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Millimeter Wave Massive MIMO Systems using Hybrid Beamforming

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ABSTRACT- The goal of next-generation wireless systems is to support many users by achieving higher data rates and reduced latency. Multiple input and multiple output systems (MIMO) are utilized in order to achieve high data rates. Multiple antennas are employed by Massive MIMO systems in both the transmitter along with the receiver. A signal processing method known as beamforming is used on several transmitting and receiving stations in order to deliver and receive multiple messages at once. To increase spectral efficiency, hybrid beamforming using a uniform rectangular antenna array is used in this research work. The results of hybrid beamforming using different numbers of antennas are compared with those of fully digital beamforming. A comparison between signal-to-noise (SNR) and bit error rate (BER) is performed. Comparing hybrid beamforming to fully digital beamforming, simulation findings show that hybrid beamforming reduces computing complexity due to reduced number of RF links. Also observed that the spectral efficiency rises with an increase in the quantity of transmitting antennas.

Keywords: Spectral Efficiency; Hybrid Beamforming; Fully Digital Beamforming; Massive MIMO.

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1. INTRODUCTION

Mobile communication was started in 1980s that was first generation networks (1G). 1G system offered 2.4Kbps data rates. With data speeds as high as 64 Kbps, second generation (2G) networks can support the Global System for Mobile Communications (GSM). 2.5 generation (2.5G) as well as third generation (3G) uses circuit switching and packet switching with data rates up to 384Kpbs and 2Mbps respectively. 3.5 G and fourth generation (4G) uses data rates of 2Mbps and 100Mbps respectively with packet switching techniques. The data rate offered by fifth generation (5G) is 10Gps and latency of 1ms. One important technology that will enable 5G and future 5G networks is massive MIMO. The benefits of 5G networks include increased energy efficiency, reduced latency, large data speeds, and higher spectrum efficiency supporting million connections. The Massive MIMO technique makes use of beamforming at the base station using hundreds of antennas.

Fifth generation (5G) networks are encountering challenges in accommodating a greater number of users due to technological advancements and rising demand. 5G network must provide services with fast data speed and minimal latency. Throughput is one of the important parameters of wireless network and it is stated by,

Throughput (bits/second) =bandwidth (Hz) * spectral efficiency (bits/second/Hz) (1)

Increasing throughput requires the use of bandwidth characteristics and spectral efficiency. One of the drawbacks of expanding bandwidth is that the transmitted power's Signal-to-Noise Ratio (SNR) decreases. Increasing spectral efficiency is preferable. To boost spectral efficiency, more transmitting and receiving antennas might be used [1]. MIMO can be single user when different streams of data are transmitted to the same user. When streams of data are transmitted to multiple users then it called as multiple user MIMO (MU MIMO).

In addition to innovative technologies including Machine to Machine communications (M2M) and the Internet of Things (IoT), mobile users are utilizing augmented reality, 3D video, and video on demand services, which is causing wireless cellular networks' data load to increase dramatically [2]. To support increased data traffic, capacity of wireless network needs to be increased. Without adding extra cells or bandwidth, wireless throughput can be increased with the use of massive MIMO technology. Massive MIMO has advanced MIMO technology, which is being used in wireless networks. Massive MIMO increases throughput and spectral efficiency at the base station by deploying hundreds or even thousands of antennas.

The rest of the paper has been organized into the following sections: *section 2* provides an explanation of the various beamforming techniques. The literature review is detailed in *section 3*. *Section 4* explains the system model for the hybrid beamforming Massive MIMO system. The analysis and outcomes of the experiment have been examined in *section 5*. *Section 6* is conclusion.

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2. BEAMFORMING TECHNIQUES

Several transmitting and receiving antennas are subjected to a signal processing technique called beamforming to deliver or receive multiple messages. Beamforming improves system output and performance. Millimetre waves cannot travel through impediments or longer distances hence beamforming is beneficial for directing focused beams to users. Beamforming is intended to accomplish directed signal transmission as well as reception, together with power change. Beamforming allows antenna arrays to vary amplitude as well as phase of the input signal. Analog, Digital, Hybrid are three types of Beamforming techniques.

Analog Beamforming- An analogy beamforming system is shown in *figure 1* provides phase as well as amplitude variation at the transmitted side of an analogy stream. Prior to the ADC conversion at the receiving end, the signals from several antennas are combined. Phase shifters are inexpensive devices which controls phase of the broadcast signal. Radio frequency chain is used to accomplish beam steering. The ADC resolution is minimized, and analogy domain interfering signals are cancelled by the use of Venkateswaran and van der Veen's proposed analogy beamforming techniques [3]. Yet incapable of directing their nulls in any particular manner.

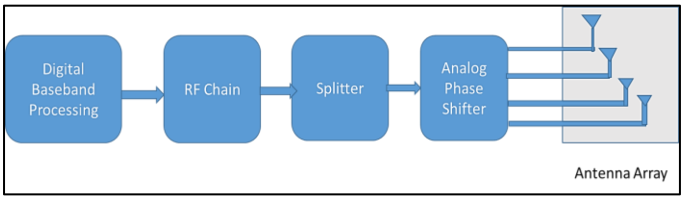

Figure 1. Analog Beamforming block diagram

Digital Beamforming- Analog to Digital (ADC) conversion of the digital signal at the transmission end is followed by the utilization of amplitude and phase variation in digital beamforming. At the receiving end, the summing is employed after the ADC and digital down converters (DDCs). In digital beamforming shown in *figure 2*, the quantity of antenna elements dictates the amount of RF chains required. Every antenna element is having separate RF chain, it increases hardware of the system. Hence fully digital beamforming in mmWave is costly and difficult to achieve. Digital beaming has several benefits, such as enhanced signal to noise ratio, estimation of direction of arrival and direction control over the null [4].

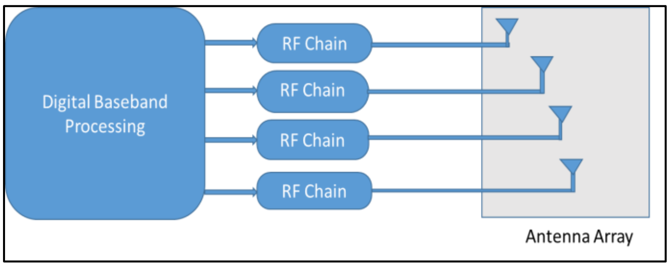

Figure 2. Digital Beamforming block diagram

Hybrid Beamforming- When compared to digital beamforming, analog beamforming is more affordable and requires less expensive phase shifters. Phase shifters perform poorly in digital beaming because their amplitudes are not variable. The issues in analog beamforming are the fine adjustment of beams and steering nulls for attending large antennas. Because each antenna in digital beamforming has its own RF chain, this results in higher power consumption and costs. To achieve better performance, analog and digital beamforming are mixed which is known as known as hybrid beamforming shown in *figure 3*.

In contrast to digital beamforming, hybrid beamforming requires fewer RF links. Hybrid beamforming can make use of fully connected and partially connected structures (FCS and PCS). To achieve a large channel capacity in FCS, every antenna element is linked with each RF chain. With FCS hybrid beamforming, the hardware is more intricate. PCS have an equal number of antennas linked to every RF chain. PCS beamforming requires less complexity of hardware as compared to FCS but lower performance.

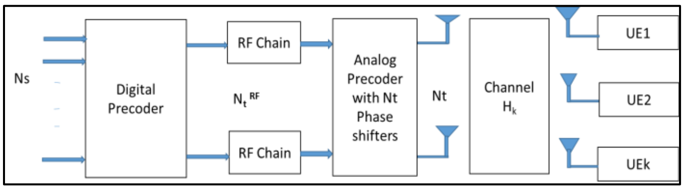

Figure 3. Hybrid Beamforming block diagram

3. LITERATURE REVIEW

Apart from hybrid beamforming within small cells along with heterogeneous wireless networks, Ahmed et al. [5] explained how system models are developed in hybrid beamforming. This study describes future research goals, resource management in hybrid beamforming, and several forms of hybrid beamforming systems.

Hybrid beamforming was classified by Molisch et al. [6] based on the complexity, carrier frequency range, and amount of required Channel State Information for the analogue beamformer element. The frequency bands for cm wave and mm wave have differing channel characteristics and RF impairments. The optimal performance and least amount of complexity can never be achieved by a single structure; instead, each design must be modified based on the needs of the application and the channel.

The beam search algorithm was proposed by Shim et al. [7] for improving the efficiency of PCS hybrid beamforming systems using codebook. Azimuth and elevation angle data for the multi-path with the maximum power are employed in the suggested method, which uses the nonlinear codebook design. Building blocks for B2 beam patterns are the multiple path azimuth as well as elevation angles which are proportionate with the quantity of B bits. Amount of RF chains affect channel estimate accuracy, and RF chain quantity grows with accuracy. Proposed hybrid beamforming system is shown to have improved average sum rate and error performance in comparison with the conventional hybrid beamforming system.

Using spatial covariance matrix (SCM), an improved Hybrid Beamforming approach for unified Analog Beamforming is proposed for handling several groups of user equipment in a huge MIMO-OFDM system [8]. The suggested method for locating the necessary SCM is called Subspace construction (SC), and it is based on partial channel state data. Much lower costs and power consumption are achievable with little performance loss.

A deep learning-based analogy beamforming algorithm is proposed for improving the system performance of mm wave massive MIMO system [9]. Different antenna arrangements were taken into consideration to show the efficiency of ABF at both ends. More spectrum efficiency is achieved by CNN-based hybrid beamforming than by hybrid beamforming algorithms based on optimization and greedy [10]. Algorithms that are greedy or optimization-based need to know about steering vectors, which are imperfect. Such knowledge is not necessary for CNN-based approaches, which use the beamformer as an output and the channel matrix as an input. The computation time required for CNN is less as compared to codebook based and optimization algorithms.

A hybrid beamforming technique called singular value decomposition (SVD) was proposed by Wang et al. [11]. By using fewer RF chains, this method lowers the complexity of hybrid beamforming. The suggested precoding approach can reduce hardware costs and power consumption by achieving great spectrum efficiency with a significantly smaller quantity of RF links.

For hybrid beamforming, the Minimum Sum Mean Square (MMSE) approach can be applied [12]. The hybrid transmits and receive beamformers are individually optimized utilizing the alternate minimization approach to get around the challenge of handling the multi-variable design problem.

When utilizing rectangular array antennas for hybrid beamforming, computational complexity is reduced in comparison to fully digital beamforming [13]. With Chebyshev tapering, side lobes are suppressed while the main lobe strength is increased. The spectral efficiency is capable of being enhanced further by employing a three-dimensional rectangular arrangement.

For millimetre Wave communications with high throughput and low energy consumption, an optimal hybrid precoding technique is employed in massive MIMO transmission [14]. By employing the Simultaneous Orthogonal Matching Pursuit (SOMP) technique, the hybrid precoder system performance is enhanced. It considers power scaling capabilities, which allows it to benefit from both perfect as well imperfect Channel State Information (CSI).

4. SYSTEM MODEL

The model of the massive MIMO system that was considered for this work is shown in *figure 4*.

In the downlink of this multi-user system, the number of antenna arrays are N_T and RF chains are N_T^{RF}, while in the uplink, the number of antennas are N_R and RF chains are N_R^{RF}. Amount of transmitting antennas (N_T) must be less than the amount of RF chains (N_T^{RF}) in the hybrid MIMO system paradigm. There must be fewer RF chains (N_R^{RF}) than receiving antennas (N_R). Hybrid MIMO system uses hybrid precoder and hybrid combiner to reduce complexity of the system as shown in *figure 4*.

The transmitted symbols are processed by the digital precoder, which then maps them into radio frequency chains. Then the symbols are processed by the analogy precoder which consists of analogy phase shifters and adders. The signal's phase can be changed using phase shifters. Apart from the analogy precoder, a digital precoder is also utilized, which facilitates adjustments to the signal's phase and amplitude.

Prior to being down converted via RF chains, the received signal is first processed in the analogy domain, followed by processing in the digital domain.

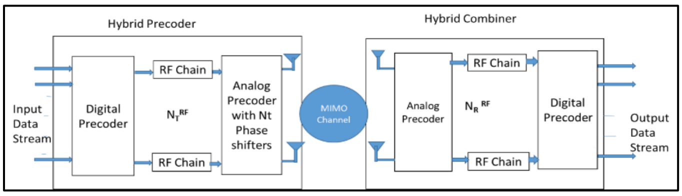

Figure 4. Hybrid MIMO System Model

The traditional digital beamforming technology requires an RF chain unique to an antenna, which adds complexity and expense to the system. Compared to digital beamforming, hybrid beamforming uses fewer antennas.

Therefore, hybrid beamforming lowers the system's hardware complexity and cost.

N_S indicates the amount of transferred data streams.

The signal that was transmitted is expressed as,

$$x = F_{RF} F_{BB} S \quad (2)$$

In the above equation, Baseband beamformer matrix (Digital Precoder matrix) F_{BB} has dimensions of $N_T^{RF} \times Ns$.

Analog beamformer matrix F_{RF} has dimensions of $N_T \times N_T^{RF}$
S is the symbol vector.

The received signal is given by,

$$y= \sqrt{\rho}\, H F_{RF} F_{BB} S+ n \quad (3)$$

In the above equation, ρ denotes the average received signal. S is the symbol vector that needs to be sent, White Gaussian noise additively expressed as n and H represent the channel matrix of dimensions $N_T \times N_R$.

Channel matrix consist of Nc clusters of Nray paths and represented with the help of Saleh- Valenzuela model (SV) as

$H = \gamma \sum_{i=1}^{Nc} \sum_{j=1}^{Nray} \propto ij\ g_R(\Theta_R^{(ij)})\, g_T(\Theta_T^{(ij)})\, a_R(\Theta_R^{(ij)})\, a_T(\Theta_T^{(ij)})$

Where $\Theta_R^{(ij)}$ denotes the angle of arrival and $\Theta_T^{(ij)}$ denotes the angle of departures.

Where $\Theta_R^{(ij)} = (\theta_R^{(ij)}\ \Phi_R^{(ij)})$ and $\Theta_T^{(ij)} = (\theta_T^{(ij)}\ \Phi_T^{(ij)})$

Here θ and Φ denote azimuth and elevation angles respectively.

$\gamma = \sqrt{\frac{N_T N_R}{N_C N_{ray}}}$ is the normalization factor, αij is the complex channel gain associated with ith scattering cluster and j^{th} path with i=1,2, -----,Nc and j=1,2,-----------,N_{ray}.

$g_R(\Theta_R^{(ij)})$ and $g_T(\Theta_T^{(ij)})$ represents the antenna array gains for receive and transmit antennas respectively.

$a_R(\Theta_R^{(ij)})$ and $a_T(\Theta_T^{(ij)})$ are $N_R \times 1$ and $N_T \times 1$ steering vectors representing the array responses at the receiver and transmitters respectively.

Receiving and processing the sent signal, analog and baseband combiners function by

$\bar{y} = W^H_{BB} W^H_{RF}\ y$

$\bar{y} = W^H_{BB} W^H_{RF}\ (\sqrt{\rho}\ H F_{RF} F_{BB} S + n)$

$$\bar{y} = \sqrt{\rho}\ H F_{RF} F_{BB} S\ W^H_{BB} W^H_{RF} + W^H_{BB} W^H_{RF}\ n \quad (4)$$

In the above equation (4) dimensions of the baseband combiner matrix W_{BB} are $N_R^{RF} \times Ns$. Dimensions of the analog combiner matrix W_{RF} are $N_R \times N_R^{RF}$.

Hybrid beamforming's spectral efficiency is provided as,

$$SE = \log_2(|I.\ N_S + ((\rho/N_S)\ A^{-1} W^H_{BB} W^H_{RF}\ H\ F_{RF} F_{BB} F^H_{RF} F^H_{BB} H^H W_{BB} W_{RF}|) \quad (5)$$

Here the term $A = \sigma^2{}_n W^H_{BB} W^H_{RF} W_{BB} W_{RF}$

This is noise term's covariance matrix.

Calculate F_{RF}, W_{RF}, F_{BB} and W_{BB} as indicated by *equation (5)* to maximize spectral efficiency. Orthogonal matching pursuit method is used to calculate precoder and combiner matrix.

5. SIMULATION OUTCOME AND DISCUSSION

For massive MIMO using uniform rectangular antenna array designs, the digital beamforming and hybrid beamforming models are simulated using MATLAB R2023. The rectangular antenna elements considered are isotropic. For simulation, it is assumed that there are 6 scattering clusters and each cluster is having 8 closely spaced scatterers with 5-degree angle spread. The assumed parameters of the simulation are listed in the table below.

Table 1. Simulation Parameters

Parameter	Range
Quantity of Transmitting Antenna array	256
Quantity of Receiving Antenna array	64
Antenna Pattern	Uniform Rectangular Array
Distance between antenna elements	λ/2
Frequency	28GHz

The spectral efficiency for both digital and hybrid beamforming has been computed for a range of data streams and a certain SNR between -40 dB and 0 dB. *Figure 5 and 6* shows the results of a simulation for a massive MIMO 64 X 16 and data streams with Ns= 1 and 2. It is found that 4 RF and 8 RF chains are utilized respectively. Fully digital beamforming having 144 RF chains and 4 RF chain hybrid beamforming have nearly comparable spectral efficiencies.

The findings show that extremely few RF chains are needed for hybrid beamforming, which reduces system complexity. The hybrid beamforming's spectral efficiency using 256 X 16 rectangular antenna array pattern with 8 RF chains is almost same as that of digital beamforming with very less deviation. Using 4 RF chains and 8 RF chains for different data streams are shown in *figure 7 and 8* respectively.

According to the analysis, the spectral efficiency of hybrid beamforming techniques, when paired with a bigger rectangular antenna array, is nearly identical to that of digital beamforming systems, which necessitate fewer RF chains and antennas.

For rectangular antenna array configurations with different numbers of transmitting antennas at SNR=0 dB, *table 2* compares the spectral efficiency of hybrid beamforming with digital beamforming. It is observed that spectral efficiency increases as the quantity of antenna arrays rises.

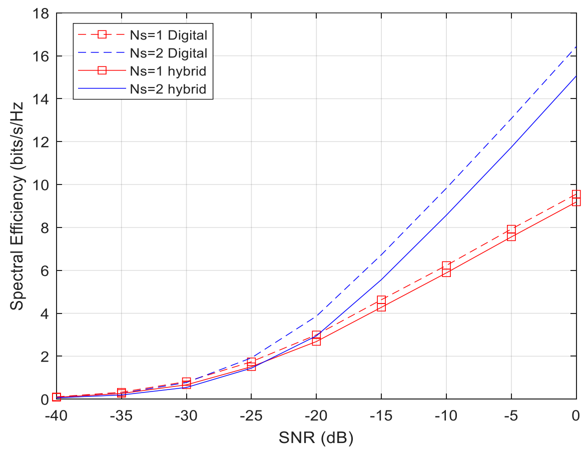

Figure 5. Digital and hybrid beamforming spectral efficiency where N_T=64, N_R=16 and N_T^{RF}=4

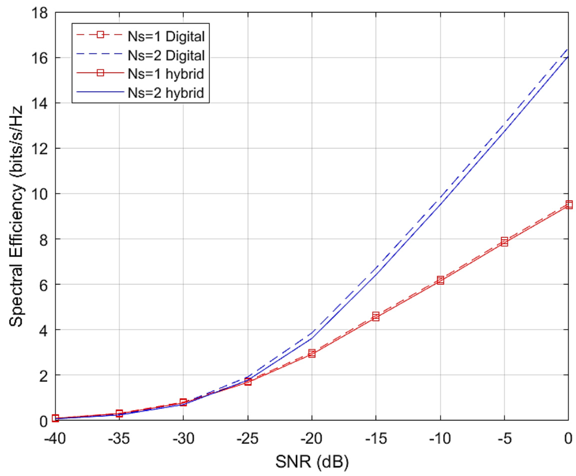

Figure 6. Digital and hybrid beamforming Spectral Efficiency where N_T=64, N_R=16 and N_T^{RF}=8

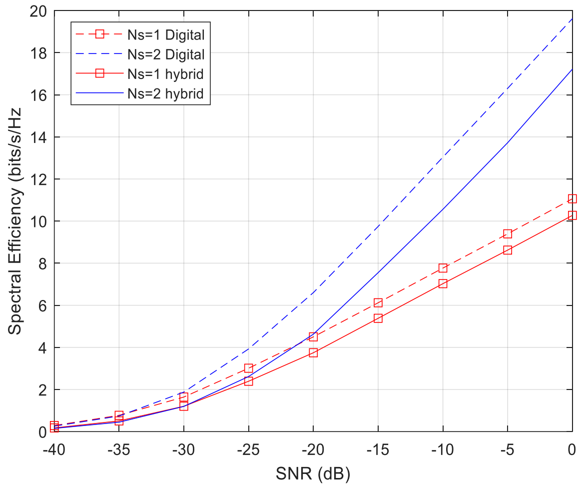

Figure 7. Digital and hybrid beamforming Spectral efficiency where N_T=256, N_R=16 and N_T^{RF}=4

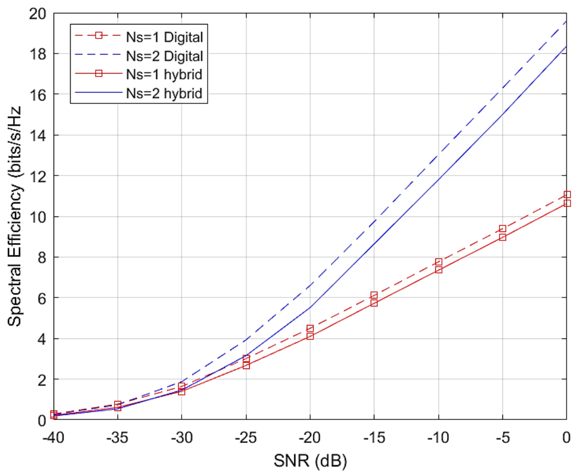

Figure 8. Digital and hybrid beamforming Spectral efficiency where N_T=256, N_R=16 and N_T^{RF}=8

Table 2. Analysis of spectral efficiency for digital beamforming and hybrid beamforming using rectangular antenna array layout and varying numbers of RF chains for massive MIMO systems with SNR=0 dB is shown.

Data Streams quantity	Spectral Efficiency in bits/S/Hz	
	Digital Beamforming	Hybrid Beamforming
64X16 Antennas	No of RF chains 64 × 16	No of RF chains 4× 4
1	9.8	9.6
2	16.1	15.6
64X16 Antennas	No of RF chains 64 × 16	No of RF chains 8X 8
1	9.9	9.8
2	16.1	16.0
256X16 Antennas	No of RF chains 256 X 16	No of RF chains 4 X 4
1	10.5	10.2
2	19.0	17.8
256X16 Antennas	No of RF chains 256 X 16	No of RF chains 8 X 8
1	10.6	10.4
2	19.2	18.4

6. CONCLUSION

This paper simulated hybrid beamforming technique of massive MIMO using a rectangle antenna array design. The results are compared with digital beamforming. According to the evaluation of the spectral efficiency metric, the suggested hybrid beamforming in a massive MIMO system based on a rectangular array antenna reduces computational complexity when compared to fully digital beamforming and achieves the same spectral efficiencies. Spectral efficiency rises with an increase in the quantity of transmitting antennas. The fewer RF links translate into lower computational complexity and expenses when compared to digital beamforming. It is possible to examine the spectral efficiency even further by taking various antenna array layouts into account. In addition, future work can build and implement the suggested hybrid beamforming in a huge MIMO system using rectangular array antenna.

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