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Large MIMO Systems and Hybrid Beamforming in 5G or Future Communication

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Abstract

Mobile and wireless communication systems have become an integral part of everyday life with profound economic and social impacts. Everything from smartphones to cars relies on some form of mobile or wireless communication infrastructure. The large or massive Multiple-Input-Multiple-Output (MIMO) with a compromising solution called hybrid beamforming, where both digital and analog beamforming modules are used is one of the promising technologies to provide high data rates, which is motivated by the requirements of the Fifth Generation (5G) or future wireless communications. Large MIMO is a new system configuration, where a base station uses a large number of transmitting and receiving antennas to serve multiple mobile users at the same time. By using a large MIMO system with beamforming technology, the channel capacity can be increased and interferences can be reduced. This paper will explore the use of large MIMO and beamforming in 5G communication, and how these techniques can be used to improve 5G systems. The results obtained showed that theoretically, the large MIMO channel technology has the ability to increase the capacity of a wireless communication link by increasing the number of transmitting and receiving antennas. At the multi-user level, the large antenna array performs beamforming to effectively achieve large antenna gains, thereby improving link capacity and reduce interferences. This improvement can be achieved in a scattering environment.

Keywords: Capacity, Hybrid Beamforming, Large MIMO, 5G

I. INTRODUCTION

The development of cellular communication systems has been driven by a combination of market demands and technological advances. As more and more devices are using cellular communication the demands for speed, reliability, and coverage are increasing. The ever-increasing demand is driven by new applications such as video live streaming, online gaming, the internet of things (IoT), smart metering, automotive driving, video surveillance, cloud computing, and eHealth services [1]. In addition to higher data rates, future communication systems must also have low delay for time-sensitive applications such as remote machine control and medical applications. The next generation of cellular communication, 5G, will combat these increasing demands. Over the past few years, there has been a paradigm shift in cellular communications research to meet both the high data rates and low delay constraints of future 5G systems. One of the research directions to meet these requirements of 5G is to use the unoccupied millimeter range, which has an available bandwidth of several gigahertz (GHz). Studies and experiments have proven that wireless communications in the millimeter waves range are possible. Although millimeter range communication is very promising, it also comes with a new set of challenges. The range of millimeter waves is shorter than that of traditional microwaves. Millimeter waves also have a harder time passing through buildings and walls, so attaining good indoor coverage can be a challenge. One innovative technology to achieve increased data rates is large MIMO systems. It can attain higher data rates by using a large number, anywhere from hundreds to a few thousand, of antennas at the base station, which serve a limited number of users [2]. When a large number of antennas are used on the same base station, new problems such as interference between users and thermal noise arise. These problems can be solved by using a linear processing technique called beamforming at the base station. This research paper will explain and illustrate the operation principles of a large MIMO channel with beamforming technology and its capacity in 5G communication.

II. HISTORY OF MIMO

The development of MIMO technology originated from the development of directed beams for radar applications formed with antenna arrays. Antenna array radar systems were developed during and after World War II. With the 1970s came digital signal processors, which allowed for more sophisticated adaptive processing. These systems were heavily developed by the U.S. military for defense applications. Researchers started to realize that MIMO systems can attain large capacity gains in wireless communications. Several researchers at AT&T Bell Labs studied MIMO technology [3]. Dr. Jack Winters pioneered MIMO techniques using spatial multiplexing and was amongst the first to propose the concept of using multiple antennas to increase capacity. Also, Dr. Winters took MIMO

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research a step further and investigates multi-user systems operating over coupled linear networks [4]. These studies are essentially coupled to specific schemes and receiver structures. In 1995, researchers came up with a more general channel capacity formula for Rayleigh channels with and without fading correlation. These studies assumed that the channels were stochastic and the capacities were expressed in statistical terms. Even today, these results are still considered the standard expression of MIMO capacity. In 1996, researchers studied the issue of delay-spread in the time domain and proposed a solution based on orthogonal frequency division multiplexing (OFDM) [3].

III. LARGE MIMO OVERVIEW

In the context of wireless communications, large MIMO denotes a system where the number of antennas at the base station is much larger than the number of the user equipment. There are many special forms of MIMO that can be used from the conventional systems with a single antenna transmitter and receiver are referred to as Single-Input-Single-Output (SISO), through systems with a single-antenna transmitter and a multi-antenna receiver are referred to as Single-Input-Multiple-Output (SIMO) [5]. Similarly, systems with multi-antenna transmitters and single-antenna receivers are referred to as Multiple-Input-Single-Output (MISO), and those with the full MIMO systems as seen in Figures 1-4.

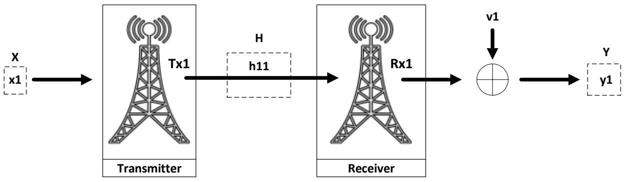

Fig. 1. SISO System with 1 transmit antenna and 1 receive antenna

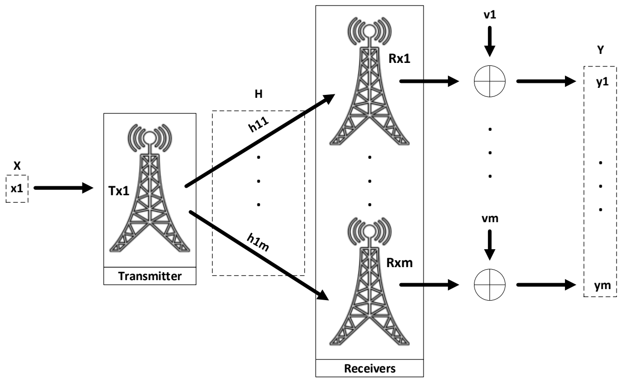

Fig. 2. SIMO System with 1 transmit antenna and m receive antennas

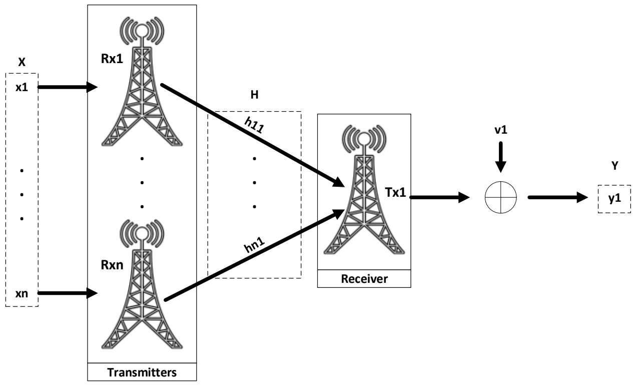

Fig. 3. MISO System with n transmit antennas and 1 receive antenna

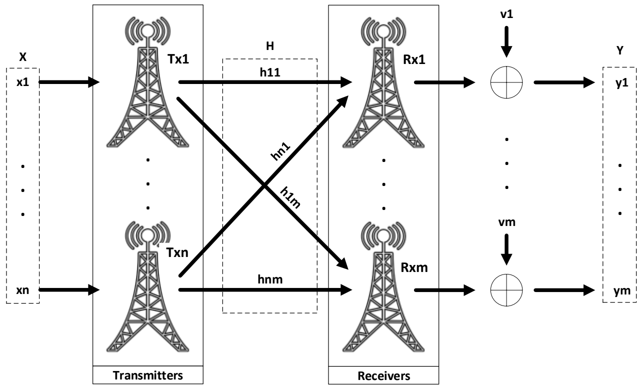

Fig. 4. MIMO System with n transmit antennas and m receive antennas

For large MIMO, the number of antennas at both ends can be up to hundreds or even thousands, that is, $m \gg 0$ and $n \gg 0$. Using vector notation, a large MIMO system that includes n transmit and m receive antennas can be represented as follows [3]:

$$y_i = \sum_{j=1}^{n} h_{ij} x_j + v_i \quad (1)$$

or in a matrix framework,

$$y = Hx + v \quad (2)$$

or equivalently,

$$\begin{pmatrix} y_1 \\ \vdots \\ y_m \end{pmatrix} = \begin{pmatrix} h_{11} & \cdots & h_{1n} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} v_1 \\ \vdots \\ v_m \end{pmatrix} \quad (3)$$

where y is the received vector, x is the transmitted vector, H is the quasi-static channel gains matrix from transmit antenna j to receive antenna i, and v is the additive white Gaussian noise (AWGN) vector. The above relation is used for transmission over one symbol interval. If $l > 1$ represents the number of symbol intervals used for transmission over a channel. Then, the large MIMO system can be expressed as the following [6]:

$$Y = HX + V \quad (4)$$

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where,

$$Y = \begin{pmatrix} y_{11} & \cdots & y_{1l} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{ml} \end{pmatrix};\ H = \begin{pmatrix} h_{11} & \cdots & h_{1n} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mn} \end{pmatrix}$$

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1l} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nl} \end{pmatrix};\ V = \begin{pmatrix} v_{11} & \cdots & v_{1l} \\ \vdots & \ddots & \vdots \\ v_{m1} & \cdots & v_{ml} \end{pmatrix}$$

If the noise is assumed to be negligible, the transmitted vector can be expressed as:

$$Y = HX \qquad (5)$$

Knowing the receiver matrix Y and channel gains matrix H, the relationship which allows the reconstruction of X is:

$$X = H^{-1}Y \qquad (6)$$

The above relation requires H to be invertible, which means that H needs to be full rank. Physically, this means that it is very important to have an environment rich in multipath to take advantage of the contributions of a large MIMO system to 5G communication [7].

IV. LARGE MIMO CHANNEL CAPACITY

In digital communication, the capacity of a system can be defined as the maximum transmission rate for which a reliable communication can be obtained [8]. When the capacity is less than the transmission rate, the system breaks down, and the receiver makes decoding errors with a non-negligible noise. Channel Capacity was first introduced by Claude Shannon using the following expression [3]:

$$C = W\ log_2(1 + SNR)\frac{bits}{second} \qquad (7)$$

where C (logarithmic function) is the number of bits that can be transmitted without error per second over a channel, W (in Hz) is the bandwidth of the line, and SNR is the signal-to-noise ratio. For a large MIMO System, Shannon's formula can be expressed as:

$$C_{MIMO} = log_2(det[I_m + \frac{SNR}{n}HH^{*T}])\frac{bits}{second} \qquad (8)$$

where, H^{*T} represents the Matrix transpose conjugate of H and det(A) denotes the determinant of matrix A. Taking the expected values of both sides and using Rayleigh approximation, it can be proved that the capacity is proportional to the number of receiving antennas m [8].

$$E[C_{MIMO}] \approx m\ log_2(1 + SNR) \qquad (9)$$

V. BEMFORMING OVERVIEW

In digital communication, beamforming is generally described as a special type of spatial filtering technique to form a beam in a particular angular direction in a system with multiple sensors [9]. The beamforming can be achieved by having M identical antenna elements with 120° half-power beam width (HPBW). As seen in Figure 5, the beamforming permits higher-power signals directed to the desired station to be transmitted while minimizing the transmission power to other stations [10].

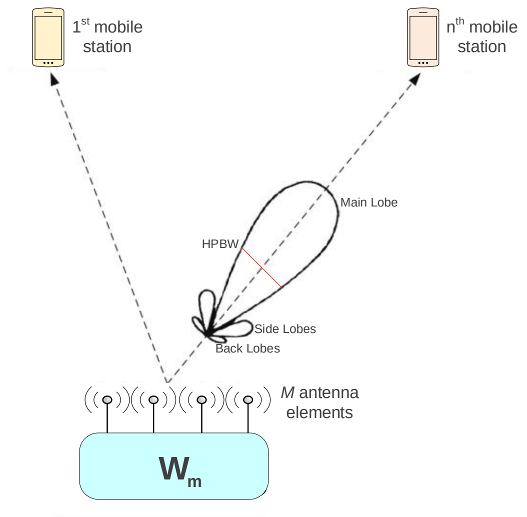

Fig. 5. Beamforming transmitter for an M antenna elements

The output of the beamforming system can be expressed as a weighted basis [10]:

$$y(t,\alpha) = \sum_{m=1}^{M} w_m x\left[t - (m-1)\frac{d}{c} sin\ \alpha\right] \qquad (10)$$

where, y(t, α) is the output signal, w_m is the complex weight, x(t) is the signal sent by the first antenna element, d is the separation distance between the multiple elements, c is the speed of the wave, and α is the direction of departure (or arrival). The output signal in Equation 10 can also be written in the frequency domain as:

$$Y(f,\alpha) = \sum_{m=1}^{M} w_m X(f) e^{-j2\pi f(m-1)\frac{d}{c}\sin\alpha} \qquad (11)$$

For the beam to be transmitted toward the desired direction α_1, and for the case of d=λ/2, we have [11]:

$$w_m = e^{j\pi f(m-1)\sin\alpha_1} \qquad (12)$$

In which, for $\alpha = \alpha_1$, Equation 11 simplified to [10]:

$$Y(f,\alpha) = M\ X(f) \qquad (13)$$

or equivalently,

$$\frac{Y(f,\alpha)}{X(f)} = M$$

which is the maximum amplitude that can be obtained by beamforming.

VI. HYBRID BEAMFORMING IMPLEMENTATION

A test system was implemented using guidance and an example from the MathWorks Documentation [12]. This system uses the Phased Array System Toolbox™ in MATLAB® and uses hybrid beamforming at the transmitter end of a multi-user large MIMO OFDM system. It also adds thermal noise of configurable magnitude to the channel to simulate real

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conditions. The system partitions the necessary precoding into digital baseband and analog RF components for the multi-user system. Simplified digital receivers are used to recover the multi-stream data to calculate the error vector magnitude and the bit error rate. The test system uses a scattering-based spatial channel model that takes into account different transmitting and receiving spatial locations and antenna patterns [12]. The system uses full-channel sounding to determine transmitter channel state information. The availability of transmitter channel information for spatial multiplexing systems allows precoding to maximize the signal energy in the channel and direction of interest. The channel is sounded first using a reference transmission, which is used to estimate the channel information, and then is used to calculate the precoding needed for the succeeding data transmission [12]. Figure 6 shows a diagram for the channel sounding model.

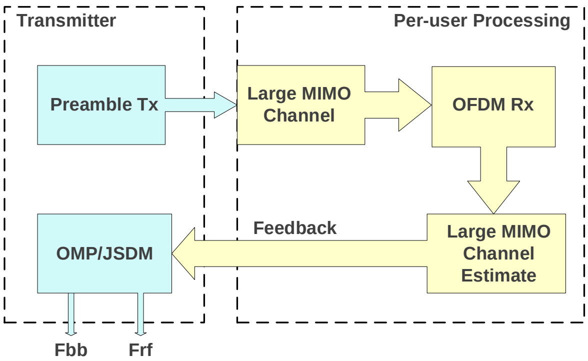

Fig. 6. Block diagram of the channel sounding model

The next step is the hybrid beamforming. This system uses the joint spatial division multiplexing (JSDM) method to calculate the RF analog and baseband precoding weights. After the weights are calculated, users with similar transmit channel covariances are grouped together, and the inter-group interference is suppressed by the analog precoder [13]. After beamforming, the next step is data transmission. This system maps each data stream from each user to an individual RF chain. Antennas are then connected to each RF chain [12]. The data transmission architecture is shown in Figure 7.

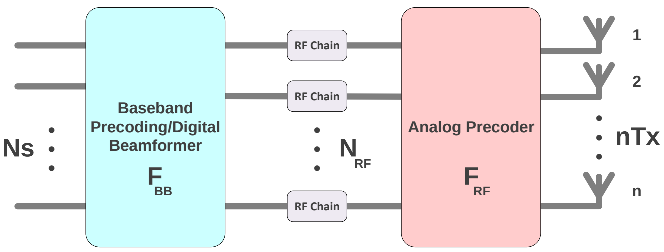

Fig. 7. Data transmission architecture

After the data transmission, the signal propagation is simulated using the helperApplyMUChannel function. The use of this function is to add various losses, interference, and noise to the system. After propagation, the signal is received, amplified, and recovered. The receiver compensates for the path loss through the amplification of each user. The receiver also adds thermal noise to better simulate real-world conditions. Similar to the transmitter, the receiver of this large MIMO system consists of many steps such as OFDM demodulation, large MIMO equalization, quadrature amplitude modulation (QAM) de-mapping, and channel decoding [12]. The overall data transmission and reception architecture is shown in Figure 8.

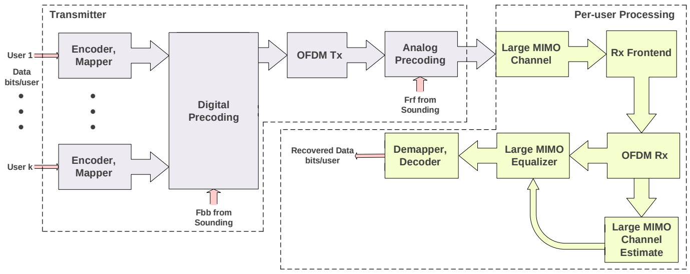

Fig. 8. Data transmission and reception architecture

VII. SIMULATION RESULTS

In Figure 9, the relationship between the number of antennas and the ergodic capacity is plotted using MATLAB®. Simulation results show that increasing the number of antennas increases channel capacity, especially for MIMO systems. Figure 10, on the other hand, shows the effect of the SNR on the channel capacity.

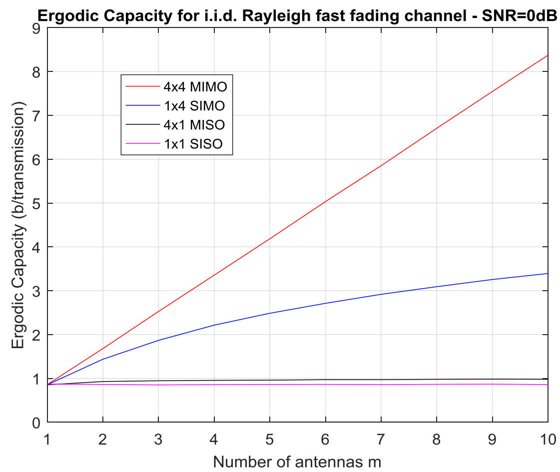

Fig. 9. Capacity vs. number of antennas for a 1 × 1 SISO system, a 1 ×4 SIMO system, a 4 × 1 MISO system, and a 4 ×4 MIMO system (SNR=0)

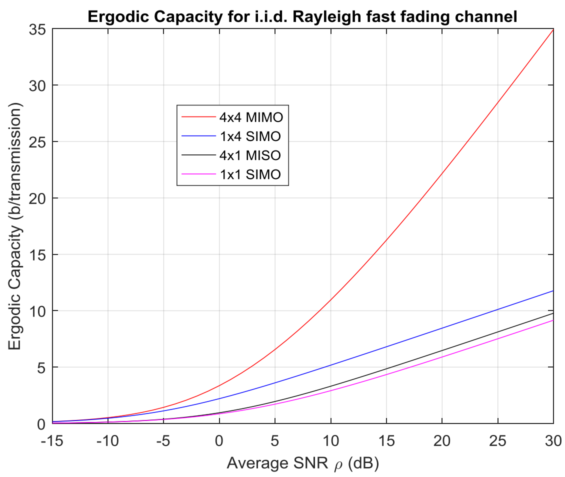

Fig. 10. Relationship between capacity and average SNR

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In the beamforming simulation setup, the implementation part of the system description is set for three users. User 1 has three data streams, User 2 has two data streams, and User 3 has one data stream. The system frequency was set to 28 GHz. The modulation was set to 16-QAM using 10 OFDM symbols. The root mean square (RMS) error vector magnitude (EVM), bit error rate (BER), number of bits, and the number of errors were calculated for each user. The results are shown below. The 3D response pattern of the system is plotted and shown in Figure 11.

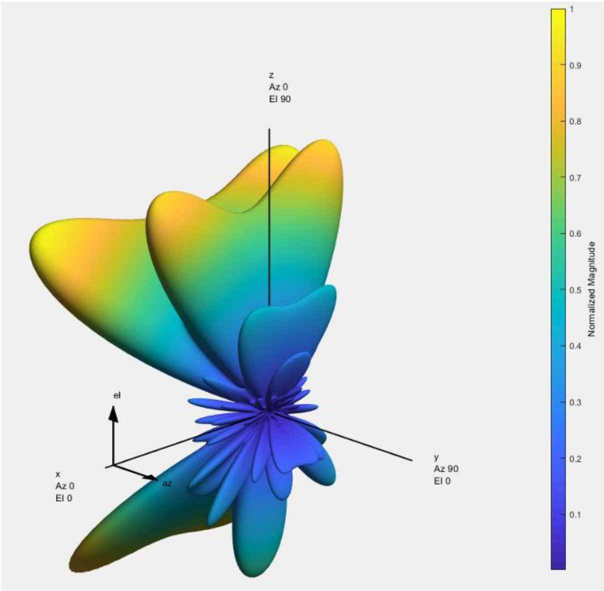

Fig. 11. 3D response pattern

The high magnitude lobes can be correlated to the various data streams for each of the users in the system. The receive constellations for the equalized symbols were also plotted, and shown in Figure 12.

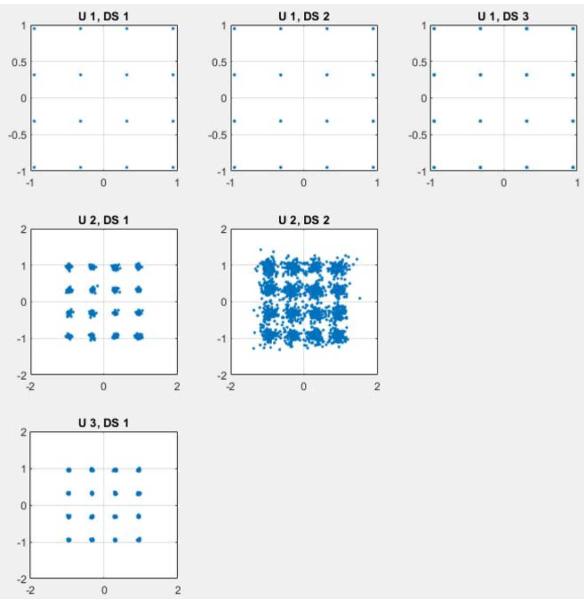

Fig. 12. The receive constellations for the equalized symbols

User 2 data stream has the largest distortion, which can also be seen by the fact that User 2 has the largest RMS EVM in Table 1 below.

Table 1. Computed EVM and Bit Rate

User #	RMS EVM (%)	BER	No. of Bits	No. of Errors
1	0.1282	0	9354	0
2	11.0356	0	6234	0
3	1.6306	0	3114	0

VIII. CONCLUSION

5G systems can offer much higher data rates but also come with its own set of challenges. 5G systems use millimeter waves, which have a shorter range, and lower permeability through buildings, structures, and walls. Large MIMO systems can help attain higher data rates by using a large number of antennas at the base station, which serve a limited number of users. By using this technology new challenges such as inter-user interference and thermal noise arise when a large number of antennas at the same base station are used. These problems can be solved by using hybrid beamforming at the base station.

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