# Single RF Chain Hybrid Analog/Digital Beamforming for mmWave Massive-MIMO

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Background and Motivation

System Model and Single RF Chain Architecture

HADP Designs Based on SRCA
- Phase Shifter Bank
- Analog Constellation
- Hybrid Beamformer with RF Multiplier

Comparison and Simulation Results

Summary and Conclusion

# Outline


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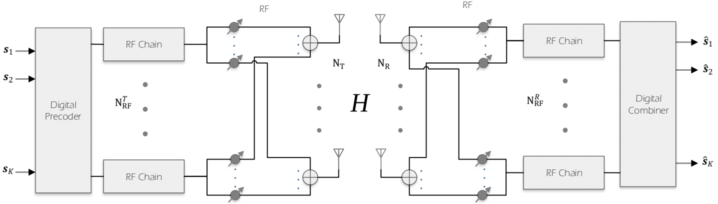
# Hybrid Analog Digital Beamforming

- Benefits of mmWave Massive-MIMO communication
  - Reducing the antenna spacing
  - Small antenna elements
  - Larger number of antennas
  - Capacity increases linearly with the minimum number of antennas
- Challenges in practical implementation of massive-MIMO
  - Power amplifiers and analog-to-digital converters (ADC) are power hungry modules
  - Conventional baseband/digital beamforming is not practical
- Hybrid Beamforming is the solution




Hybrid Analog Digital Massive-MIMO System

# Paper contributions

## Objective

To design novel HBF schemes which single RF chain analog/digital beamforming

## Main contributions

- Discuss implementation aspects of Single RF Chain Architecture (SRCA)
- HBF schemes based on SRCA:
  - Phase-Shifter Bank
  - Analog Constellation
  - Hybrid Beamformer with RF Multiplier
- Precoding applications:
  - Single-user
  - Multi-user

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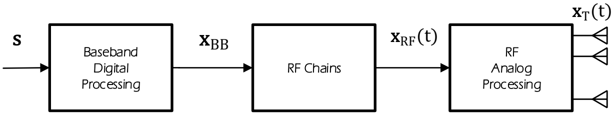
# Transmitter with Precoder




- $N_T$ antennas
- $N_{RF}$ RF chains
- $K$ data streams
- $d$ symbols for each stream
- $\mathbf{s}_i = [s_{i,1}, s_{i,2}, ..., s_{i,D}]^T$ is the symbol vector of the $i$th user
- $s_{i,j}$'s taken from constellation $\mathscr{A}$ (such as M-QAM or M-PSK)
- $\mathbf{s} = [\mathbf{s}_1^T, \mathbf{s}_2^T, ..., \mathbf{s}_K^T]^T \in \mathscr{A}^{N_s}$, $N_s = DK$ is fed to precoder
- $\mathbf{x}_{\mathrm{BB}}^T \in \mathbb{C}^{N_{RF}}$ is the output vector of the digital module in baseband
- $N_{RF}$ RF chains convert $\mathbf{x}_{\mathrm{BB}}^T$ into an RF analog signal $\mathbf{x}_{\mathrm{RF}} \in \mathbb{C}^{N_{RF}}$
- $\mathbf{x}_{\mathrm{RF}}$ is fed to the analog processing module (analog precoder)
- The output signal $\mathbf{x}_{\mathrm{T}} \in \mathbb{C}^{N_T}$ is then transmitted via antenna array

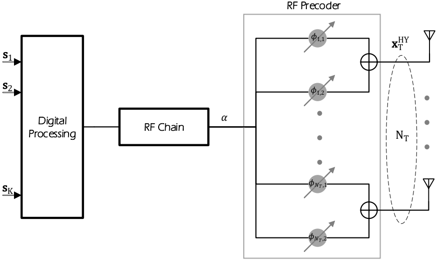
# Single RF chain Architecture

- Any FDP can be realized by a single RF chain HADP as shown in the figure below with the following parameters [Morsali et al., 2017]:

$$\alpha \geq \frac{1}{2}|x|_{max} \quad (1a)$$

$$\phi_{i,1} = \vartheta_i - \cos^{-1}\left(\frac{|x_i|}{2\alpha}\right) \quad (1b)$$

$$\phi_{i,2} = \vartheta_i + \cos^{-1}\left(\frac{|x_i|}{2\alpha}\right). \quad (1c)$$




- where $x_i = |x_i|e^{j\vartheta_i}$ denote the polar representation of the $i$th entry of the vector $\mathbf{x}_{\mathrm{T}}^{\mathrm{FD}}$ also, $|x|_{max}$ and $|x|_{min}$ are defined as the minimum and maximum values of $|x_i|$ for $i = 1, \ldots, N_T$

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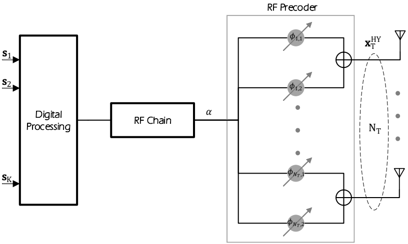
# Beamformer designs based on SRCA

- SRCA enables us to generate any desired signal vector $\boldsymbol{x}$ of size $M$ in RF domain with one RF chain
- Let us introduce $\mathcal{S}_M(\boldsymbol{x}, \alpha)$ as a primary block which generates the given signal $\boldsymbol{x}$ in RF domain if RF signal $\alpha$ is fed to it



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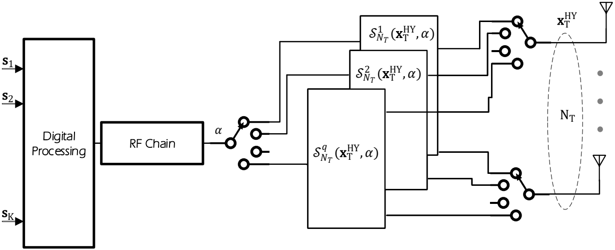
# Phase Shifter Bank

- Our proposed FDP realization [Morsali et al., 2017] [1] requires analog precoder to be updated at each symbol period $T_s$
- For particular implementations which cannot meet this requirement, we present an alternative design based on phase shifter banks
- Assuming the minimum update period of the chosen phase shifter is $T_p$, this structure requires phase shifter bank of size $q \geq \lceil \frac{T_p}{T_s} \rceil$
- Each analog beamformer and consequently each phase shifter must be updated $qT_s \geq T_p$

[1] A. Morsali, A. Haghighat and B. Champagne, "Realizing Fully Digital Precoders in Hybrid A/D Architecture with Minimum Number of RF Chains," in IEEE Communications Letters, vol. PP, no. 99, pp. 1-1. doi: 10.1109/LCOMM.2017.2717824

# Phase Shifter Bank




- Output of the RF chain is connected to an analog switch (multiplexer) and the switch selects each of the analog beamformers in turn
- Each antenna is connected to an analog switch which selects the active analog precoder
- Since power consumption is the key challenge, adding extra hardware is acceptable in the system design

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# Baseband digital precoder

- To realize a fully digital baseband precoder we must have:

$$\mathbf{x}_{\mathrm{T}}^{\mathrm{HY}} = \mathbf{P}_{\mathrm{FD}}\mathbf{s} \quad (2)$$

- The FDP matrix can be written as:

$$\mathbf{P}_{\mathrm{FD}} = [\mathbf{p}^1, \mathbf{p}^2, ..., \mathbf{p}^{N_S}] \quad (3)$$

where $\mathbf{p}^j$'s are columns of the precoder matrix

- Having $\mathbf{s} = [s_1, s_2, ..., s_{N_s}]^T$, vectorizing $\mathbf{P}_{\mathrm{FD}}$ as:

$$\mathbf{p} = [\mathbf{p}^{1^T}, \mathbf{p}^{2^T}, ..., \mathbf{p}^{{N_S}^T}]^T \quad (4)$$

and defining:

$$\mathbf{S} = [s_1\mathbf{I}_{N_T}, s_2\mathbf{I}_{N_T}, ..., s_{N_s}\mathbf{I}_{N_T}] \in \mathbb{C}^{N_T \times N_T N_s} \quad (5)$$

- Therefore, (2) can be also written as:

$$\mathbf{x}_{\mathrm{T}}^{\mathrm{HY}} = \mathbf{S}\mathbf{p} \quad (6)$$

# Analog Constellation Beamformer

Using algorithm 1, vector $\mathbf{p}$ can be generated by one RF chain and matrix $\mathbf{S}$ is implemented by analog constellation (AC) blocks which consist of phase shifters and switches

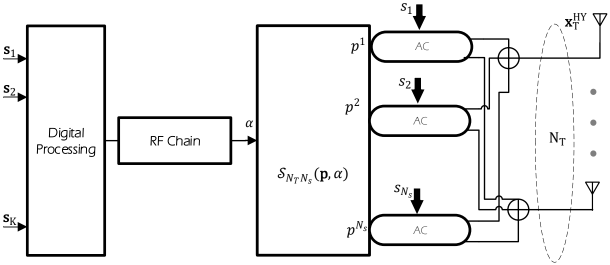


Figure: Analog Constellation beamformer

# Analog Constellation

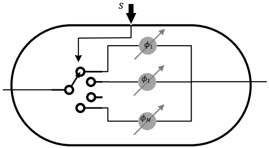


Figure: Analog Constellation block for M-PSK.

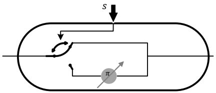


Figure: Analog Constellation block for BPSK.

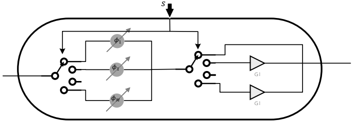


Figure: Analog Constellation block for M-QAM.

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# Analog precoder by RF multipliers

- Using RF multipliers, we present a new structure for hybrid beamforming which relaxes the unit modulus constraints of the analog precoder
- RF multipliers are not useful in conventional FDP and even modern hybrid design because:
  - Implementation of conventional FDP with RF multipliers requires more RF chains than baseband FDP, i.e., $(N_T + 1)N_s$ RF chains!
- However, using RF multipliers in SRCA simplifies the RF precoder design
- We introduce a general structure which can be used for designing various hybrid signal processing systems
- This technique relaxes the the unit modulus constraint of analog precoders

# Hybrid Beamformer with RF Multipliers

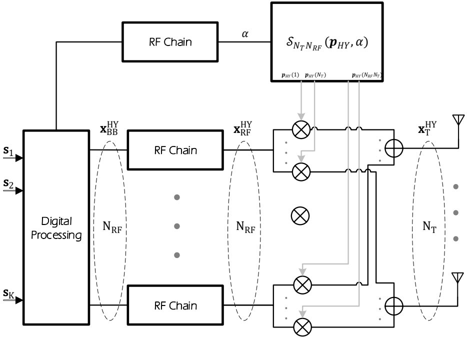


Figure: Hybrid beamformer with RF multipliers.

# Hybrid Beamformer with RF Multiplier

- The output of the system is:

$$\mathbf{x}_{\mathrm{T}}^{\mathrm{HY}} = \mathbf{P}_{HY}\mathbf{x}_{\mathrm{RF}}^{\mathrm{HY}} \tag{7}$$

where

$$\mathbf{P}_{HY} = [\mathbf{p}_{HY}^{1}, \mathbf{p}_{HY}^{2}, ..., \mathbf{p}_{HY}^{N_S}] \in \mathbb{C}^{N_T \times N_{RF}} \tag{8}$$

is the new analog precoder

- Vectorizing the matrix $\mathbf{P}_{HY}$, we have:

$$\mathbf{p}_{HY} = [{\mathbf{p}_{HY}^{1}}^{T}, {\mathbf{p}_{HY}^{2}}^{T}, ..., {\mathbf{p}_{HY}^{N_s}}^{T}]^{T} \tag{9}$$

- The vector $\mathbf{p}_{HY}$ is generated using SRCA
- The most trivial design is to set $\mathbf{P}_{HY} = \mathbf{P}_{\mathrm{FD}}$ and $\mathbf{x}_{\mathrm{RF}}^{\mathrm{HY}} = \mathbf{s}$
- However, more sophisticated decompositions minimize the number of RF chains which will be done in the future.

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# Comparison

Table: Comparison of different structures

| - | $N_{RF}$ | PUP[2] | Applications |
|---|---|---|---|
| Phase-shifter bank | 1 | $T_p$[3] | BF[4], STC[5], CE[6] |
| Analog constellation | 1 | $T_c$[7] | BF |
| SRCA with multiplier | 2 to $K+1$ | $T_c$ | BF,STC,CE |
| Fully digital | $N_T$ | - | BF,STC,CE |
| Existing hybrid designs | $K$ to $N_T$ | $T_c$ | BF |

[2] Phase-shifter update period
[3] Symbol period
[4] Beamforming
[5] Space-time coding
[6] Channel estimation
[7] Channel coherence time

# System Parameters

- In our simulations we consider the follwoing channel model for massive-MIMO mmWave with sparse scattering environments [Ayach et al., 2014, Yu et al., 2016, Morsali et al., 2017]:

$$\mathbf{H} = \sqrt{\frac{N_T N_R}{L}} \sum_{l=1}^{L} \alpha^l \mathbf{a}_r(\phi_r^l)\mathbf{a}_t(\phi_t^l)^H \tag{10}$$

- where, $\alpha^l \sim CN(0,1)$ is the complex gain of $l^th$ path
- $\mathbf{a}_r$ and $\mathbf{a}_t$ are the antenna array responses of receiver and transmitter, respectively
- $\phi_r^l$ and $\phi_t^l$ are arrival and departure angles and have uniform distribution over $[0, 2\pi)$
- Uniform linear configuration with $N = 64$ antennas is used

# Simulation Result

- mmWave channel with $L = 10$, 4-QAM constellation and $N_R = 8$

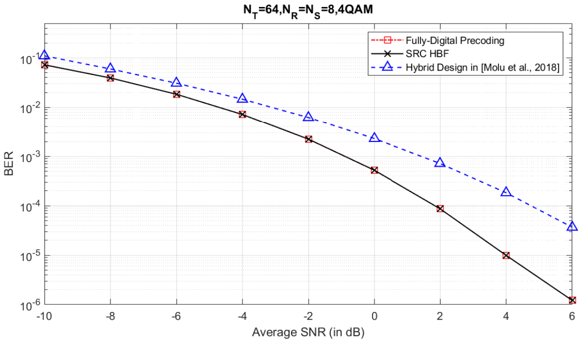


Figure: BER versus SNR for [Molu et al., 2018], fully digital precoding and our design in a $64 \times 8$ massive-MIMO system.

# System Parameters

- In our simulations we used independent multipath channel model [Li et al., 2016], where the channel vector of k-th user can be modeled as:

$$\mathbf{h}_k = \sqrt{\frac{N_R}{L}} \sum_{l=1}^{L_k} \alpha^{k,l} \mathbf{a}_r(\phi^l) \tag{11}$$

- where, $\alpha^{k,l} \sim CN(0, p_{k,l})$ is the complex gain of $l^th$ path with:

$$\frac{1}{L_k} \sum_{l=1}^{k} p_{k,l} = 1 \tag{12}$$

# Simulation Result

- mmWave channel with $L = 10$, 4-QAM constellation and $K = 8$ users

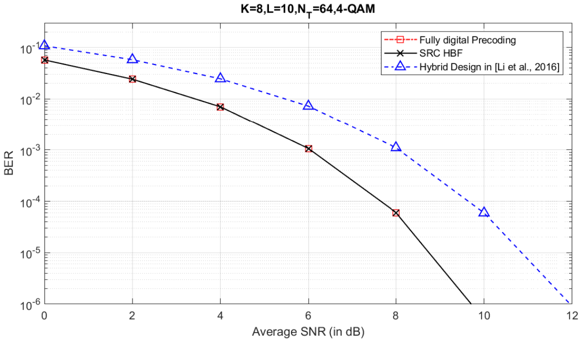


Figure: BER versus SNR for [Li et al., 2016], fully digital precoder and our design in a MU setup with a $64$ massive-MIMO BS.

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# Summary and Conclusion

- We investigated implementation aspects of SRCA
- Single RF chain architecture was presented
- Based on the the single RF chain architecture, three novel hybrid designs where introduced:
  - Phase shifter bank
  - Analog constellation
  - RF multiplier beamformer
- Performed simulation studies and verified the defectiveness of the proposed method

Thank you very much

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