Title: **Practical Massive MIMO: Performance Bottlenecks and How to Overcome Them**

Duration: Half-day (3 hours)

Presenters (in alphabetical order by last name):

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Description of the Tutorial:

This is a three hour (half day) tutorial that discusses the causes and effects of different impairments in a practical massive MIMO system, along with techniques to mitigate them. The recent popularity of massive MIMO systems is due to the high spectral and energy efficiencies offered by them, even with simple linear signal processing techniques being employed at the BS. These advantages require the availability of accurate and up-to-date channel state information (CSI) at the BS. However, the accuracy of the CSI at the BS is compromised due to several reasons, e.g. as pilot contamination, channel aging and reciprocity imperfections in massive MIMO system and severely limit the performance of these systems. In the context of millimeter wave (mmWave) communications, the hybrid analog-digital architecture and low resolution ADCs further limit the performance. While these effects have been studied independently, in this tutorial, we aim to bring all these effects under a common umbrella. We first discuss the modelling of the effects of these impairments. Following this, we use signal processing tools, mainly based on blind channel estimation and tracking to develop techniques for mitigating the effects of these impairments. Finally, we relate these to more recent attempts at mitigating these imperfections using machine learning (ML) based methods.

Organization of the Tutorial

I. **Setting the Stage (15 mins)**
    a. Introduction to large MIMO and massive MIMO systems
    b. Core analysis techniques, basic results
    c. The importance of accurate CSI and its acquisition
    d. Introduction to CSI impairments
        i. Pilot Contamination
        ii. Channel Aging
        iii. Reciprocity Imperfections
II. **Pilot Contamination (15 mins)**
    a. The problem of limited duration training: pilot contamination
    b. List of solutions without detailed derivations
    c. Non-orthogonal pilot design to mitigate pilot contamination
    d. NOMA transmission in Massive MIMO systems with contaminated pilots
III. **The Problem of Channel Aging (45 mins)**
    a. Causes and effects
    b. A first example: The large MIMO case
    c. Aging under FDD massive MIMO: More antennas are not always better

d. Aging with controlled pilot contamination and NOMA: What is good in a static channel may be bad in an aging channel
e. The massive MIMO-OFDM case: dealing with the loss of subcarrier orthogonality
f. Channel aging in cell-free massive MIMO systems

IV. Dealing with channel aging (35 mins)

a. Users at different velocities: One size does not fit all
b. Tracking of aging channels
    i. Kalman Filtering
    ii. Adaptive Filtering
    iii. Machine Learning

V. Reciprocity Imperfections (30 mins)

a. Causes and effects
b. Mitigating the detrimental effect of reciprocity imperfections
    i. Blind channel estimation
    ii. Limited downlink pilots
    iii. Full downlink training

VI. Beyond 5G Systems (30 mins)

a. Out of band Radiation
b. Effects of quantization and low-resolution ADCs
c. mmWave communications: hybrid architectures, low resolution ADCs
d. Cell free systems and small cells, and their resilience to impairments

VII. Open problems and discussion; future outlook (10 mins)