Conclusion and Future Work

Advancement in seamless wireless connectivity has led to an upsurge in data traffic over a wireless network which necessitates the efficient utilization of available resources. To support such data traffic, wireless communication systems need to deploy multi-antenna and multi-carrier modulation techniques such as MIMO-OFDM. However, MIMO-OFDM is still not enough as a standalone to fulfill the ever increasing demand for high data rate transmission. To satisfy this demand, the new features of LTE-A standard such as CA and MU-MIMO can be used together with OFDM which significantly boosts the performance of the wireless communication systems. However due to inherent nonlinear behavior of the HPA, the performance of MIMO-OFDM based system degrades considerably. To ensure the linear operation, HPA can be forced to operate with high IBO; however, it compromises its power efficiency. DPD is another solution to mitigate the nonlinear distortion without affecting its power efficiency. The nonlinear distortion caused by HPA becomes more severe in the presence of MU and CA-OFDM signals. Furthermore, the non-ideal oscillators cause phase noise which disrupts the orthogonality among subcarriers of the OFDM signal and leads to ICI which also degrades the performance of the MIMO-OFDM system. These impairments severely limit the gains provided by the MIMO-OFDM systems as compared to the linear systems.

In this dissertation, it has been shown that the hardware impairments create challenges while evaluating the performance of MIMO-OFDM based system which are not adequately addressed in the literature. These challenges and research gaps are summarized as:

- The conventional behavioral models are insufficient to characterize the nonlinear distortion caused by the HPA when driven by multi-band CA-OFDM signal.

- The nonlinear distortion depends on the number of users and affects the performance of MU-MIMO-OFDM system different as compared to the conventional MIMO-OFDM system.
The complete theoretical analysis of the joint CA and MU-MIMO techniques along with OFDM signals in the presence of nonlinear HPA has not been investigated.

The phase noise caused by the non-ideal oscillator makes the frequency domain analysis of the MU-MIMO-OFDM system more complex. As a consequence, it is difficult to theoretically analyze the impact of phase noise on MU-MIMO-OFDM system.

There is no behavioral model present in the literature to characterize the cascaded DPD+HPA architecture. Thus, it is not feasible to mathematically analyze the end-to-end performance of the MIMO-OFDM systems in the presence of both DPD and HPA.

7.1 Summary of the Contributions

The primary goal of this dissertation has been the development of the analytical framework to evaluate the end-to-end performance of the MIMO-OFDM based systems in the presence of nonlinear transceivers. First, the impact of nonlinear HPA is investigated on the performance of the CA and MU techniques both separately and together for the MIMO-OFDM system followed by evaluation of the performance of MU-MIMO-OFDM system in the presence of both nonlinear HPA and non-ideal oscillators. Finally, the mathematical representation of the cascaded DPD+HPA architecture is proposed to evaluate the performance of the nonlinear multi-carrier wideband communication systems in the presence of the DPD. Specifically, the contribution of this dissertation is concluded as follows:

- The performance of CA-MIMO-OFDM system in the presence of nonlinear HPA for a multi-path Rayleigh fading MIMO channel is analytically evaluated. The nonlinear distortions at the output of the HPA are canonically characterized in terms of complex attenuation factor and additive zero-mean Gaussian nonlinear noise. Their generalized expressions are derived that are applicable to any number of aggregated bands with any nonlinearity and memory depth. From the expressions, a complete analytical approach is presented to obtain the SER and EVM for each subcarrier of the CA-MIMO-OFDM systems. It was also observed that the nonlinear distortion caused by multi-band HPA increases with an increase in the number of aggregated bands which diminishes the gain due to diversity and SNR.

- The impact of the nonlinear transmitter on the performance of DB MU-MIMO-OFDM system is theoretically investigated in terms of SER and overall capacity. The analytical expressions for nonlinear interference caused due to HPA nonlinearity and SINR are derived. It was observed that the nonlinear interference is a function of the number
of users and number of aggregated bands which deteriorates the performance of the nonlinear DB MU-MIMO-OFDM system by introducing an irreducible error floor. It was also observed a trade-off between the improvement in capacity and operating HPAs with higher IBOs. Although for nonlinear MU-MIMO-OFDM system capacity scales moderately with the number of users and bands, the gains are severely limited when compared to the linear system. Thus, the transmitter nonlinearity not only compromises the reliability but also restricts the average capacity of the system.

- The analytical methodology is proposed to study the joint impact of non-ideal oscillators and nonlinear HPAs on the performance of the MU-MIMO-OFDM system. The impact has been investigated by deriving the closed-form expressions for SER and capacity of the MU-MIMO-OFDM system in the presence of both phase noise and nonlinear distortion. It has been shown that by utilizing these derived expressions, it is possible to evaluate the performance of MU-MIMO-OFDM system in the presence or absence of any of these impairments. The joint impact of phase noise and nonlinear distortion significantly deteriorate the performance of the MU-MIMO-OFDM system as compared to the ideal system. There are three trade-offs associated with the MU-MIMO-OFDM system in the presence of hardware impairments: 1) Trade-off between MUI elimination and transmit diversity, 2) Trade-off between operating HPA with high back-off and power efficiency, 3) Trade-off between phase noise tolerance and the number of users to achieve maximum capacity. These trade-offs severely restrict the performance gains of the MU-MIMO-OFDM system.

- The impact of DPD on the in-band signal quality of the nonlinear MIMO-OFDM system is evaluated in the presence of the multi-path Rayleigh fading MIMO channel. The JNP model is proposed to represent the characteristics of the cascaded DPD+HPA architecture. It was shown that the received symbol after the MIMO-OFDM demodulation consists of residual noise and a multiplicative factor. The closed-form expression of the multiplicative factor and variance of the residual noise are derived. Using these expressions, a complete analytical methodology is developed to obtain the closed-form expression of SER of MIMO-OFDM systems with cascaded DPA+HPA architecture. It was observed that even the lower order DPD can be used to mitigate the in-band distortion which in turn helps in improving the system reliability.

The above proposed frameworks can easily be utilized in various wireless standards and will be useful for a communication engineer to design a link budget for MIMO-OFDM based wireless systems without performing extensive simulations or tedious experiments.
7.2 Future Work

There are many possible directions in which the work articulated in this dissertation can be extended. Some of the future research directions are underlined as:

- Apart from nonlinear distortion and phase noise, there are several other transceiver impairments present in the wireless communication systems such as MIMO crosstalk and I/Q imbalance. These impairments also deteriorate the performance of the wireless communication system. Hence, it is imperative to take into account the impact of all impairments while analytically evaluating the performance of CA MU-MIMO-OFDM system.

- In this dissertation, a memoryless JNP model is proposed to characterize the cascaded DPD+HPA architecture. However, it does not consider the memory effects. Thus, an enhanced JNP model can be developed which considers the memory effects of cascaded DPD+HPA architecture. Furthermore, the expression of the coefficients of the proposed JNP model are specific to a certain nonlinearity order of HPA and DPD. Therefore, the generalized expression of the coefficient of the JNP model can also be derived which can be applied to any nonlinearity order and memory depth of both DPD and HPA. Furthermore, this model can also be extended for cascaded DPD+Crosstalk+HPA architecture.

- In-band full-duplex (IBFD) system has recently garnered significant attention in academia and industry because it has the potential of being able to increase spectral efficiency without the need for additional frequency resources. In the IBFD system, there is simultaneous transmission and reception of data signals within the same frequency band. On utilizing the benefits of MU-MIMO and IBFD together, the spectral efficiency of the wireless communication system can be improved significantly. This merger of MU-MIMO and IBFD system can be commonly referred as MU-IBFD system. The performance of this system can be analyzed in the presence of the non-ideal devices. Furthermore, the joint linearization and interference cancellation technique can also be developed to simultaneously mitigate the nonlinear distortion (by HPA), the multi-user interference (due to MU-MIMO transmission), and the self-interference (due to IBFD transmission).