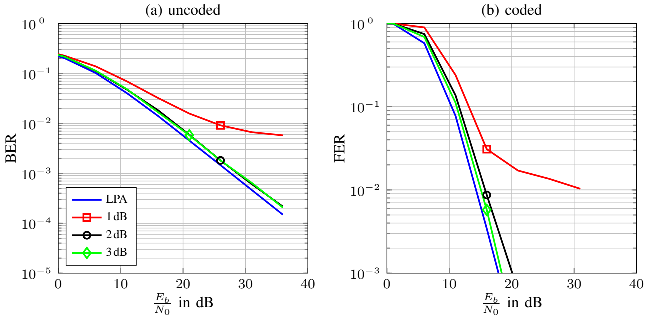

Fig. 3: Performance of OFDM using NPA with different OBO values, (a) for uncoded BER and (b) for coded FER.

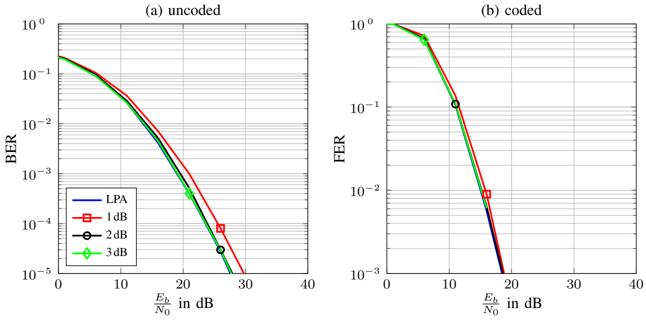

Fig. 4: Performance of SC-FDE using NPA with different OBO values, (a) for uncoded BER and (b) for coded FER.

Fig. 3 and Fig. 4 show the performance of OFDM and SC-FDE using NPA with different output back-off (OBO) values, respectively. The power loss due to OBO is not considered in these figures but will be included in the full paper. SC-FDE is shown to be much more robust against signal distortions from NPA than OFDM. For example, in uncoded cases with OBO = 1dB, SC-FDE approaches the ideal case with LPA within a few dBs whereas OFDM encounters even a high error floor. This indicates that OFDM is very sensitive to NPA due to higher PAPR resulting in large dynamic range of the transmit signal envelope. In case of coded systems, the impairment from NPA is mitigated by channel coding. For instance, as observed in Fig. 4(b) for SC-FDE, OBO = 1dB already approaches the ideal case and outperforms this case for OFDM in Fig. 3(b).

IV. SUMMARY AND OUTLOOK

In this extended abstract, the impact of hardware impairments from PN and NPA are analyzed and compared for both OFDM and SC-FDE transmissions in an outdoor urban mmWave environment. Numerical results indicate that OFDM is slightly more robust against PN than SC-FDE. On the other hand, SC-FDE is more immune to imprecisions caused by NPA. In the full paper, NPA will be further studied with optimal OBO values considering the power loss by OBO. The impact of IQ imbalance and ADC/DAC resolution will also be elaborated. Moreover, a more detailed illustration and extended performance evaluation will be provided, e.g., for higher modulation schemes.

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