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MIMO versus Phased Array Antenna Systems for 5G Mobile Communication Systems

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***Abstract:* Antenna technology is a critical component of mobile communications. With every upgrade in generation of mobile communications, antenna technology has been ameliorating in performance, starting from simple omnidirectional antennas for analog communication in the first generation, to digital antenna arrays (smart antenna) in second and third generation to MIMO antenna arrays in fourth generation. Fifth generation of mobile communications is expected to have significant increase in data rates, capacity and number of users. This demands an advanced antenna technology capable of meeting the requirements. This paper aims to compare the performance of two of the existing antenna technologies: MIMO and phased array and highlight their usage in 5G technologies.**

***Keywords:* MIMO; Phased array; 5G; Hybrid beamforming; Channel state estimation**

I. INTRODUCTION

The exceptional increase in usage of mobile devices has resulted in new technologies and standards. The fifth generation of mobile communication systems represent a significant growth in number of end devices and data rates, with the advent of Internet of Things. It aims to achieve latency of the order of milliseconds and serve almost 300,000 end devices per access node, with more efficient user experience. It also aims to provide D2D (device to device) communication, where direct communication between devices without the need for routing through network infrastructure is possible. Antenna technology plays a crucial role in the development of 5G mobile communication, enabling better coverage and higher data rates. Two major technologies: MIMO (Multiple Input Multiple Output) and beam forming using phased arrays are capable of catering the needs of the fifth generation wireless communication systems. The "all-band-to-5G" transition necessitate antenna systems which could support all bands. Further, the antennas must be flexible enough to adopt to diversified applications. Also, single antenna must support C Band and MM Wave spectrum resources to support 5G NTNR features. The antenna must be designed to support all band configuration and beam coverage must be precise to cater to the applications such that the beam energy is concentrated on desired areas and at the same time, it must not cause interference to non-desired coverage areas. The antennas must support multiuser beam forming, allowing multiuser beams to share the time and frequency domain resources to maximize the spectral efficiency. Accurate null steering control on antennas would help to suppress the interference caused by resource sharing. Further, the antennas have be designed such that the maximum radiated energy must be concentrated on the desired areas. Hence there is a need to compare the two major antenna technologies to study the feasibility of their use in 5G. The paper is organized as follows: Section II deals with the concepts of MIMO and Massive MIMO. Section III deals with the concept of phased arrays and beamforming using them. Section IV deals with the concept of hybrid beamforming in 5G mobile communication. The paper is concluded in Section V.

II. MIMO

MIMO is wireless communication methods where multiple transmit and receive antennas are used to improve the capacity of a link. It utilizes the concept of multipath propagation, where a single radio signal can reach the receiver via different paths. MIMO splits a signal into several low data rate sub-signals and transmits them via spatially separated antennas using the same frequency channel. Due to multipath propagation, they are received via different paths at the receiver. The receiver separates these signals into parallel streams, which are then processed to recover the original signal. MIMO offers a significant increase in channel capacity without any additional bandwidth and power consumption.

The channel throughput can be increased linearly with the addition of transmit and receive antenna pairs. MIMO technology has been standardized for 4G mobile communication networks and now in commercial use. 4G-LTE has different MIMO schemes for uplink and downlink. LTE downlink schemes assume a 2x2 configuration as the baseline [1], i.e. two transmit and two receive antennas. The individual antenna transmits a diverse stream of data while individual receive antenna can receive stream of data from all the individual transmit antennas. Precoding of the streams before transmission results in spatial multiplexing. To account for the complexity of end devices, uplink MIMO schemes differ from downlink schemes [1]. Two options are Single user MIMO (SU MIMO) and Multiple user MIMO (MU MIMO). In SU MIMO, the access point can use multiple spatial streams to send data to an individual client, while in MU MIMO the access point can use multiple streams to send separate transmissions to distinct clients simultaneously [1]. 5G mobile communication networks aims to improve the capacity of a channel beyond that of 4G-LTE. One of the solutions to this is Massive MIMO technology. This goes beyond the 2x2 configuration of conventional MIMO, using several simultaneous transmit and receive streams to improve network capacity. The larger antenna array used in Massive MIMO also improves spectral efficiency via better spatial multiplexing. Each antenna in the array will have its own RF and digital baseband chain, allowing for complete coherent digital processing of signals from all the antennas. This reduces the dependence of assumptions on propagation channel and allow fast response to changes in the channel.

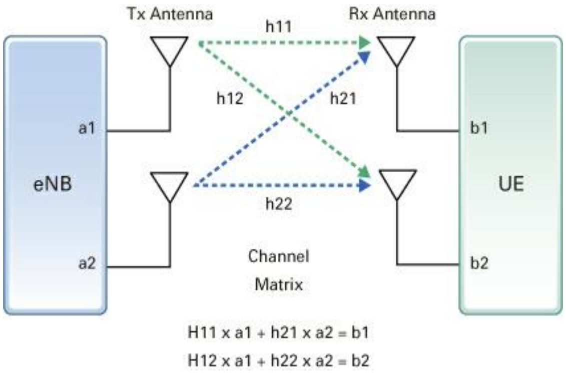

Fig 1. 2x2 MIMO configuration in 4G-LTE

A. Challenges faced in Massive MIMO

The Massive MIMO requires a huge number of antenna elements separated sufficiently to avoid correlation among different channels. Thus, in practical implementations, it is not possible to separate antenna elements in a very large array without having a significant increase in array size [3]. Mm Wave MIMO transmission incurs higher attenuation during propagation due to Friss law [2]. Using a highly directive antenna with a small beam width, steerable over large angles would ensure high gain. This beamforming requires antenna elements to be spaced at $\lambda/2$, where λ is the carrier wavelength. At millimeter wavelengths, it is possible to construct such antenna arrays that can be used for mobile communications. Another issue that massive MIMO implementation face is the frequency selective fading that channels practically show. This requires expensive RF amplifiers along all the stages of the network, which also reduces the efficiency of the network. Combining massive MIMO with OFDM is one of the answers to this problem, as it reduces the fading effect of channels at select frequencies. Most research work on massive MIMO is based on TDD (time division duplexing) transmission. However, most present-day communication systems use FDD (frequency division duplexing) transmission. Implementing FDD for massive MIMO requires immense computation of channel states [3]. Thus, a highly efficient precoding scheme that is based on partial or no CSI (channel state information) is required, since calculating CSI for each individual antenna requires immense computation overhead.

III. PHASED ARRAYS

A phased array, also called as an electronically scanned array, is an array of antennas which is controlled by a computer that can create and steer radio wave beams to different directions without the movement of the antennas. Generally, a single RF source feeds all the antenna elements with the correct phase relationship between them so as to enable interference between beams produced by individual elements, such that the resulting beam is in a desired direction and can be steered by changing the phase relationship between the antenna elements. Phase shifters are used to control the phase relationship between different antenna elements electronically. Increasing the number of individual antenna elements in a phased array reduces the beam width and provides more granular control over beam steering. Phased arrays can be classified into 2 types: passive phased arrays (PESA) and active phased arrays (AESA). Passive phased arrays have all the individual antenna elements connected to a single RF source via phase shifters. They can produce and steer a beam of a single frequency at a time. In active phased arrays, each antenna element is connected a solid state transmit-receive module, which serves as both the transmitter and receiver for that antenna. Thus, it can radiate and steer beams of multiple frequencies at the same time [4]. It also has higher spectral efficiency compared to a passive phased array, as it can spread the radiations over a wider range of frequencies. Phased array concepts provide important contributions to 5g mobile communication systems. The concept of digital beamforming is a useful concept in 5G systems. These systems are stated to operate at millimetre wavelengths. Antenna size at this wavelength is extremely small. An array of 1024 antenna elements can be as small as 4 square inches. Thus, adopting a phased array module for mobiles is definitely possible. The mobility of users, random movement of mobile devices as well as indoor and outdoor propagation in urban environments are essential factors that influence architecture of any mobile communication system. In 5G systems, LOS (Line of sight) operation becomes critical to achieve good SINR (signal to-interference-plus-noise ratio). To achieve this, high-gain directional antennas are needed. Thus, to obtain a good link, beam-steering should be employed on both the base stations and end devices.

IV. HYBRID BEAMFORMING WITH SPATIL MULTIPLEXING

A promising solution to the problems faced by massive MIMO and multibeam phased array technologies is the concept of hybrid transceivers. These use a combination of analog beamforming in the RF domain and digital beamforming in the baseband. Precoding in the baseband reduces the hardware resources needed for analog beamforming in the RF domain [6]. In this section, we shall discuss two different hybrid beamforming approaches.

A. Uniform Linear Array with beamforming and spatial multiplexing based on statistical CSI model

The requirements of beamforming and spatial multiplexing contradict each other: one requires antenna elements that are closely spaced, typically at λ /2 intervals with high coherence, while the latter requires no coherence between the antenna elements to produce parallel data streams.

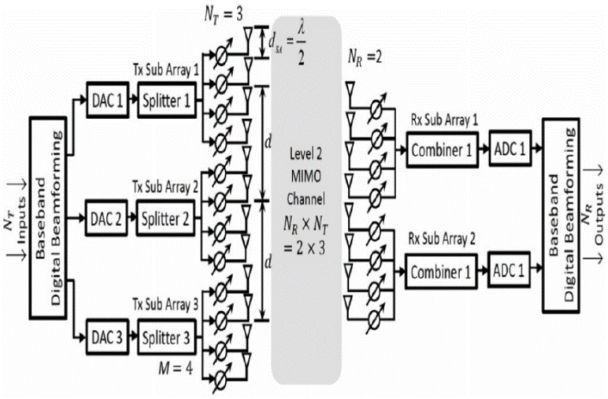

Fig 2. Mm Wave hybrid beamforming based on statistical channel model [2]

A two-level approach has been implemented in [2] to achieve the hybrid beamforming architecture. In level 1, analog beamforming is achieved using sub-arrays that are closely spaced with high coherence. These produce highly directive beams and provide the necessary beamforming gain. The subarrays are a uniform linear array of antennas that are connected via phase shifters. Each sub-array is connected to the baseband processor that produces the symbols with appropriate precoding. In level 2, spatial multiplexing is achieved by a MIMO system that increases the channel capacity through parallel data streams that are transmitted in directions that was selected by the sub-arrays in level 1. Line-of-sight operation is the primary channel considered here. The level 2 sub-arrays must maintain sufficient lateral separation to enable spatial multiplexing and create favorable MIMO conditions. Increasing the number of sub-arrays to increase channel capacity by realizing 3x3 or 4x4 MIMO degrades the channel condition. Thus, increasing the number of sub-arrays without any change in the lateral separation between them creates unfavorable conditions for MIMO spatial multiplexing. Mm wave propagation exhibits a unique feature of forming spatial lobes (SL) even in line-of-sight (LOS) channels due to scattering. This approach takes advantage of this feature, by ensuring different angle-of-departure at the transmitter angle of-arrival of these spatial lobes at the receiver using the level 1 sub-arrays, even in LOS operation. This eliminates the interference loss caused due to these lobes in normal SU-MIMO operation in mm Wave channels. MIMO operation requires the channel state information (CSI) to be known to both transmitter and receiver beforehand. There are mainly two types of CSI estimation, namely instantaneous CSI and statistical CSI estimation. The former requires the current channel conditions to be known, while the latter requires only the statistical characterization of the channel to be known, such as the spatial correlation, average channel gain and fading distribution model. Statistical models are employed in fast changing channels, where channel conditions vary rapidly. Here, the model is based on a 3D statistical spatial model for urban line-of-sight and non-line-of-sight channels. The channel parameters include frequency of operation, type of cell architecture, transmitter power, attenuation levels from various sources, antenna types at and number of antenna elements both transmitter and receiver.

B. Hybrid beamforming based on Instantaneous CSI

In this section, hybrid beamforming is employed based on the availability of instantaneous CSI. The architecture has a baseband precoder that processes data streams that are then sent to an analog precoder that creates the appropriate phase relationship before sending to the antenna arrays [7]. Dividing the set of antennas available to sub-arrays reduces the complexity at the cost of performance (beam steering, beam width).

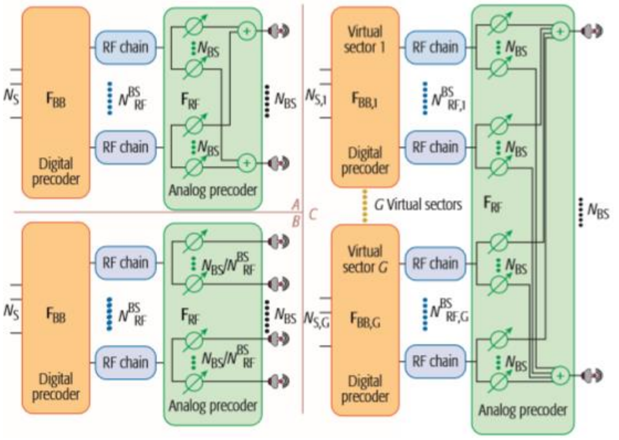

Fig 3. Hybrid beamforming structures for downlink transmission.

Fig. 3 shows the Hybrid beamforming structure for downlink transmission. A,B and C represent full-complexity, reduced complexity and virtual sectorization structures. The architecture here assumes the availability of instantaneous CSI to the transmitter. However, even with this condition being satisfied, calculating the beamforming matrices is still quite difficult due to the following reason: The finite resolution of the phase-shifters, which creates a finite set of beam directions would result in beamforming and channel estimation algorithms that cannot be solved in polynomial time (NP hard problems) [6]. The coupling between the analog and digital beamformers and both ends also makes optimization in beamforming and channel matrices difficult. Decoupling of the beamformer design allows for the matrices to be solved sequentially. This can be achieved in a couple of ways: One can ignore the impact of the coupler on the precoders by assuming that the receiver uses a minimum mean square error (MMSE) estimator. Another method would be to assume to effect of the digital precoder during coupling is constant or unitary. By knowing the effect of the analog precoder, the digital precoders actual effect can be obtained. Another issue with the architecture is controlling signaling coverage. Narrow beams are preferred for user-data plane information, while wide beams are preferred for control plane information. Splitting these planes so that they may be transmitted at different frequencies is a solution. However, this brings in frequency-domain scheduling, as having only spatial multiplexing will be insufficient. The major challenge in this hybrid beamforming architecture is the overhead for acquiring instantaneous CSI at the base station. Based on the type of duplexing used, the computational overhead limits the gain achievable. Thus, techniques that reduce the dimensions of the CSI matrix is needed to relieve the overhead. Some of the proposed solutions [hybrid beamforming paper] suggest using different CSI models for each stage: a slow varying model (average CSI model) for the first analog stage and a fast varying model for the digital beamforming stage. With this approach, the process of decoupling the analog and digital beamformers now changes - we first need to design the beamforming matrix for the digital beamformer and derive the analog beamformers matrix from it. This increases the mathematical computation.

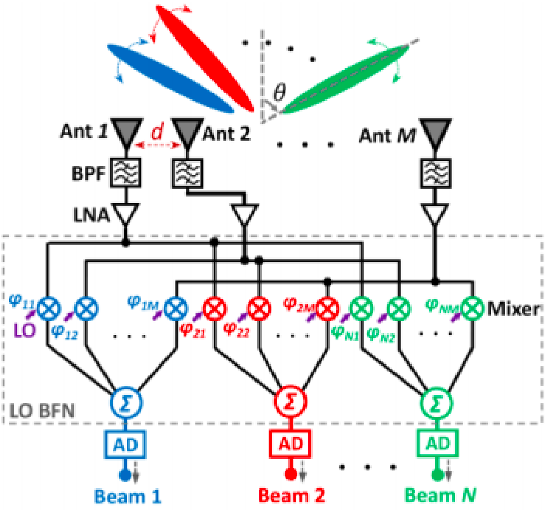

Fig 4. Example of active phased array antenna in receiving mode [5]

There are several options for Multi-beam antenna technologies for 5G wireless communications. Each antenna technology is weighted based on their ability to radiate/receive multiple independent beams, the gain generated and the ability to steer those beams across the aperture. Multibeam antennas employing phased array concepts have several advantages over standard multibeam antenna technologies that employ reflectors and lenses [4]. They produce agile beams compared to having a fixed number of prefixed number of beams pointing at prefixed directions. Multibeam phased arrays based on active phased arrays provide better system noise figure, higher receiver sensitivity, higher power efficiency and better system linearity compared to those based on passive phased arrays. However, for massive MIMO applications, a large quantity of antenna elements would be required. Even with the smaller wavelength of millimeter waves, such a system would have a large device footprint that would prevent its use in mobile communications. There are workarounds to reduce the device footprint and the number of phase shifters used, such as dividing the total number of antennas into sub-arrays. If there are M antenna elements that produce N beams, they can be divided into P groups, each containing M/P antenna elements. These elements are connected via equal length transmission lines [5]. Hence, instead of having NM phase shifters, we will only need NP number of phase shifters, where N phase shifters are connected to P sub-arrays. Another approach is to create segmented phased sub-arrays, where the M antennas are divided into Q sub-arrays, each producing N/Q beams. This reduces the number of phase shifters needed to MN/Q. However, this approach sacrifices beam quality by increasing the beam width. Increase in beam width increases beam interference since the beams will no longer be orthogonal to each other [5]. This increase in beam width is needed to maintain the spatial coverage of the array.

V. INTELLIGENT NETWORK DESIGN USING ARTIFICIAL INTELLIGENCE (AI)

The use of AI in communication network is attracting researchers' attention due to its wide scope in optimizing the network design. Radio planning and optimization could be done efficiently when AI is used. AI promises to address the design complexity of the network. The powerful machine learning algorithms could be used to improve the RF parameters such as channel bandwidth, spectral efficiency, antenna sensitivity etc. Algorithms could be developed for intelligent allocation of the spectrum for different applications based on the popularity of the applications. For example, if a spectrum is allocated for remote monitoring of patients in rural areas, depending on the number of patients, spectrum could be allocated dynamically. Also when the spectrum is not in use by a particular application, the same spectrum could be allocated to other applications, if the allocated spectrum is not sufficient. The AI based network operation and maintenance leads to efficient use of resources and also improves spectral efficiency. The antennas must be designed to support beam visibility and adjustment on the network operation center. Fig. 5 shows the beam patterns for different coverage scenarios.

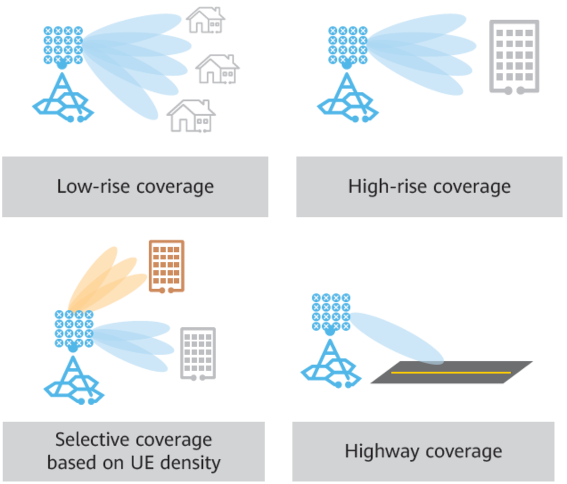

Fig 5. Beam patterns for different scenarios [9].

In such scenarios, AI based algorithms can automatically identify the scenarios and configure the beam widths accordingly. In the above example, there are four such scenarios and automatic reconfiguration of the beam width could improve the customer experience. The early prediction of antenna failure due to aging, its behavior in different scenarios could be provided by the development of powerful machine learning algorithms [10].

VI. CONCLUSION

Hybrid beamforming techniques are expected to be an integral part of massive MIMO and 5G communication systems. Their use of analog and digital beamforming results in beams with good spatial resolution and reduces the number of conversion chains. Some of the major challenges in realizing these structures are CSI computation, decoupling of the analog and digital sections through which the optimization curve can be made convex and the finite resolution of the optimal analog beamformer which lies in a discrete set, leading to NP hard programming problems. Among these, CSI estimation is a major hurdle. Estimating CSI by using training sequences that use pilot signals is one of the current techniques employed in 4G mobile communications. The computation overhead of estimating CSI for 5G networks need to be alleviated by the use of novel strategies. Instantaneous CSI estimation is extremely difficult to be achieved for 5G communication channels. Statistical methods for CSI estimation requiring training sequences with well-known noise distributions are quite accurate but are dependent solely on the availability of noise and channel fading distributions. A blind approach where CSI estimation is solely based on received data, without transmitting any pilot sequence has the least computation overhead and bandwidth required. However, this comes at the cost of accuracy. Currently, statistical methods based on Bayesian estimation (MMSE estimation) have the highest accuracy among the statistical methods and are most likely to the method adopted in 5G mobile communication systems. The use of AI would help the user to have better experience in different scenarios.

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REFERENCES

[1] Brig (Dr) Navjot Singh Bedi, July 2019, [Electronic], " 5G, IoT & ITâ€™S Relevance for the Armed Forces", available at : https://cenjows.gov.in/article-detail?id=187

[2] J. Lota, S. Sun, T. S. Rappaport and A. Demosthenous, "5G Uniform Linear Arrays With Beamforming and Spatial Multiplexing at 28, 37, 64, and 71 GHz for Outdoor Urban Communication: A Two-Level Approach," IEEE Transactions on Vehicular Technology, vol. 66, no. 11, pp. 9972-9985, 2017.

[3] Gupta, Manisha, "Massive-MIMO- Past, Present and Future: A Review", Indian Journal of Science and Technology. 9. pp 1-13, 2017.

[4] W. Hong et al.," Multibeam Antenna Technologies for 5G Wireless Communications,", IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6231-6249, Dec. 2017.

[5] W. Hong et al., "Limitations of phased arrays for 5G wireless communications," 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, CA, 2017, pp. 1467-1468.

[6] A. F. Molisch et al., "Hybrid Beamforming for Massive MIMO: A Survey," IEEE Communications Magazine, vol. 55, no. 9, pp. 134-141, 2017.

[7] Z. Li, S. Han and A. F. Molisch, " Hybrid beamforming design for millimeter-wave multi-user massive MIMO downlink," 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, 2016, pp.1-6.

[8] I. Ahmed et al.," A Survey on Hybrid Beamforming Techniques in 5G: Architecture and System Model Perspectives," IEEE Communications Surveys & Tutorials Vol 20 , Issue: 4 , PP 3060-309, November 2018.

[9] New 5G, New Antenna, 5G antenna white paper, Huawei, available at: carrier.huawei.com/~/media/CNBGV2/download/products/antenna/New-5G-New-Antenna-5G-Antenna-White-Paper-v2.pdf,2019.

[10] Hilal M. El Misilmani and Tarek Naous, "Machine Learning in Antenna Design: An Overview on Machine Learning Concept and Algorithms", 17th International Conference on High Performance Computing & Simulation, Dublin, Ireland, July 2019, pp 600-607.