Hybrid Beamforming Based mmWave for Future Generation Communication

Himanish Guha[1], Anshu Mukherjee[2], Dr. M. S. Vasanthi[3]

[1,2,3] Dept. of Information and Telecommunication Engineering, SRM Institute of Science and Technology, Chennai, India

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Abstract— *Massive MIMO is the key technology that will enable us to develop and implement 5G networks. But there are a few problems with MIMO technology. These MIMO systems will use huge antenna arrays. Now, this will hugely improve gain, but they also pose a lot of problems including increase in cost. All of these problems can be solved by the use of hybrid beamforming. Hybrid beamforming combines high dimensional analog precoding and postcoding with digital processing which has a lower dimension, using hybrid multiple antenna transceivers. This is the most viable approach as it reduces the cost of hardware equipment and training overheads. Another key point which we discuss in this paper is about millimeter waves. Most of the MIMO equipment will run in the millimeter wave frequency spectrum. Designing antenna arrays that will work in the mm wave domain is difficult for many reasons. One such reason being that mm wave signals have huge path loss and faces difficulties during propagation. So for this, we have two options. We could have dedicated receiving and transmitting paths for each array element. This would be an all-digital architecture which would provide more flexibility. The other option being hybrid beamforming. In this, analog phase shifters are integrated with digital circuitry. Although the former seems more efficient, the latter is more practical and economical.*

Keywords*—Beamforming, MIMO, mm wave, Precoder, Precoding, Switching, Phase Shifter, Channel State Information (CSI), Spectral Efficiency (SE).*

1. INTRODUCTION

Massive MIMO wireless systems have become a leading technology for accessing 5G wireless access [1], [2]. Along with mm Wave technologies, cognitive radio networks, that were recently recognized as a requirement for coping with the less amount of spectrum available[3], it offers higher sum and data rates and much more capacities than traditional MIMO systems. Array gains higher than anything before can be achieved by the use of large scale antenna arrays at the transmitting and receiving end. Precoding and combining methods are required in order to utilize this gain. Usually these methods need a radio frequency part for every antenna and they need to be implemented traditionally in the baseband (BB). When working with a huge number of antennas, we have to take into account the huge computational complexity and cost. The RF components have a massive power consumption especially when working in a mm wave environment and furthermore, they are very costly. Thus it is necessary to work on and develop cheap economical hardware which will fully utilize the Potential gain from the antennas. The cheap antennas being huge in number, generates a huge potential gain and this is achieved by using a small number of costly RF chains. Now there is a solution that has been proposed to meet the goal. By the use of hybrid analog-digital schemes, these goals can be met with very efficiently.

Now, in hybrid beamforming, the operations of the precoding and combining are divided into digital and analog domains. A low dimensional digital precoder operates on the transmitted signal at BB at the transmitted side. The small number of digital outputs are mapped to a large number of antennas by an analog precoder. The similar process is performed on the reverse side.

Common analog architectures are based on analog phase shifters and switches. Depending on the power and budget, the specificity of the schemes can be varied. Two main parts are the fully and partially connected structures. The data is mapped from each antenna to each RF chain due to the fully connected networks. As a result, there is an increase in precoding and combining gain. But in case of partial connection scheme, less number of analog components are used. As a result, the gain achieved is less, but the power consumption is considerably low and the hardware complexity is reduced as well. The transmitter sends multiple streams of data using known precoding techniques. The transmitter transmits to the receiver over the constant and known channel.

This happens in the data phase of each coherence interval of the MIMO communication. Then the collected data vector is estimated by a combiner at the receiver. Some performance measures are optimized by the precoder and combiner. These include estimation of error or spectral efficiency of the system.

When we consider the hybrid case, unlike the digital beamformer, we cannot consider arbitrary entries for the precoder and combiner matrices. They are constricted by specific hardware choices. For instance, we consider only unimodular matrices when we use a phase shifter network at the analog side. The main aim is to yield a non-convex difficult optimization problem by optimizing the performance over all parts of the digital and analog precoder matrices.

2. EXISTING PROBLEMS

2.1 Channel Hardening

Multiple-input multiple-output (MIMO) is, the use of multiple antennas at transmitter (TX) and receiver (RX), has been, as an essential approach to attain high spectral efficiency (SE).The MIMO technology when used in multi user form, can hugely improve the spectral Efficiency. They are:

• Multiple User Equipments (UE), which are on the same time-frequency channel resource can communicate simultaneously with the help of a single base station (BS).

• Each UE and BS can communicate easily by transferring multiple streams of data between them

The sum of all UE antenna elements and the small number of BS antenna elements is the factor which upper limits the total number of data streams that is the sum of all UEs in a particular cell. Multi user MIMO has been there for a long time but now, a new field has opened up with the introduction of the concept of "massive MIMO", a whole new field has opened up. In massive MIMO, the number of antennas reaches hundreds. Now, this allows even more data streams to be transmitted and also simplifies the signal processing. It also gives rise to a phenomenon called "Channel hardening". Now this channel hardening is a very common phenomenon. A very major impairment in wireless communication is channel fading. Even microscopic changes in the propagation environment can cause random fluctuations in the channel gain. Channel hardening refers to a fading channel which acts as if it is non-fading, but randomness is still present, it is very negligible [5]. There are problems like having to collect the CSI for each antenna and the increased complexity due to a huge number of RF chains. Hybrid beamforming provides a simple solution to all this.

Although massive MIMO is proven to be quite *beneficial* at centimeter-wave (cmWave) frequencies, but is *essential* at the millimeter-wave (mmWave) bands. This is because at those frequencies, even to obtain the sufficient amount of SNR (even at a moderate distance of 100m), high array gains are needed. But massive MIMO also presents us with problems due to its large number of antennas.

• A huge number of radio frequency (RF) chains is needed (one for each antenna element). This significantly increases cost and energy consumption.

• The channel state information (CSI) between each transmit and receive antenna is required. This uses a large amount of spectral resources.

The concept of hybrid transceivers provides a great solution to all these issues. These use a combination of analog beamformer in the RF domain Along with digital beamformer in the baseband domain. Hybrid beamforming is based on the fact that number of data streams lower limits the number of upconversions and downconversions. Whereas the number of antenna elements gives the gain and diversity order. But this is properly done only if the suitable beamformings are done. Although the concept was devised for MIMO with unimodular or arbitrary matrices of antenna elements, this is particularly helpful in the field of massive MIMO

Although hybrid beamforming has been there for quite some time [6],[7], but a keen interest has been taken in the past few years.

Thus, the time is perfect for the development of the state of the art transceiver architectures and algorithms to provide support for this newly revived concept of hybrid beamforming which aims to solve so many of the existing problems.

2.2 Spectrum Crunch

Multiple input multiple output (MIMO) system is one of the most promising techniques for exploiting the spectral efficiency of wireless channels [8],[9]. To exploit the full potential of a MIMO system, one must influence the conventional beamforming techniques (i.e., digital beamforming). Recently the concept of massive MIMO has been receiving much attention. This refers to the use of huge number of antennas at the transmitter and receiver. By the use of the law of large numbers (which states that events with the same likelihood of occurrence evens out), we can state that by utilizing simple digital beamforming techniques like zero forcing (ZF) or maximum ratio transmission (MRT), we can achieve the full potential of a massive MIMO system. But even after all the efforts to employ efficient techniques and methods, the wireless industry always faces spectrum crunch at one or the other frequency range, especially at the microwave range. So there is always a need and interest to exploit the parts of spectrum which are not utilized or under-utilized. These include the millimetre wave frequency spectrum which can be utilized for mobile communications. There are however difficulties while using the mm wave domain. They experience severe path loss, they cannot penetrate into deep spaces, faded easily and can be easily scattered or absorbed by gases. To cope with these changes, the mm wave systems require very high gain antennas. Millimetre waves are already used for maintaining the outdoor point to point backhaul links of cellular systems. But in this, the antenna required needs a large physical aperture. This is required to achieve the necessary link gain which is not economical Due to this, analog beamforming influences the working and feasibility of the massive MIMO model and is suggested for use in the millimetre domain of frequency [10].The basic idea of analog beamforming is to control the phase of each transmitter antenna's signal using low cost phase shifters [10], [11], [12]. The method is cost effective because each of the analog beamforming coefficients has constant modulus. Digital beamforming is performed at the BB stage at the transmitter side. This means that the transmitted signal's phase and amplitude is determined at the BB frequency. The BB processing needs a dedicated RF chain for each antenna, which increases the cost. At the receiver side, where digital beamforming takes place, initially the received signal from each antenna is individually obtained in digital form. Then the received samples are jointly processed. After the transmitted bits are decoded, we get the full signal. Thus we see that in the case of digital beamforming, the number of antennas required for receiving the analog signal (which is very large because of massive MIMO) is same as the number of analog to digital converters (ADCs). This hugely increases the cost. Hence digital beamforming for massive MIMO seems to be hugely impractical. But analog beamforming can be implemented very easily with the help of low cost phase shifters. So we see that analog beamforming is more economical than digital beamforming. But we also have to consider the fact that we are compromising on the working and performance. The amplitude of the phase shifter maybe constant for both cases, but the performance of an analog beamformer is much inferior to that of a digital beamformer [13]. So to achieve better performance, a hybrid solution is proposed.

So the aim is to design a hybrid beamforming system which is suitable for multiuser massive MIMO systems. Only at the transmitter can we get perfect channel state information (CSI).This can be achieved by simple time division duplexing. Our main aim is to achieve a performance that is close to the performance provided by digital beamforming. It is simple to design the hybrid beamforming model in such a way that the performance gap between the hybrid and digital beamformings is almost constant for each of the symbols. To achieve this, we need to consider the weighted sum mean square error rather than the sum mean square error minimization when considering digital beamforming. The mean square error (MSE) weight of each symbol depends on the design and the beamforming we applied. We also consider the total sum rate which we will be getting at the end and maximization problem. To resolve this issue, the digital beamforming uses block diagonalization whereas the hybrid beamforming uses a WSMSE minimization scheme. Here, the MSE weight of each symbol is selected as the inverse of the square of its digital beamforming gain. The WSMSE result that we get is solved by using the compressed sensing theory. Once the hybrid beamforming is designed, the relation between the hybrid and digital beamforming is studied by varying parameters like the amount of multiplexed symbols, ADCs and RF chains implemented. Simulated results show that the performance gap between digital and hybrid beamforming can be decreased by decreasing the number of multiplexed symbols, for a given amount of RF chains and ADCs. We have also seen that increasing the number of RF chains and ADCs, gives an increased total sum rate, given that we keep the number of multiplexed symbols constant.

3. HYBRID BEAMFORMING AT MM WAVE

Hybrid beamforming systems and algorithms in the cm-wave-frequency domain can in principle be used at mm-wave domain frequencies. But in practical situations, there are many factors that we need to take into account before we can infer that the cm wave systems actually work in case of mm wave systems. Factors like propagation channel and RF hardware aspects vary hugely and so a practical approach is required. At mm wave frequencies, the multipath channels suffers huge propagation loss [14]-[16]. Now this needs to be satisfied by gains attained from the transmission, reception antenna arrays. Even though the antenna arrays have reasonably manageable physical size, due to the short wavelengths, fully digital beamforming is not feasible. On the other hand, hybrid solutions becomes harder to implement due to the power and cost related constraints of the RF chains and hardware. Also in case of mm wave, very few spatial degrees of freedom is available due to the fact that these channel might be sparser. But this can be used for optimizing channel estimation and beam training.

3.1 Hybrid beamforming methods exploiting channels' sparsity

The simplest form of implementation of hybrid beamforming in SU-MIMO is to exploit the channel's sparsity This focuses the array gains to a limited number of RF multipath chains while allocating powers in the baseband and multiplexing the data streams at the same time. The asymptotic nature of the hybrid architecture makes it ideal for large antenna arrays. For systems with practical array sizes, hybrid beamforming is highly beneficial [17]. In addition to this, what makes this model more desirable is the reduction of hardware components and reduction of computational complexity. For all these reasons, a number of methods have been proposed. Some of them are discussed below.

- Use of codebooks: The codebook-based beamforming Performs downlink training using already defined beams and the only feeds back these selected beam's IDs to the transmitter, instead of directly estimating the large CSI matrix at the receiver. A codebook for full complexity hybrid architecture can be made to use the sparsity of mm wave channels. This would reduce the complexity and feedback overhead for large antenna systems. Each codeword is constructed uniquely based on the algorithm of Orthogonal

- Spatially sparse precoding: This method finds the approximation of the unconstrained (i.e., fully-digital) beamformer electrically large arrays. We can safely approximate close to the optimal precoder using the correct number of antenna elements in the antenna array. The multipath sparsity restricts the proper setting up of array response vectors by the analog precoders. It also hinders the setting up of baseband precoder optimization. The solution then can be obtained by using OMP. Fig. 5 compares the Spectral Efficiency with unconstrained fully digital beamfrming with perfect transmit CSI.

- Antenna selection: In general the structure for mm wave beamforming channel is the same as the one for cm-waves. But mm wave channels are sparse and fast. Hybrid antenna selection can perform better than a sparse hybrid combiner with roughly quantized phase shifters when comparing in terms of power consumption. Both have the same SE performance, but there is still a huge gap in SE between the hybrid combiner with switches and fully-digital one with ideal phase shifters.

- Beam selection: Using continuous Aperture Phased MIMO transceivers is another hybrid beamforming solution. Instead of phase shifters or switches, it uses lens antennas to realize the Beamspace MIMO (B-MIMO). An antenna array beneath the lens electrically excited the large lens antenna setup. The antenna produces high gain beams that point to different angles depending upon the antenna feed, hence the feed array is called a beam selector. The CAP-MIMO can select a couple of feed antennas using a limited number of RF chains like that in spatially sparse coding. By doing this, they can efficiently utilize the low dimensional gain beamspace of the multipath channel which is very high.

3.2 Hybrid beamforming in mm-wave MU scenarios

Hybrid beamforming solution also provides the application of multi user MIMO or MU-MIMO into practical use. The hybrid structure at the base station is capable of transmitting multiple multiplexed data streams to multiple UEs. Now the UEs can be fitted with an antenna array or be equipped with fully analog beamforming

Fig. 1 shows achievable rates of hybrid beamforming in MU multi-cell scenarios [18]. Considering the situation where a UE, consisting of a single RF chain and many antennas which select the strongest beam pair to form the analog beamforming.

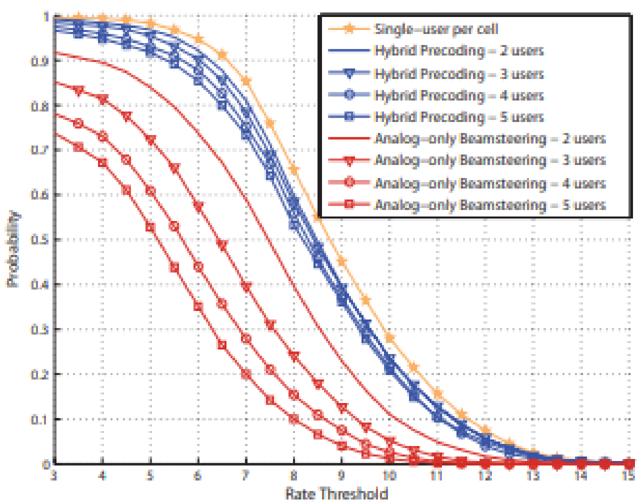

Fig. 1 Comparison of achievable rates for hybrid precoding and analog-only beamsteering

The hybrid beamforming is based on beam selection and B-MIMO concept can also be extended to the MU-MIMO systems with the use of linear baseband precoders. The effectiveness of hybrid beamforming has been already proven in case of mm wave MU-MIMO systems. It has also proven its effectiveness in case of multi user scheduling and 2D, 3D lens array designs, but these are still to be researched and studied upon.

3.3 Impact of transceiver imperfections

The SE is degraded in different ways due to the imperfections in the trasceiver e.g., If the beamformer gain is high, it becomes difficult to get accurate transmit; the instantaneous channel gain (therefore the SNR) determines the nonlinear distortion at the receiving end. As suggested by previous studies of the cm wave beamforming The SE performance achieved by the hybrid structures is the same as that of a full digital beamforming given that the number of data streams is half the number of RF chains at each end The transceiver being imperfect and these imperfections being more noticeable at the mm level, the SE and SNR of hybrid precoders doesn't match with that of the RF Chains.

Fig. 2 shows us the comparisn of spatially sparse hybrid precoding, including RF imperfections, with that from fully-digital beamforming based on SVD [19]. The roughly quantized phase shifters and the transceivers' imperfections espicially at the mm waves level significantly degrade the SE.Hence it is important to know about the transceiver imperfections as it is a detrimental factor in the understanding of the SE in MIMO

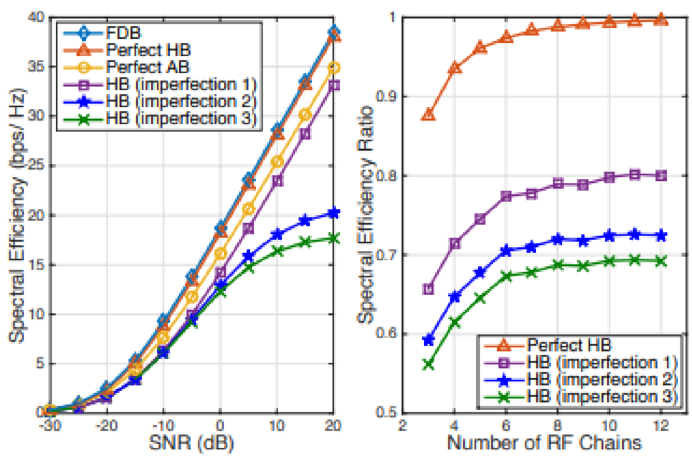

Fig. 2 SNR vs SE and Number of RF chains vs SE for diferrent beamforming method

3.4 Spectral-energy efficiency tradeoff

Here, we see the relationship between energy efficiency and spectral efficiency of hybrid beamforming structures at mm waves based systems. Figure 3 shows the EE-SE graph, indicating the optimal number of RF chains needed for achieving the maximal EE for any given SE

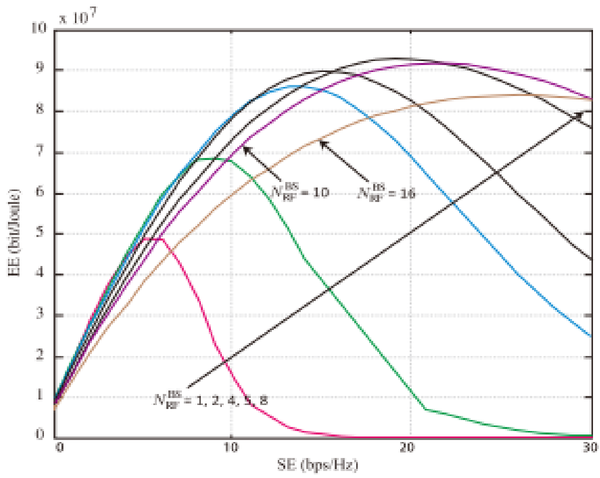

Fig. 3 EE-SE relation of mm-wave massive MIMO system

4. CONCLUSION

Hybrid beamforming is a technology that has been there for quite a long time, but now, it is gaining interest once more. Previously, it was being used for signal frequency adjustment, but now with the advent of MIMO, it is gaining more and more importance and as newer fields of research are coming up. By the use of hybrid beamforming, we are able to exploit the mm wave domain of the spectrum which help us gain access to a wide range of spectrum on which we can work on.

Hybrid beamformers use a combination of analog and digital beamforming while keeping the number of RF up/down conversion chains within reasonable limits. Hence this reduces the cost to a great extent. In this paper, we study how hybrid beamforming works and why is it needed. We also see the different kinds of beamforming methods applied. We can conclude that there is not one specific best method which is suitable for every situation, instead there are different beamforming methods which can be employed in different cases.

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