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Hybrid Analog & Digital Precoding in Millimeter Wave Massive MIMO Systems with Realistic Hardware & Channel Constraints

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Signal Processing for 5G Wireless Access 2017, Gothenburg, Sweden

Abstract

Millimeter-Wave (mmWave) systems recently attracted attention as one of the key enablers for the Fifth Generation (5G) networks. The small wavelength at mmWave frequencies enables deploying massive Multiple Input Multiple Output (MIMO) antenna arrays with reasonable form factor. However, **Massive MIMO** mmWave systems suffer from a lot of practical limitations, specifically due to **channel** and **hardware** characteristics at such high frequencies. In this poster we propose multiple solutions to design a realistic massive MIMO cellular system that takes into account the imposed **limitations** and achieves considerable **gains** in terms of spectral efficiency.

Research Objectives

Transmit Beamforming

Different Architectures (Digital-Analog-Hybrid)

Channel Estimation

Spatial sparsity of channel – Compressive Sensing

Course Quantization

Analog to Digital Converters (ADCs) with few quantization bits (Large BandWidth (BW) – low Signal to Noise Ratio (SNR))

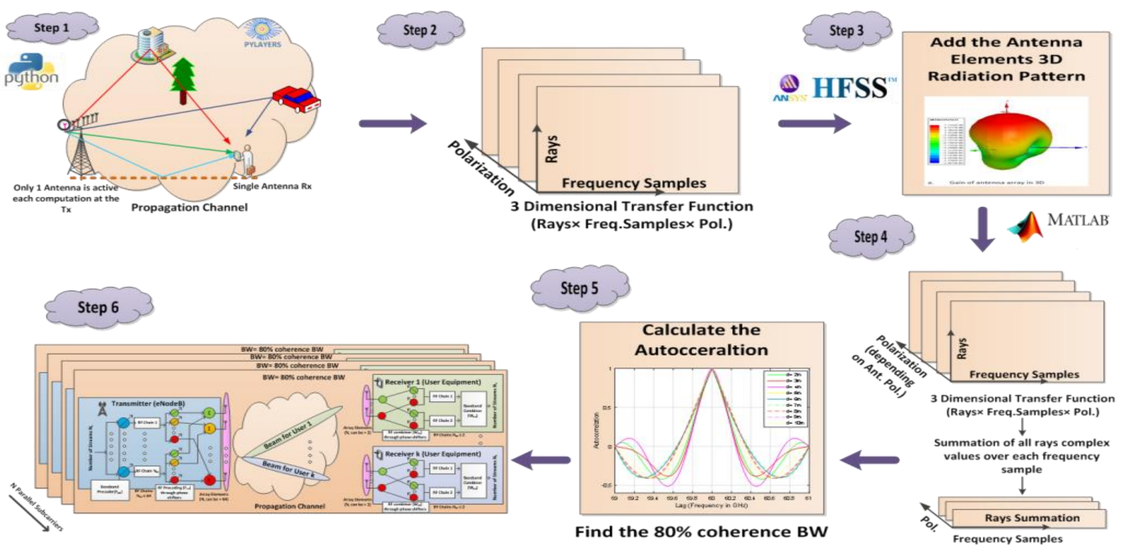
Analog Impairments

Phase Shifters' limitatons (constant amplitude – quantized phases – power loss)

Antenna Array

Directive Antennas to compensate for severe pathloss.
Array structures that provide direct access to the beamspace (Lens Array – Buttler Matrix)

System & Channel Model



Simulation Chain Architecture

- Multi-User (MU) MIMO system with K User Equipments (UEs) each equipped with N_r antennas.
- The transmitting Base Station (BS) is equipped with N_T antennas & serving each UE with N_s streams.
- The received signal vector $\boldsymbol{y}$ is given as follows (we omit the UE index k for clarity):

$$\boldsymbol{y} = \sqrt{\rho}\boldsymbol{W}^H\boldsymbol{H}\boldsymbol{F}\boldsymbol{s} + \boldsymbol{W}^H\boldsymbol{n}$$

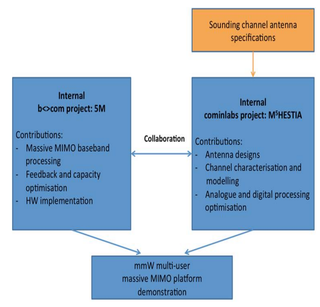
AWGN; Transmit power; Combiner matrix of dimensions $N_s \times N_r$; Precoder matrix of dimensions $N_T \times N_s$; Signal vector of dimensions $N_s \times 1$

$$\boldsymbol{H} = \sum_{l=1}^{N_p} \boldsymbol{\alpha}_l e^{-j2\pi f \tau_l} \boldsymbol{a}_R(\theta_{R,l}, \varphi_{R,l}) \boldsymbol{a}_T{}^H(\theta_{T,l}, \varphi_{T,l})$$

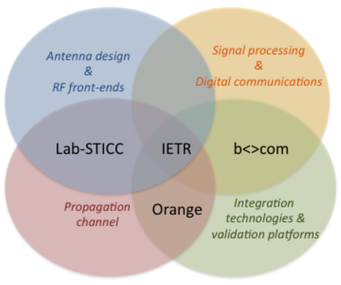
Number of paths; Complex gains considering pathloss and reflections; Delays; Receive steering vector, where: $\theta_{R,l}$: Elevation angle, $\varphi_{R,l}$: Azimuth angle; Transmit steering vector, where: $\theta_{T,l}$: Elevation angle, $\varphi_{T,l}$: Azimuth angle

M[5]HESTIA

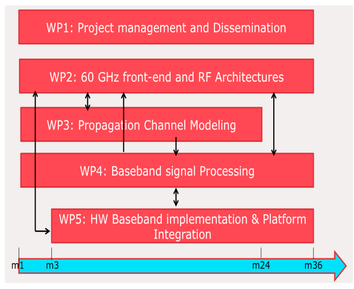
MHESTIA: Millli-Meter-wave Multi-user Massive MIMO Hybrid Equipment for Sounding, Transmissions and hardware ImplementAtion.



2 projects in parallel

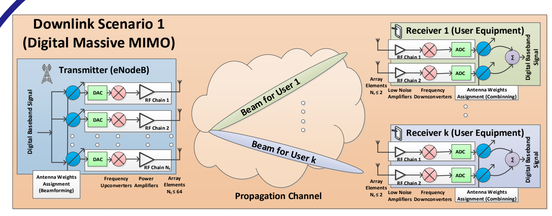


Consortium



project Organization

Beamforming Scenarios



Digital Beamforming

$$\boldsymbol{y} = \sqrt{\rho}\boldsymbol{W}_{BB}{}^H\boldsymbol{H}\boldsymbol{F}_{BB}\boldsymbol{s} + \boldsymbol{W}_{BB}{}^H\boldsymbol{n}$$

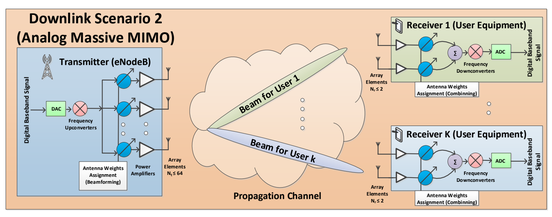
Total transmit power constraint: $\|\boldsymbol{F}_{BB}\|^2_F \leq 1$

Advantages

- Can serve interference free MU scenarios with number of UEs = N_T
- A lot of existing digital precoding techniques exist in the literature

Disadvantages

- RF chain is required for each antenna
- This applies limitations on implementing Massive MIMO mmWave systems, since RF chains are complex and power hungry in mmwave regime



Analog Beamforming

$$\boldsymbol{y} = \sqrt{\rho}\boldsymbol{W}_{RF}{}^H\boldsymbol{H}\boldsymbol{F}_{RF}\boldsymbol{s} + \boldsymbol{W}_{RF}{}^H\boldsymbol{n}$$

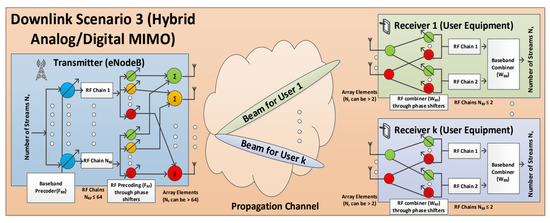
Phase shifters constraints (constant Amplitude & quantized angles): $\boldsymbol{F}_{RF} \in \mathcal{F}_{RF}, \boldsymbol{W}_{RF} \in \mathcal{W}_{RF}$

Advantages

- Low hardware complexity and power consumption (Only 1 RF chain is required)
- Can increase the link budget
- Can serve MU scenarios through multiplexing in Time/Frequency

Disadvantages

- Can't support MU MIMO scenarios with spatial multiplexing
- Therefore it is not favourable from Spectral Efficiency (SE) point of view



Hybrid Beamforming

$$\boldsymbol{y} = \sqrt{\rho}\boldsymbol{W}_{BB}{}^H\boldsymbol{W}_{RF}{}^H\boldsymbol{H}\boldsymbol{F}_{RF}\boldsymbol{F}_{BB}\boldsymbol{s} + \boldsymbol{W}_{BB}{}^H\boldsymbol{W}_{RF}{}^H\boldsymbol{n}$$

Total transmit power constraint: $\|\boldsymbol{F}_{RF}\boldsymbol{F}_{BB}\|^2_F \leq 1$
Phase shifters constraints (constant Amplitude & quantized angles): $\boldsymbol{F}_{RF} \in \mathcal{F}_{RF}, \boldsymbol{W}_{RF} \in \mathcal{W}_{RF}$

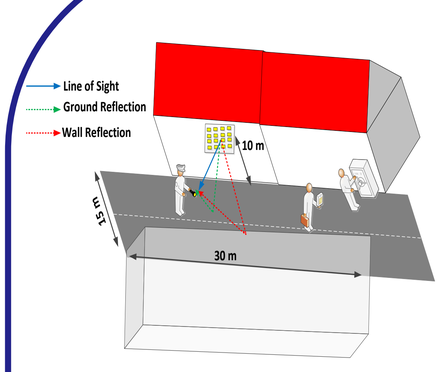
Advantages

- Can employ much more transmit antennas than the number of RF chains
- Henceforth, can achieve higher transmit gain compared to digital systems with the same number of RF chains (hardware complexity)

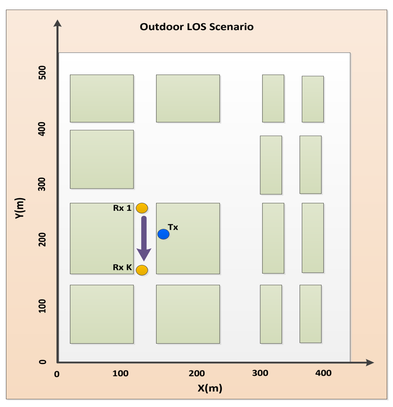
Disadvantages

- Analog impairments due to the power loss and limited resolution of phase shifters

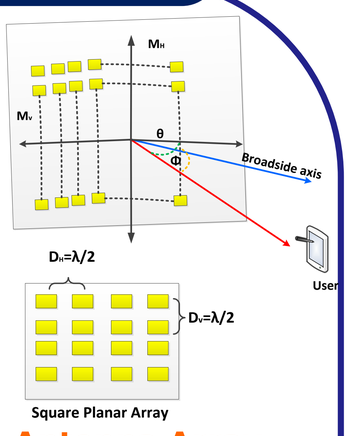
Initial Results



Street Canyon



METIS TC2 (Madrid Grid)

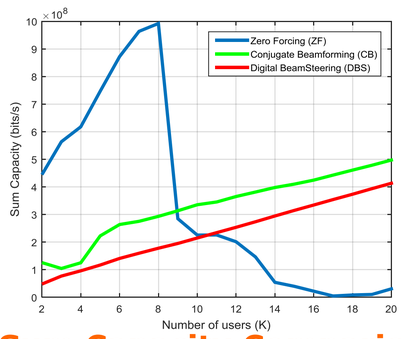


Antenna Array Structure

Precoding	Complexity	$\mathbf{W}_n$	Maximize
CB	++	$\mathbf{H}_n^H$	SNR
ZF	+++	$\mathbf{H}_n^H(\mathbf{H}_n\mathbf{H}_n^H)^{-1}$	SIR
DBS	+	$\mathbf{A}^H$	SNR

Simulation Parameters:

- Environment: Street Canyon
- System: MU-MIMO
- Channel Model: PyLayers [1]
- Antenna Array height: 10m
- Antenna Spacing: $\frac{\lambda}{2}$
- Scenario: Outdoor LoS
- Center Frequency: 60 GHz
- Intercarrier spacing: 20 MHz
- Transmit Antennas: 16
- Transmit Antenna Array: Square
- Receive Antennas: 1
- UEs interdistance: 1m
- Transmit Power: 26 dbm



Sum Capacity Comparison

Conclusion:

- ZF overperfoms CB and DBS in sum capacity when the number of UEs is smaller than the channel rank.
- CB and DBS still achieve high sum capacity in mmWave systems even with exceeding the degrees of freedom with lower complexity compared to ZF.
- The main advantage of the DBS lies on estimating only $2K$ angles instead of $\frac{K \times N_T \times N_{FFT}}{N_{BC}}$ parameters in ZF and CB.

K: the number of UEs N_T: number of transmit antennas, N_{FFT}: number of subcarriers, N_{BC}: number of subcarriers per coherence BW

[1] *PyLayers : An Open Source Dynamic Simulator for Indoor Propagation and Localization*, N. Amiot, M.Laaraiedh, B.Uguen, Communications Workshops ICC 2013

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