UNIVERSITY GRANTS COMMISION
BAHADUR SHAH ZAFAR MARG
NEW DELHI-110002

Final Report/ Executive Summary

1. Title of the Project: GREEN COMMUNICATION TECHNOLOGIES FOR MULTI-STANDARD AND MULTI-BAND TRANSCEIVERS
2. NAME AND ADDRESS OF THE PRINCIPAL INVESTIGATOR: Prof. Vivek Ashok Bohara, Dept. of Electronic and Communication Engineering, IIIT Delhi
3. NAME AND ADDRESS OF THE INSTITUTION: Indraprastha Institute of Information Technology, Delhi Okhla Industrial Estate, Phase III, (Near Govind Puri Metro Station), New Delhi, India - 110020
4. OBJECTIVES OF THE PROJECT: The objective of the project can be summarized as follows:

   Power efficiency, energy consumption and linearity are going to be major bottlenecks to realize low-power multi-band multi standard transceivers. The operation of these transceivers necessitates a trade-off between energy consumption, efficiency and linearity. Hence, the major objective of the proposal are but not limited to the following:
   1) Designing an energy efficient transceivers by utilizing advance energy harvesting technique such as RF energy harvesting.
   2) Analyzing the performance of wideband transceivers in presence of nonlinear high power amplifiers.
   3) Development of novel digital predistortion algorithms for high power amplifiers.
   4) Development of state-of-art in-house testbed based on DPD and RF energy harvesting techniques for multi-band power transceivers.

   In addition to above, we expect to pass on our expertise on the above domain to the Masters and Doctoral level students.

5. WHETHER OBJECTIVES WERE ACHIEVED (GIVE DETAILS): We investigated the various linearization and energy harvesting techniques proposed to increase the efficiency and mitigate the distortions due to high power amplifiers (HPAs). We analyzed the multi-carrier signal when it is passed through a nonlinear HPA with memory in fading and non-fading channel conditions. We did a theoretical characterization of nonlinear distortion effects with memory on multi-carrier system in fading channels. We show that the nonlinear distortion with memory can be canonically characterized by a complex attenuation component and nonlinear noise component. Analytical expressions for the complex attenuation component and nonlinear noise component are derived. Thus a complete closed form evaluation of multi-carrier system performance in presence of nonlinear HPA with

memory in a fading and non-fading channel can be done in terms of received SNR and Bit Error Rate (BER). We also designed and implemented a RF energy harvesting circuit that converts the incident RF energy into DC power.

6. ACHIEVEMENTS FROM THE PROJECT: Various research findings have been published in reputed journals and also been presented in a number of IEEE conferences.
7. SUMMARY OF THE FINDINGS (IN 500 WORDS): The summary of the project findings are as follows:

1) **Analyzing the impact of nonlinear power amplifier on multi-carrier and multi-band transceivers:** We analyzed a multi-carrier system which includes a bandpass nonlinear block with memory at the transmitter and provides a theoretical interpretation of effects of nonlinear distortion and fading in a transmission system. The analysis was based on the application of Bussgang's Theorem to memoryless bandpass nonlinearities with complex Gaussian nonzero-mean non-stationary inputs. In this project, by modeling the nonlinear power amplifier with memory as a memory polynomial model. We do a theoretical characterization of nonlinear distortion effects with memory on multi-carrier system in fading channels. We show that the nonlinear distortion with memory can be canonically characterized by a complex attenuation component and nonlinear noise component. Analytical expressions for the complex attenuation component and nonlinear noise component are derived. Thus a complete closed form evaluation of multi-carrier system performance in presence of nonlinear HPA with memory in a fading and non-fading channel is done in terms of received SNR and Bit Error Rate (BER).

2) **Error Vector Magnitude Analysis for Carrier Aggregated OFDM signals with Nonlinear HPA**: Carrier aggregation of OFDM signals as proposed in Long Term Evolution Advanced (LTE-A) further increase the PAPR of the transmitting signal. In carrier aggregation, multiple unused discrete frequency bands are aggregated together to transmit wideband signals. Carrier aggregation further increases the PAPR of transmit signal, which experiences nonlinear distortion when it is passed through a nonlinear HPA. In order to attain maximum efficiency, PA are generally operated near saturation region, however due to high PAPR they may cross over to nonlinear region resulting in adjacent channel interference and EVM degradation.
   In this project, we have analyzed the EVM performance of dual band carrier aggregated OFDM signal in presence of nonlinear HPA. The closed from expression of EVM is derived by modeling the HPA as an 2D generalized memory polynomial (GMP) (2D GMP) model. Further, the impact of input back off (IBO) on EVM has also been investigated.

3) **Studying of the nonlinear transmitter constraints on the Downlink Multi-User MIMO-OFDM system:** Combining OFDM with MU-MIMO, the problem of

intersymbol interference can be resolved which is not possible in case of other MU-MIMO systems. This further increases the efficiency of MU-MIMO system, and is commonly known as MU-MIMO-OFDM system. However, like MIMO-OFDM systems, MU-MIMO-OFDM systems also suffers from high peak-to-average-power ratio (PAPR) which leads to performance degradation in the presence of nonlinear High power amplifiers (HPAs), which are the main contributor of nonlinear distortion in transmitter. In this work, we analyzed the impact of HPA nonlinearity on the performance of both single band and carrier aggregated dual band MU-MIMO-OFDM system. The nonlinear behavior of the HPA has been characterized by a memory polynomial (MP) model for single band system and by two-dimensional generalized memory polynomial (2D-GMP) model for dual band system. The performance has been quantified by measuring the symbol error rate (SER) at the receiver.

8. CONTRIBUTION TO THE SOCIETY:
    1) Energy efficient transmission methodology has been proposed for wireless transmitter which will lead to considerable amount of power savings and reduction in carbon footprints.
    2) The proposed methodology will also reduce the cost to run a base- station hence will bring down the operating cost of an operator.

9. WHETHER ANY PhD ENROLLED/PRODUCED OUT OF THE PROJECT: Yes, one PhD student (Ms. Mansi Peer)
10. NO. OF THE PUBLICATION OF THE PROJECT (PLEASE ATTACH):

[1] P. Aggarwal and V. A. Bohara, ”Characterization of HPA using two dimensional general memory polynomial for dual band carrier aggregated mimo-OFDM systems,” 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, 2016, pp. 1-7.

[2] P. Singhal, P. Aggarwal, V. A. Bohara, Analysis of Carrier Aggregated OFDM signals in presence of Dual band Power amplifiers 2015 Twenty First National Conference on Communications (NCC), Mumbai, 2015, pp. 1-6. doi: 10.1109/NCC.2015.7084855

[3] P. Aggarwal, A. Agarwal, V. A. Bohara, “Error Vector Magnitude Analysis for Carrier Aggregated OFDM signals with Nonlinear HPA” 2016 IEEE International Conference on Advanced Networks and Telecommunications Systems (IEEE ANTS 2016), IISC-Bangalore, 2016, pp. 1-3. doi: 10.1109/ANTS.2016.7947866.

[4] P. Aggarwal and V. A. Bohara, “A Nonlinear Downlink Multiuser MIMO-OFDM Systems” in IEEE Wireless Communications Letters, vol. 6, no. 3, pp. 414-417, June 2017.

[5] P. Aggarwal and V. A. Bohara, “Nonlinear Transmitter Constraints on the Downlink Carrier Aggregated Dual Band Multi-User MIMO-OFDM System” in IEEE Transactions on Communication, Oct. 2017

[6] P. Aggarwal and V. A. Bohara, "End-to-End Theoretical Evaluation of a Nonlinear MIMO-OFDM System in the Presence of Digital Predistorter," in *IEEE Systems Journal*, vol. 13, no. 3, pp. 2309-2319, Sept. 2019, doi: 10.1109/JSYST.2018.2872609.

[7] N. Gupta, V. Singh, S. Sharma, V. A. Bohara, “Testbed Implementation and Proof-of-Concept Demonstration for Cooperative Device-to-Device Communication Framework” accepted to 2017 IEEE International Conference on Advanced Networks and Telecommunications Systems (IEEE ANTS 2017), Bhubaneswar, 2017.

[8] N. Jain and V. A. Bohara, “Energy Harvesting and Spectrum Sharing Protocol for Wireless Sensor Networks,” IEEE Wireless Communication Letter, vol.4, no.6, pp.697-700, Dec. 2015 (JCR Impact Factor: 2.449),

[9] M. Peer and V. A. Bohara, “Spectrum and Energy Harvesting Protocols for Wireless Sensor Nodes,” accepted as book chapter in Wireless Energy Harvesting for Future Wireless Communications, to be published by Springer-Verlag New York, USA.

[10] A. Jolly, M. Peer, V. A. Bohara and S. Verma, “Design and Development of Dual-Band Multi-Stage RF Energy Harvesting Circuit for Low Power Applications” accepted to Proceedings of IEEE International conference on advance networks and telecommunication systems (IEEE ANTS 2017), Bhubaneshwar, India, Dec., 2017.