ERCIM "ALAIN BENSOUSSAN"
FELLOWSHIP PROGRAMME

Scientific Report

First name / Family name	Indrakshi / Dey
Nationality	India
Name of the *Host Organisation*	NTNU, Norway
First Name / family name of the *Scientific Coordinator*	Pierluigi / Salvo Rossi
Period of the fellowship	01/06/2016 to 31/05/2017

I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

Several distinct applications have been identified under 5G (5th Generation) and advanced 5G wireless network technology that include applications like, vehicle-to-vehicle and vehicle-to-infrastructure communication systems, smart homes and cities, augmented reality services etc. that can generate sporadic traffic and therefore are quite spectrum hungry, as well as, delay-tolerant, narrowband applications like smart grids, smart metering, industrial automation and utilities etc. However, in both cases, huge volumes of end-points will be served by low-cost sensors and modules, all sending their observations to the base stations or decision fusion centers equipped with a large array of antennas, thereby, representing a distributed virtual Massive multiple-input-multiple-output (MIMO) system set-up.

The main goal of my research at NTNU was concentrated on understanding and summarizing the practical implications of using Massive MIMO for experimental analysis of future WSNs through a measurement campaign using the Massive MIMO testbed developed by National Instruments (NI). This campaign accounted for characterization of the propagation channel between multiple sensors at different indoor locations communicating simultaneously with a decision fusion center (DFC), realistic comparison of receivers and algorithms for DFC equipped with multiple integrated antennas and activity patterns of different communication entities (sensors and fusion center) including output power, temporal traffic distribution and spatial distribution of spectral occupation.

At NTNU, my research and measurement campaign looked at a Cognitive Machine-to-Machine communication kind of scenario where the mobile units will communicate with the DFC through collaborative spectrum sensing. An orthogonal frequency division multiplexing (OFDM) system is considered with one primary user (PU) and K (unauthorized) secondary users (SUs) that want to transmit in the licensed band if the (authorized) PU is silent. The total spectrum is divided into L sub-channels. The SUs sense those L frequency bands and transmit 1-bit to represent their local decisions on the PU being silent or active, on L sub-carriers of the OFDM symbol (one per frequency band). The DFC provides a reliable decision about the activity of the PU based on the decision taken locally by the SUs independently on each sub-carrier and finally gets a picture of the white spaces available.

To achieve this, 7 mobile NI Software Defined Radios (SDRs) acting as users or sensors (1 as the PU and 6 as the SUs) are deployed on the transmit side but within the transmission power range of the DFC, each SDR being equipped typically with 1 antenna. The PU transmits intermittently on each of the sub-carriers and the SUs will sense it and transmit their decisions accordingly. On the receive side, the DFC set-up is equipped with minimum of 32 antennas. Software modifications are accommodated to the already existing Massive MIMO framework on the receive side to correlate received signals with the synchronization sequence to determine the optimum sampling points for each OFDM packet. On the transmit side, software modifications were done to synchronize among the SUs to ensure that all the SUs fire their decisions on the activity of the PU at the same time, and control pilot transmission for channel estimation.

II – PUBLICATION(S) DURING YOUR FELLOWSHIP

Accepted:

1. I. Dey and P. Salvo Rossi, “Second-Order Statistics for Indoor Wireless Joint Fading/Shadowing Channels," accepted to *IEEE Antenna & Propagation Letters* on Jan. 2017, DOI: 10.1109/LAWP.2017.2651153 (published).
   Abstract - In this letter, we consider the joint fading and two-path shadowing (JFTS) channel model which has been found suitable for characterizing indoor large open office environments with low mobility and stationary users. We derive useful expressions of fundamental channel statistics like the number of level crossings in time, frequency and space as

well as average fade duration, bandwidth and length for the JFTS faded/shadowed link. We also compare numerical results and their impact on system design over a variety of realistic propagation scenarios, that can be modeled by varying the JFTS parameters.

2. I. Dey and P. Salvo Rossi, "Probability of Outage due to Self-Interference in Indoor Wireless Environments," *IEEE Communications Letters*, vol. 21, no. 1, pp. 8 - 11, Jan. 2017 (published).
   Abstract - In this letter, we derive a mathematically-tractable expression for the outage probability in presence of self-interference over indoor wireless environments modeled through the recently proposed joint fading and two-path shadowing (JFTS) channel model. The effect of self-interference is studied under two different conditions encountered in single frequency network (SFN) architectures: i) long propagation delay and correlated shadow fading in a densely-deployed single access point to single mobile user communication scenario and ii) interference between radiated and received signal power in full-duplex radios equipped with multiple antennas both for transmission and reception of data. The analysis is validated numerically both for single-channel and multiple-channels receivers.

3. I. Dey, G. G. Messier and S. Magierowski, "Average Error Rates and Achievable Capacity in Large Office Indoor Wireless Environments," accepted to *IEEE Transactions on Communications*, Under Final Revision (accepted).
   Abstract - Performance of common digital modulation techniques is analyzed over indoor wireless environments modeled through the recently proposed joint fading and two-path shadowing (JFTS) channel model. Mathematically tractable expressions for the instantaneous signal-to-noise ratio (SNR) statistics, average bit error rates (ABER) and achievable channel cutoff rates are derived. Analytical results are used to i) investigate the impact of different JFTS model parameters and different modulation techniques on bit error rates and cutoff rates and, ii) demonstrate how the JFTS channel model affects system performance in comparison to conventional empirical channel models. Finally, simulation results are used to corroborate this analysis and evaluate the usefulness of such an analysis.

4. I. Dey and R. Y. Chang, "Adaptive Coded Modulation for Mobility Constrained Indoor Wireless Environments," in *Proc. IEEE PIMRC 2016* (Valencia, Spain), Sep. 4 - 7, 2016, 6 pages, DOI: 10.1109/PIMRC.2016.7794696 (published).
   Abstract - The performance of rate adaptive trellis-coded and uncoded M-ary quadrature amplitude modulation (M-QAM) over large open office indoor wireless environments is studied in this paper. An appropriate composite fading/shadowing channel model termed the joint fading and two-path shadowing (JFTS) model is adopted for such an indoor wireless environment, where mobility of users remains constrained within a small space. Mathematically tractable expressions for the spectral efficiency and average bit error rate (ABER) of adaptive coded and uncoded M-QAM over the JFTS channel are derived. Numerical results demonstrate that in contrast to conventional fading models like Rayleigh and Nakagami-m distributions, the error probability performance of rate adaptive M-QAM over a JFTS faded/shadowed link never approaches zero for lower channel signal-to-noise ratios (CSNRs).

5. I. Dey G. G. Messier and S. Magierowski, "Adaptive Modulation and Coding for Large Open Office Indoor Wireless Environments," in *Proc. IEEE VTC Fall 2016* (Montreal, Canada), Sep. 18 - 21, 2016, 5 pages, DOI: 10.1109/VTCFall.2016.7880891 (published).
   Abstract - The performance of rate adaptive M-ary quadrature amplitude modulation (M-QAM) and adaptive trellis-coded M-QAM in large open office indoor wireless environments is studied in this paper. An appropriate composite fading/shadowing channel model termed the Joint Fading and Two-path Shadowing (JFTS) model is adopted for the indoor wireless environment. Mathematically tractable expressions for the spectral efficiency and average bit error rate (ABER) of adaptive coded and uncoded M-QAM over the JFTS channel are derived. Analytical results demonstrate the performance of adaptive M-QAM over different JFTS channel configurations, and simulation results corroborate the derived analytical ABER expressions.

Papers under preparation:

1. Dey, P. Salvo Rossi and D. Ciuonzo, “Wideband Collaborative Spectrum Sensing using Massive MIMO Decision Fusion," to be submitted to *IEEE Communications Letters*.
2. I. Dey, H. Melby, P. Salvo Rossi and D. Ciuonzo, “Experimental Analysis of Wireless Sensor Network Channels and Decision Fusion Performance using Massive MIMO Test-bed," to be submitted to *IEEE Transactions on Wireless Communications*.
3. I. Dey and P. Salvo Rossi, “Distributed MIMO Wireless Sensor Network - Channel Modeling and Fusion Performance Analysis," to be submitted to *IEEE Transactions on Communications*.
4. I. Dey, A. Krishnamoorty, M. Landmann, M. Kaske, F. Raschke and M. Breiling, “Modeling of Deployment Scenario for Stationary SUDAS - A Distributed Antenna System for Outdoor-to-Indoor Communication,” to be submitted to *IEEE Transactions on Communications*.
5. I. Dey, A. Krishnamoorty, P. Salvo Rossi and M. Breiling, “Diversity Analysis for Implementation of SUDAS - A Distributed Antenna System,” to be submitted to *IEEE Wireless Communications Letters*.

III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

Conference: International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2016 conducted by IEEE in Valencia, Spain, on September 4 - 7, 2016.

IV – RESEARCH EXCHANGE PROGRAMME (REP)

The research exchange program (REP) consisted of two parts.

Part I: *Location* - Fraunhofer IIS, Erlangen, Germany
Scientific Coordinator – Dr. Marco Breiling
Duration – 27/03/2017 – 31/03/2017

In the first part, I visited Broadband & Broadcast department of the Fraunhofer IIS, Erlangen, Germany to discuss in detail on the technical requisites for the development of the Shared User-equipment (UE) side Distributed Antenna System (SUDAS). SUDAS is a distributed antenna system for outdoor-to-indoor communication developed by Fraunhofer IIS and is a promising contender for 5G standardization for indoor usage scenarios. SUDAS components act as outdoor-to-indoor relays that forward outdoor MIMO signals to indoor UEs over millimeter (mm) wave links.

To evaluate the performance of SUDAS in various realistic deployment scenarios, radio frequency wave models for various indoor environments are necessary. Interesting deployment scenarios for SUDAS include: medium sized office environments such as conference rooms; home environments with multiple rooms and fixed obstructions (walls); and large environments such as operas or theatres with no obstructions but large communication distances. With these analytical models, simulations may be performed to evaluate the deployment parameters such as location of SUDACs (roofs, floor level, outlet level, etc.) and their constellation (minimum distance, pattern, etc.). The simulations can in turn help to identify new/unidentified challenges in mm-wave communication leg of SUDAS (such as beamforming, waveform design challenges.)

SUDAS is a 2-hop relaying solution using sub-6 GHz in the first hop and mm-wave (say 60 GHz) in the second. Therefore, to evaluate the performance of SUDAS in various realistic deployment scenarios, detailed measurement campaigns for various indoor environments are necessary. Very broadly, there are two primary requirements for the SUDAS measurements,

- To characterize the outdoor-to-indoor "base-station to SUDAS" channel in sub-6 GHz
- To characterize the mm-Wave indoor channel "SUDAS to UEs" around 60 GHz.

Part II: *Location* - Fraunhofer IIS, Ilmenau, Germany
Scientific Coordinator – Dr. Markus Landmann
Duration – 03/04/2017 – 07/04/2017

In the second part of REP, I conducted a detailed measurement campaign at the Facility Over-the-Air Research and Testing (FORTE) of Fraunhofer IIS in Ilmenau, Germany. The campaign is intended for capturing propagation characteristics for an outdoor-to-indoor "base-station to SUDAS" communication scenario in a sub-6 GHz band. In the campaign, the time-varying complex impulse response of an 8 X 8 multiple input multiple output (MIMO) channel with 20 MHz bandwidth will be measured. The antennas on the transmit side are mounted at a height of around 48m on a tower. Four different dual-polarized antennas are used for transmission, where both the polarization in each case are activated to have functionally effective 8 antennas on the transmit side. The transmit antennas set-up on the tower are arranged in two columns, two antennas on each. In that case, the antennas transmit with ±45 degrees polarizations. On the receive side, 8 half-omnidirectional antennas are deployed simultaneously at different heights and various locations in 2 different rooms of the FORTE building. The channel measurements are conducted and recorded using the MEDAV RUSK – HyEff MIMO channel sounder.

Two rooms are selected of which, one is located on the 2nd floor and the other one is located on the 1st floor of the building. These rooms are chosen such that a wide variety of indoor communication environments can be measured and characterized. Some of the interesting scenarios include room with keyhole effect (rooms with no windows) and with no direct line-of-sight (LOS) communication, conference room (with both direct LOS and non-line-of-sight (NLOS) communication paths) and room with cluttered with several noisy electrical, metering equipment etc. (potential scenarios for future industrial automation).

For each measurement set, the 8 receive antennas are deployed simultaneously but at different heights, namely, near the ceiling, near the ground, at the heights of 1m, 1.5m and 2m, and at various locations, namely, distributed on all 4 walls, on only 3 walls, on only 1 wall at a time etc. For the room, upstairs (conference room), each measurement set is repeated for a stationary scenario and people moving on a defined track through the scenario. In case of the stationary scenario, each measurement set is recorded for 1000 snapshots, each snapshot being 6.4 µs long. In case of dynamic scenario, measurement is recorded for the time duration it takes for one person to walk through the entire room (around 19 - 20 secs). For the room downstairs (instrumentation room with no windows), each measurement set is conducted only for the stationary scenario due to the improbability of any dynamic scenario in an automation/factory/instrumentation environment. In this case, each measurement set is recorded for 5000 snapshots, each snapshot again of being 6.4 µs.

V – CONCLUDING REMARKS

The next step is to analyse the data collected from both the measurement campaign, one conducted to model virtual Massive MIMO communication scenario in WSN using a NI software architecture based Massive MIMO test-bed developed at NTNU and the other, conducted to model communication with SUDAS systems using the virtual MIMO channel sounding facility and distributed antenna components developed by Fraunhofer Institute for Integrated Circuits IIS. The entire analysis will take a few more months beyond the timeline of the original fellowship. I will continue to work on them delivering all the required analysis, results and publications as a side-project during my next tenure at Trinity College Dublin, Ireland as a Marie Currie Fellow. There are possibilities that several interesting results will come up from the detailed study of the measured data and will help me to set-up future long-term research collaborations with both NTNU and Fraunhofer.