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
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
- \( s_i = [s_{i,1}, s_{i,2}, \ldots, s_{i,D}]^T \) is the symbol vector of the \( i \)th user
- \( s_{i,j} \)'s taken from constellation \( \mathcal{A} \) (such as M-QAM or M-PSK)
- \( s = [s_1^T, s_2^T, \ldots, s_K^T]^T \in \mathcal{A}^{N_s} \), \( N_s = DK \) is fed to precoder
- \( x_{BB}^T \in \mathbb{C}^{N_{RF}} \) is the output vector of the digital module in baseband
- \( N_{RF} \) RF chains convert \( x_{BB}^T \) into an RF analog signal \( x_{RF} \in \mathbb{C}^{N_{RF}} \)
- \( x_{RF} \) is fed to the analog processing module (analog precoder)
- The output signal \( x_T \in \mathbb{C}^{N_T} \) 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 \( x^{FD}_T \) 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 $\mathbf{x}$ of size $M$ in RF domain with one RF chain.
- Let us introduce $S_M(\mathbf{x}, \alpha)$ as a primary block which generates the given signal $\mathbf{x}$ 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] 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 $qT_s \geq T_p$.

---

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:

\[ x_T^{HY} = P_{FD}s \]  

(2)

- The FDP matrix can be written as:

\[ P_{FD} = [p^1, p^2, \ldots, p^{N_S}] \]  

(3)

where \( p^j \)'s are columns of the precoder matrix

- Having \( s = [s_1, s_2, \ldots, s_{N_s}]^T \), vectorizing \( P_{FD} \) as:

\[ p = [p^1^T, p^2^T, \ldots, p^{N_S}^T]^T \]  

(4)

and defining:

\[ S = [s_1I_{NT}, s_2I_{NT}, \ldots, s_{N_s}I_{NT}] \in \mathbb{C}^{NT \times NT \times N_s} \]  

(5)

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

\[ x_T^{HY} = Sp \]  

(6)
Analog Constellation Beamformer

Using algorithm 1, vector $p$ can be generated by one RF chain and matrix $S$ 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:

\[ x_{HY}^T = P_{HY}x_{RF} \]  \hspace{1cm} (7)

where

\[ P_{HY} = [p_{HY}^1, p_{HY}^2, \ldots, p_{HY}^{N_S}] \in \mathbb{C}^{N_T \times N_{RF}} \]  \hspace{1cm} (8)

is the new analog precoder.

Vectorizing the matrix \( P_{HY} \), we have:

\[ p_{HY} = [p_{HY}^1 \, T, p_{HY}^2 \, T, \ldots, p_{HY}^{N_S} \, T]^T \]  \hspace{1cm} (9)

The vector \( p_{HY} \) is generated using SRCA.

The most trivial design is to set \( P_{HY} = P_{FD} \) and \( x_{RF}^{HY} = s \).

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

<table>
<thead>
<tr>
<th>-</th>
<th>$N_{RF}$</th>
<th>PUP$^2$</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-shifter bank</td>
<td>1</td>
<td>$T_p^3$</td>
<td>BF, STC$^5$, CE$^6$</td>
</tr>
<tr>
<td>Analog constellation</td>
<td>1</td>
<td>$T_c^7$</td>
<td>BF</td>
</tr>
<tr>
<td>SRCA with multiplier</td>
<td>2 to $K + 1$</td>
<td>$T_c$</td>
<td>BF, STC, CE</td>
</tr>
<tr>
<td>Fully digital</td>
<td>$N_T$</td>
<td>-</td>
<td>BF, STC, CE</td>
</tr>
<tr>
<td>Existing hybrid designs</td>
<td>$K$ to $N_T$</td>
<td>$T_c$</td>
<td>BF</td>
</tr>
</tbody>
</table>

$^2$Phase-shifter update period

$^3$Symbol period

$^4$Beamforming

$^5$Space-time coding

$^6$Channel estimation

$^7$Channel coherence time
In our simulations we consider the following channel model for massive-MIMO mmWave with sparse scattering environments [Ayach et al., 2014, Yu et al., 2016, Morsali et al., 2017]:

\[
H = \sqrt{\frac{N_T N_R}{L}} \sum_{l=1}^{L} \alpha^l a_r(\phi^l_r)a_t(\phi^l_t)^H \tag{10}
\]

- where, \(\alpha^l \sim CN(0, 1)\) is the complex gain of \(l^{th}\) path
- \(a_r\) and \(a_t\) are the antenna array responses of receiver and transmitter, respectively
- \(\phi^l_r\) and \(\phi^l_t\) 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.
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:

\[ h_k = \sqrt{\frac{N_R}{L}} \sum_{l=1}^{L_k} \alpha^{k,l} a_r(\phi^l) \] (11)

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

\[ \frac{1}{L_k} \sum_{l=1}^{k} p_{k,l} = 1 \] (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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- We investigated implementation aspects of SRCA

- Single RF chain architecture was presented

- Based on the single RF chain architecture, three novel hybrid designs were introduced:
  - Phase shifter bank
  - Analog constellation
  - RF multiplier beamformer

- Performed simulation studies and verified the defectiveness of the proposed method
Thank you very much
References

*IEEE Transactions on Wireless Communications*, 13(3):1499–1513.


