Improving Energy Efficiency of Hybrid Beamforming System

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Abstract. Hybrid beamforming which combines conventional digital beamforming with analog beamforming system is promising model in wireless communication. The problem is using RF chain in digital precoder spends high cost and variable phase shifter exist at analog precoder processing network. Dealing with this problem, many architectures emerge to make lower hardware complexity and power consumption. This paper proposes low-resolution solution using phase over-sampling(POS) and switches(SW) on Radio Frequency(RF) chain to improve energy efficiency. We analyze proposed POS-SW hybrid beamforming system. In the simulation, the estimate is channel capacity in different signal-to-noise and energy efficiency during increasing number of RF chain on 3 dimension(3D) channel environment. It is shown that the proposed system has almost same channel capacity and high energy efficiency compared to the conventional system.

1. Introduction

Millimeter wave(mmWave) in wireless communication is a key feature in the fifth generation(5G) communication. When using high frequency band, size of required antenna is under 1cm that make array to building transmission system due to not enough output power. The main component of hybrid beamforming structure is Radio Frequency(RF) chain and phase shifters(PSs) \textsuperscript{[1]}. RF chain converts analog to digital data to transmit in low frequency and PSs help controlling beam phase and amplitude to develop the shape of beam. Digital beamforming system uses multiple RF chains performing with each antenna that spend high cost. Whereas, analog beamforming system consists of only one RF chain and multiple PSs that have an antenna array. The main problem comes from the high-resolution phase constraints of the PSs. Hybrid beamforming has been proposed as a possible solution \textsuperscript{[2]}. In mmWave communication system, conventional hybrid beamforming is required the large number of high-resolution PSs to construct analog beamformers to solve higher power consumption and hardware complexity. For limited technology of device, hybrid beamforming system has been studied to address the issue in low-resolution PS system. 3 dimension(3D) beamforming is used for fully dynamic adaptation of the beamforming. 3D beamforming based on 3D channel model that were designed to support antenna configurations that are capable of adaptation in azimuth only.

In this paper, the authors propose advanced hardware efficient phase over-sampling(POS)-switches(SW) system based on hybrid beamforming \textsuperscript{[3]}. The limited number of POSs and SWs in analog beamformer part depends on input data bits and antenna array which achieves high energy efficiency as well as maintains high-resolution channel capacity \textsuperscript{[4]}. Although POS-SW architecture is simple, antenna array steers proper beam shape in transmitter. This paper introduces conventional, proposed architecture and 3D channel model. Next, simulation result shows trade-off relationship between channel capacity and energy efficiency on 3D channel environment.
2. Hybrid beamforming

2.1. Traditional PS structure based on hybrid beamforming

‘Figure 1’ shows system model of conventional hybrid beamforming. At the transmitter, a baseband digital precoder process \( N_s \) input data stream to handle \( N_{RF} \) RF chain. Each RF chain combines \( N_{Tx} \) antenna array with PSs called analog precoder. \( N_{Tx} \times N_{RF} = N_T \) antennas and \( N_T \) PSs are used in transmission stage.

\[
\text{Figure 1. Traditional Hybrid Beamforming System}
\]

\[
\text{Figure 2 POS-SW Hybrid Beamforming System}
\]

The general equation of transmit signal for the \( K \) users is as follows:

\[
x = V_{RF}V_{D}V_{s} = \sum_{i=1}^{K} V_{RF}V_{D}V_{s_i},
\]

where \( V_{RF} \) represents digital precoder matrix and \( V_{D} \) represents analog precoder that dimension is \( (N_T) \times N_{RF} \). Thus, the \( k \)-th received signal after decoding processing is as follows:

\[
y_k = H_kV_{RF}V_{D}V_{s_k} + H_k \sum_{i \neq k} V_{RF}V_{D}V_{s_i} + n_k,
\]

where \( s_k \) represents the \( k \)-th user data stream and \( n_k \) denotes Gaussian noise vector that expectation is 0 and variance is 1. Then, the final processed signal can be written as follows:

\[
y_k = W_{RF}H_kV_{RF}V_{D}V_{s_k} + W_{RF}H_k \sum_{i \neq k} V_{RF}V_{D}V_{s_i} + W_{RF}n_k.
\]

In such a system, the overall \( k \)-th user channel capacity \( R_k \) can be written as follows [5]:

\[
R_k = \log_2 \left\{ 1 + W_{RF}C_{k}^{-1}W_{RF}H_k \left( V_{RF}V_{D} \right) \left( V_{RF}V_{D} \right)^{H} H_k^{H} \right\}.
\]
The covariance of the interference plus noise at user $k$ $C_k$ is as follows:

$$C_k = \mathbf{W}_{RF}^H \mathbf{H}_k \left( \sum_{l=1}^{K} (\mathbf{V}_{RF} \mathbf{V}_{D_l}) (\mathbf{V}_{RF} \mathbf{V}_{D_l})^H \right) \mathbf{H}_k \mathbf{W}_{RF} + \sigma^2 \mathbf{W}_{RF}^H \mathbf{W}_{RF}. \quad (5)$$

Based on the energy consumption, since $N_{RF}$ RF chain and $N_T$ PSs are used in system model, the energy efficiency $\eta$ can be designed as follows [6]:

$$\eta_{N=0} = \frac{R_i}{P_i + N_{RF}P_{RF} + N_T P_{PS}} \text{(bps/Hz/W)}, \quad (6)$$

where $P_i$ is the transmitted energy, $P_{RF}$ is the energy consumption by RF chain, $P_{PS}$ is the energy consumed by PS.

2.2. Proposed system architecture: POS-SW

`Figure 2` shows system model of proposed hybrid beamforming. The system utilizes the limited number of simple POSs and switches network. The number of POSs is decided by the resolution of phase. Resolution of analog precoder is $N$ and the number of POSs is $2^N$. POSs values are complex plane angles between maximum and minimum in each antenna array phase divided by $2^N$. POSs values $v_{V_{RF},n}$ express as follows:

$$v_{V_{RF},n} = \min \left( \mathbf{V}_{RF} \right) + \frac{\max \left( \mathbf{V}_{RF} \right) - \min \left( \mathbf{V}_{RF} \right)}{2^N - 1} (n-1), (n=1,2,\ldots,2^N), \quad (7)$$

where $\mathbf{V}_{RF}$ is the matrix of phase analog precoder elements at $T_x$-th RF chain.

Since POSs are connected at antenna array, the number of switches is same as $N_{Tx}$. The proposed hybrid beamforming system also uses digital and analog precoder in different way. Then, the channel capacity is same as conventional system like equation (4). The proposed system energy efficiency is different because conventional PS are replaced by SW. POSs are implemented by simpler inverters or microstrip delay lines. So, POSs have negligible power consumption. The energy efficiency $\eta$ can be redesigned as follows:

$$\eta_N = \frac{R_i}{P_i + N_{RF}P_{RF} + N_T P_{SW}} \text{(bps/Hz/W)}, \quad (8)$$

where $P_{SW}$ is the energy consumed by switch.

2.3. 3D channel model

3D channel model is indispensable system for beamforming system to shape beam pattern. This section describes the 3D channel model proposed by the 3rd generation partnership project(3GPP) and how to express analog precoder based on proposed POS-SW system. Designing hybrid precoder, digital and analog precoder, requires full knowledge of channel state information(CSI). CSI is shown in 3D geometric stochastic model, describing the scattering environment between base station and users. To design 3D channel, the angle of shape of beam direction expressed by $\theta$ the zenith direction
and $\phi$ the azimuth direction [7]. The $r_x$ and $r_z$ are each receiver and transmitter aspherical unit vectors expressed in Cartesian coordinates. They are defined as follows:

$$r_x, r_z = \begin{cases} x = \sin \theta \cos \phi \\ y = \sin \theta \sin \phi \\ z = \cos \theta \end{cases}$$ \hspace{1cm} (9)$$

The $d_{BS}$ is the location vector of basement station antenna array element, the $d_{BS}$ is as follows:

$$d_{BS} = \begin{pmatrix} 0 \\ (p-1)d_H \\ (q-1)d_V \end{pmatrix}$$ \hspace{1cm} (10)$$

where the $p$ and $q$ are index number of antenna element in the horizontal and vertical direction. The $d_H$ is element spacing in the horizontal direction and $d_V$ is element spacing the vertical direction. In hybrid beamforming system, using $r_{tx}$ and antenna array is important point to design analog precoder.

3. Simulation Result

In this section, simulation results are presented to show the difference performance between the conventional and proposed system. As simulation parameter, the number of data streams is 4 and $N_{RF} = 4$, $N_{Tx} = 4$. The users are $K = 2$ and the channel path is 7 in full dimension fading channel. Based on orthogonal frequency division multiplexing (OFDM) system, FFT size is 64 and cyclic prefix (CP) size is 16.

![Figure 3](image1.png)

**Figure 3.** Channel capacity comparison of conventional and POS-SW system

![Figure 4](image2.png)

**Figure 4.** Energy efficiency comparison of conventional and POS-SW system

‘Figure 3’ shows the different channel capacity for conventional and proposed system. Channel capacity of conventional system is the highest because of infinite resolution $N = \infty$ which means PSs steer proper direction in analog beamformer transmitter. In contrast, using POSs and SW has lower channel capacity than conventional system because of low-resolution. ‘Figure 3’ proves that high resolution has similar channel capacity as infinite resolution. In addition, the gap between each line goes lower having high resolution.
‘Figure 4’ shows energy efficiency POS-SW system and conventional system in terms of the number of RF chains based on equation (6), (8). The energy efficiency is defined as the ratio of spectral efficiency to the total power consumed at the transmitter. The simulation uses general power values of SW and PS, $P_{SW}$ is 5mW and $P_{PS}$ is 40mW [4]. Transmitted energy $P_t$ assumed 1W. Signal-to-noise ratio is 30dB, as expected, conventional system model is lower estimate than POS-SW system and using 16 ($N=4$) POSs system has best energy efficiency. The reason of this difference is PSs consume high power consumption than phase over sampler. The result of energy efficiency is trade-off relation with channel capacity. It can be observed that the proposed POS-SW system gives significant energy efficiency advantages comparing to conventional infinite resolution hybrid system.

4. Conclusion
This paper analyses the POS-SW structure on hybrid beamforming system for mmWave communication on 3D channel model. The limited number of POS decides on the resolution of antenna array and the value of POSs are designed from maximum and minimum phase angle antenna array. Energy efficiency goes higher without using phase shifter although channel capacity is nearly similar as conventional system. All system utilized 3D channel model that considering steering angle of beam in CSI. Finally, simulation result shows that proposed system has almost same performance of channel capacity and the higher energy efficiency compared to the conventional hybrid beamforming system. For future research, it would be interesting to investigate that POS-SW model is same performance of full digital beamforming capacity spend less energy.

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Reference
[1] Andreas F M, Vishnu V, Shengqian H, Zheda L, Sinh L H N, Linsheng L and Katsutuki H. 2017. Hybrid Beamforming for Massive MIMO: A survey. IEEE Communications Magazine. 55, pp.134-41
[2] Robert W H J, Nuria G, Sundeep R, Wonil R and Akbar M S. 2016. A Overview of signal processing techniques for millimetre wave MIMO system. IEEE Wireless Communications. 10(3), pp.436-53.
[3] Ming L, Zihuang W, Hongyu L, Qian L and Liang Z. 2019. A Hybrid digital and analog beamforming solution for mmWave MIMO systems. IEEE Wireless Communications. 1. pp.137-43
[4] Roi M, Cristian R, Nuria G, Ahmed A, Robert W H. 2016. Hybrid MIMO architectures for millimeter wave communications: phase shifters or switches?. IEEE Wireless Communications. 4. pp.247-67
[5] Foad S and Wei Y. 2016. Hybrid digital and analog beamforming design for large-scale antenna arrays. IEEE Wireless Communications. 10(3). pp.501-13
[6] Xinyu G, Linglong D, Shuangfeng H, Chin-Lin I and Robert W H. 2016. Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays. IEEE Wireless Communications. 34(4). pp.998-1009
[7] Fjolla A, Martin T and Markus R. 2016. 3GPP 3D MIMO channel model: A holistic implementation guideline for open source simulation tools. EURASIP Journal on Wireless Communications and Networking. 2016(55).