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DOCTORAL DISSERTATION

Improvements of the Performance of Energy-Efficient 5G Massive MIMO Base Stations

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Abstract

Massive MIMO (multiple-input multiple-output) base stations, deployed in 5G cellular networks, enable unprecedented increase in the achievable data rates due to spatial multiplexing of multiple users. Since the base station sites account for most of the electric energy consumed in the cellular networks, an energy-efficient operation of Massive MIMO base stations is the key for sustainable provision of high-end performance to many users.

A considerable portion of the Massive MIMO literature either assumes that the distortion introduced in the base station transmitters (TXs) combines incoherently at the user equipment (UE) or ignores the impact of the hardware non-idealities altogether. This may be a feasible simplification when saturation in the power amplifiers (PAs) is avoided. However, usage of a high input back-off (IBO) to achieve this degrades the energy efficiency. Aiming to decrease the IBO, many studies on peak-to-average-power ratio (PAPR) reduction exploit the excess degrees of freedom in the Massive MIMO channel, striving to achieve a distortion-free transmission. This constraint may be too restrictive in practice. Receiver noise and intra- or inter-cell interference experience by the UEs limits downlink (DL) data rates, regardless of any distortion effects.

The ultimate objective of this dissertation is to clarify whether the residual TX impairments in Massive MIMO base stations have substantial impact on the DL data rates. The nonlinear distortion introduced by peak power limitation, resulting either from saturation in linearized PAs or PAPR reduction, is in the focus. The analysis covers compact arrays, utilizing either linear or rectangular layout of co-located antennas.

The first contribution of this dissertation is the proposal of two models for predicting the per user error vector magnitude (EVM) performance in line-of-sight (LoS) scenarios, based on the expectation of the radiation patterns of third-order intermodulation products (IMPs). The proposed simplified best-case model relies on categorization of IMPs, as either user-directed or spatially filtered (radiating in distinct directions). The portion of the IMP energy explicitly directed to users reduces with increasing the number of spatially multiplexed UEs. However, analytical analysis revealed existence of unfavorable combinations of UE angular locations, resulting in part of the spatially filtered IMPs to radiate in the UE directions as well. The proposed precoding-based model covers the cases of unfavorable combinations of angular directions and reflects the effects of limited angular resolution of the antenna array.

The comparison of the EVM statistics obtained from Monte Carlo trials of varying UE locations for the numerical simulation with precoding-based model and the link-level

simulation (LLS), using iterative clipping and filtering (ICF) as the source of nonlinear distortion, suggests that the proposed model can relatively well reflect the performance of peak power limitation. The prediction was generally pessimistic, as expected due to modeling only third-order IMPs, with a typical deviation of about 0.7 dB.

The spectral efficiency calculation was extended by reflecting the power of distortion received by UEs (estimated based on the proposed EVM prediction models), to consider the impact of the residual TX impairments on the achievable DL data rates. The relation between the signal-to-interference-plus-noise ratio (SINR) distribution in a multi-cell network and the impact of distortion was studied using Monte Carlo numerical simulations. As expected, the range of observed SINRs was relatively wide (about 20 dB spread between 10th and 90th percentiles), leading to different impact for different UEs. In the 16-cell example with ICF, decrease of the IBO from 10 dB to 6 dB resulted in over 20% reduction in the estimated energy consumption at a cost of less than 3% drop in the cell throughput.

Worst-case combinations of UE angular locations, resulting in all the IMPs to radiate in the UE directions, were identified analytically and confirmed in the LLS. In these outlier scenarios a full coherent combination of distortion at the UE locations is expected, irrespective of the number of antennas and spatially multiplexed UEs, resulting in lack of observable improvement in the per user EVM compared to the per antenna EVM. For example, for 6 spatially multiplexed UEs about 6 dB difference in the per user EVM between the best- and worst-case sets of user angular directions was observed in LLS. It was demonstrated that precoding-based prediction of the radiation pattern of spatially filtered IMPs can be used to improve the EVM performance by avoiding co-scheduling certain UEs.

The second contribution of this dissertation is a novel approach for exploiting the excess degrees of freedom available in the Massive MIMO channel, by using the power headroom in a subset of antennas to compensate for the distortion introduced in a different subset of antennas. The efficacy of the proposed solution was demonstrated in LLS for the ICF-based PAPR reduction as the source of distortion in a tapered linear array. An improvement of over 10 dB in EVM was observed in all the verified cases with LoS, when half of the antennas were compensating and zero forcing was used to precode the compensation signal.

This dissertation proves that the TX distortion, introduced in Massive MIMO base stations, may have visible impact on the DL data rates. Since a distortion-free operation is not required in practice, the balance between the DL data rates and energy consumption can be explored, taking into consideration the SINR distribution expected in a given deployment.