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Performance Analysis of Correlated Channel Capacity for Large Scale Multiple Input Multiple Output System

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Abstract— *Large scale multiple antenna system is regarded as an important technique to achieve the high data rate requirements in 5G and future generation wireless communication networks for efficient multimedia application. The majority of the research carried out regarding maximising channel capacity in wireless network data transmission for multimedia application have considered conventional multiple-input multiple-output (MIMO) system and in cases where large scale MIMO have been considered, it has been assumed that the channels are uncorrelated. But, this is ideal scenario and it is not realistic valid. Hence, this work attempted to maximize the channel capacity of wireless communication networks for multimedia application by extending a conventional MIMO channel model to implement large scale multiple antenna system when the channels are correlated and the base station (BS) and mobile station (MS) employ different antenna arrangements. This paper considered the analysis of MIMO system in terms of data transmission when the channel is correlated. Three main parameters of interest for the correlated channels are the signal power expressed in terms of signal to noise ratio (SNR) in dB, the spacing between antennas, and the number of antennas. Simulation analysis was performed in terms of ergodic capacity (uncorrelated) and correlated ergodic capacity including the bit error rate (BER) performance of the correlated channel when different MS transmits to BS. In order to further study and validate the capacity performance of the proposed system employing massive multiple antenna arrays considering a more realistic channel scenario, correlation was taken into account and the capacity of system was observed for, say M = N = 20, the capacity was 172.4 bps/Hz for uncorrelated channel and 111 bps/Hz for correlated capacity. However, the ergodic capacity of correlated channel provides more realistic scenario about the channel than uncorrelated channel. Generally, simulation results have shown that near optimal performance can be achieved for channel capacity in wireless network data transmission for multimedia application by increasing the number of antennas even in correlated channel scenario.*

Keywords—Correlated channel, Ergodic capacity, Large scale MIMO, Wireless network

1. INTRODUCTION

Wireless communication system using more than one antenna at the input and the output are usually called multiple-input and multiple-output (MIMO) system. This antenna arrangement results in MIMO channel that is designed to improve communication performance. Multiple antenna system has advanced such that it is regarded as technique for increasing the capacity of a radio communication system by taking advantage of multipath propagation [1]. The functions of MIMO system are categorized into two main formats spatial multiplexing and spatial diversity [1]. Each of these categories depends on the antenna and the channel characteristics. The two categories mentioned earlier can be used to model MIMO channel such that spatial multiplexing provides multiple data rates and spatially orthogonal channels, while spatial diversity offers improve in signal to noise ratio (SNR) and mitigation of various forms of fading and thereby improve system reliability.

The evolution of MIMO system has resulted in the emergence of novel communication systems such that multiple user equipment can now be connected with MIMO enhancing capacity. This technology is usually called multiuser MIMO (MU-MIMO) system.MU-MIMO is often regarded as an extension of Space-Division Multiple Access (SDMA) [2]. Hence, multiple connections on a single conventional channel where spatial signatures are used to identify different users are supported by this technology. Spatial signature is a base station antenna array response vector to a mobile terminal at a given location. In mobile wireless communication, subscribers at different locations show different signatures. Thus, the main underlying concept of SDMA is simply leveraging of spatial diversity, which is the difference of spatial signatures. SDMA employs spatial multiplexing and facilitates higher data rate, which can be achieved by utilizing multipath as different data carrying channel. The MU-MIMO technology offers this seamless possibility, whereby multiple users can be served independently at the same time with high transmitting data rate.

Though previous studies have focused on using multiple antennas technology to increase channel capacity so as to address the problem of low data rate due to limited bandwidth, but in situations where these variables have been considered, implementations have been limited to conventional MIMO system with up to 8×8 antenna array. With the recent development in wireless system, large scale multiple antennas (massive MIMO) are believed to be the technology that will provide more high speed for data sharing between multimedia devices. However, vast majority of the works on large scale multiple antenna system has assumed the channels to be uncorrelated, which is highly idealistic [3]. Therefore, a MIMO system with correlated channel is evaluated with massive antenna array to provide maximum channel capacity in multimedia application.

2. CHANNEL CAPACITY AND MIMO SYSTEM

In this section a concise review of channel capacity and MIMO system is performed to provide a clear direction for the main goal of this paper.

2.1 Channel Capacity

In the study of wireless systems, one of the main measurements to characterize the performance is the channel capacity, and in addition basically serves as a guide to appropriately design the transmitted signals including the processing of the signal received [4]. In order to examine the most efficient capacity increase, different implementations were considered regarding the application of multiple antennas [5]. These implementations as regards the use of multiple antennas can be done by adding antennas to the transmitter, to the receiver, or to both sides of the wireless system. The concept of channel capacity from communication theory was pioneered by Claude Shannon with a deduced definition usually referred to as Shannon's capacity (Borges et al., 2021):

$$C = B \times \log_2\left(1 + \frac{p|h|^2}{B \times n_0}\right) \tag{1}$$

where C represents the channel capacity in bit per second (b/s), B is the channel bandwidth in hertz (Hz), p is the symbol power, h is the channel gain, and n_0 is the noise variance [6]. Taking into account the theoretical upper limit, in which $E[|h^2|] = 1$, and the fixed channel bandwidth removed, the expression for the channel capacity can be simplified as:

$$C = \log_2(1 + SNR) \tag{2}$$

where C is now measured in bits per hertz (b/Hz) and the signal to noise ratio, $SNR = p/n_0$ at the receiver.

2.2 Channel State Information

The transmitter will be able to know the state of the channel when channel state information (CSI) technique is applied. TheCSI technique enables the channel matrix (or gain) H to be fed back to the transmitter from the receiver. Therefore, prior to the transmitter transmitting data over the channel, it knows it state. An illustration of CSI scheme is shown in Fig. 1. The figure shows a downlink transmitter receives information from the receiver based on feedback mechanism. However, in this paper, a perfect channel has been assumed.

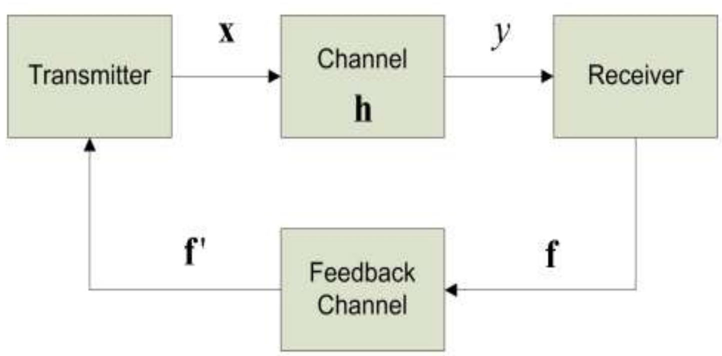

Fig. 1 Block diagram of channel state information technique [7]

2.3 Multiple Input Multiple Output Technique

This scenario involves the use of more than one antenna at the transmitter side and the receiver side that results in a wireless communication called MIMO system. The technology has become a common configuration of antenna employed in several latest wireless networks in recent times [8]. MIMO is famous in Long Term Evolution (LTE), Wi-Fi and other wireless radio network to increase link reliability, capacity, speed of data transfer (data rate), and spectral efficiency. Several wireless routers employing MIMO system are presently in the market and in so doing has made it more popular. A typical MIMO channel is shown in Fig. 2.

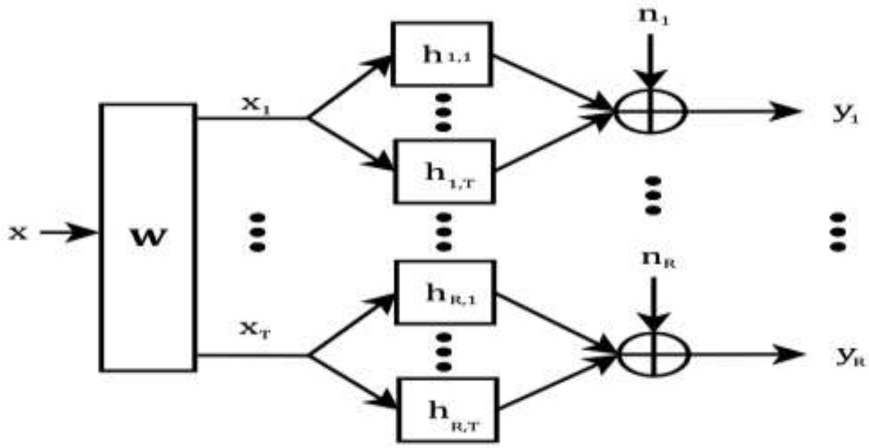

Fig. 2a Model of MIMO signal [5]

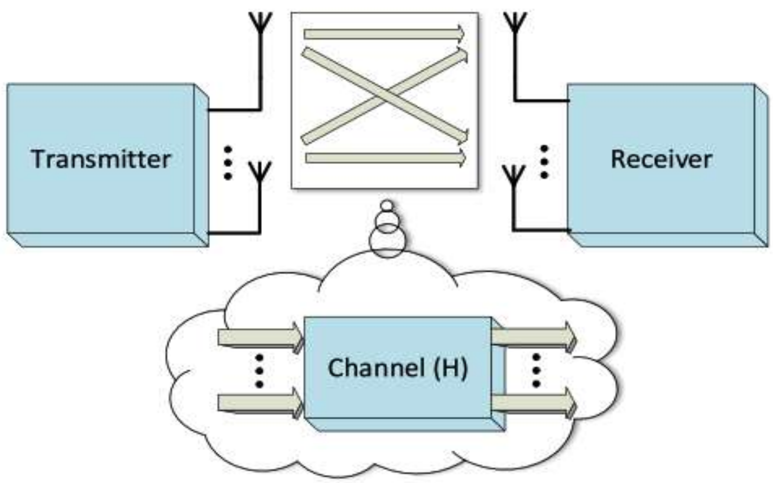

Fig. 2b MIMO system configuration [5]

Assuming M transmit antennas and N receive antennas, the receive signal y_n expressed in terms of the transmit signal x_m, the channel gain $h_{n,m}$ that corresponds to the path or channel response from the mth transmit antenna to the nth receive antenna and the n_r corresponding to the noise with respect to the receive antenna dimension given by Eq. (3). The channel capacity of MIMO system can be expressed as in Eq. (4) [6].

$$y_n = \sum_{m=1}^{M} h_{n,m} x_m + n_r \quad (3)$$

$$C = S \times \log_2 (1 + SNR) \quad (4)$$

where C is the capacity of the channel, S represents the parallel channels, and SNR is the signal to noise ratio.

2.4 Massive Multiple Input Multiple Output System

In current wireless system, MIMO systems are an integral component, and have in recent years been extensively employed to meet high spectral efficiency and energy efficiency. SISO systems were mostly employed prior to the introduction of MIMO, but its throughput was very low and not able to support a large number of mobile terminals (or users) with high reliability [9]. In order to contain this increase in user demand, various MIMO technologies such as SU-MIMO, MU-MIMO, and network MIMO were proposed. Nevertheless, these MIMO systems are not sufficient to contain the ever growing user demands. The number of wireless users has grown exponentially in recent times and trillions of data generated by these users that must be efficiently handled with improved reliability [9].

In addition to the increased wireless users, large number of Internet of Things (IoT) technologies having various applications in smart/intelligent healthcare, smart homes and cities, and smart energy and power system. This has contributed immensely to the volume of data traffic generated in wireless system. Chataut and Akl [9] stated that it was predicted that by the end of 2020 about 50 billion devices would be connected. Wireless networks such as fourth generation (4G)/LTE using conventional MIMO systems are not able to support the large influx in data traffic with increased speed and link reliability. Therefore, future wireless networks such as fifth generation (5G) is taking into consideration the large scale MIMO technology famously known as massive MIMO system, as a possible solution to addressing the problem caused by huge data traffic and increased number of users [4], [10]. Many research works have been done on massive MIMO systems and the benefits have been summarized in Borges et al. (2021) to include:

a) Large spectral efficiency,
b) Reliability of communication link,
c) High energy efficiency,
d) Signal processing of low complexity,
e) Favourable propagation,
f) Hardening of channel.

The basic notion about massive MIMO is that it is physical-layer system in which each BS is equipped with large number of active antennas that can be employed to spatially multiplex many mobile terminals or UEs in order to communicate with them on the same time-frequency resource [5]. Massive MIMO is the most interesting technology for 5G and future wireless system [9]. Massive MIMO takes all the advantages of conventional MU-MIMO such that with M number of BS antennas and K number of single antenna users a diversity of order M and a multiplexing gain of min (M,K) can be achieved [5]. It is regarded as an advancement of current MIMO technologies employed in contemporary wireless networks that assembles hundreds and even thousands of antennas at the BS and serves tens of users at the same time [11], [12]. A large spectral efficiency can be achieved by increasing both M and K, while high link reliability can be obtained with simple linear precoding such as maximum ratio combining (MRC), zero forcing (ZF), maximum ratio transmission (MRT), and minimum mean square error (MMSE). The use of extra antennas by massive MIMO helps to focus energy into a smaller region of space to offer improved throughput and spectral efficiency. Besides, from the perspective of information theory, spectral efficiency performance strongly depends not only on SNR but also the level of correlation [3].

3. CORRELATED CHANNEL

The mathematical derivation of a correlation based stochastic model (CBSM) is presented for large scale multiple antenna (called massive MIMO) system in this work. The model combines statistical characteristics and spatial correlation for PAS to implement a channel model for multiple antenna technology and it is called Intelligent Multi-element Transmit and Receive Antennas (I-METRA). The statistical model of correlated multiple antenna fading channel consisting of M transmit antennas at base station (BS) and N receive antennas at mobile terminal (MT). The narrowband channel (Rayleigh correlated channel) H_w of multiple antenna system is statistically described by M × N matrix as using Kronecker model [7], [13]:

$$H_w = R_n^{1/2} \times H_{iid} \times R_m^{1/2} \tag{5}$$

where R_n and R_m are the receive and transmit antennas correlation matrices, and H_{iid} denotes the independent and identically distributed fading channel [14], which is the uncorrelated channel matrix [7]. Equation (5) shows that correlation matrices are independent from each other assuming the spacing between transmit antennas at the transmitter and the spacing between receive antennas at the receiver is less than the distance between the transmitter and the receiver.

The application of Kronocker product is used to determine root power correlation matrix Γ. Thus, using the square root decomposition for real matrices, the root power correlation matrix with field type is thus given by:

$$\Gamma = \begin{cases} \sqrt{R}, \text{ for field type} \\ R, \text{ for complex type} \end{cases} \tag{6}$$

where R is given by:

$$R = \begin{Bmatrix} R_{BS} \otimes R_{MT} \\ R_{MT} \otimes R_{BS} \end{Bmatrix}$$

(7)

The Cholesky decomposition for complex matrices is used by the matrix with complex type given by:

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$$\Gamma = GG^T \quad (8)$$

where G represents the correlation shaping matrix.

4. Simulation Results

The simulation results obtained regarding the performance analysis of correlated MIMO channel. In order to perform simulation in MATLAB environment, the parameters for typical micro strip antennas designed and implemented for MIMO system were used. Number of BS antennas (M) is $8 \le M \le 128$, Number of mobile station antennas (or receive antennas) (N) is ≤ 20, signal to noise ratio (SNR) is 30, distance between antennas (spacing) is 0.5λ, modulation scheme is PSK, azimuth spread (at transmitter) is 10 degrees, angle of arrival (at transmitter and receiver) is 20 degrees, frequency 1×10^9 Hz, and wavelength is 3×10^8/frequency. The simulation analysis is conducted for correlated channel capacity against SNR, system capacity (bit error rate (BER)) performance against base station antennas under varying number of mobile stations (N), and lastly performance comparison of ergodic capacity and correlated ergodic capacity.

4.1 Ergodic Capacity of Correlated Channel

The ergodic capacity of correlated channel multiple antenna system is presented in this section. A single main direction of departure and arrival has been assumed for simulation in this work. The spacing of the array element is taken to be half wavelength. Figure 3 is the simulation result showing the plots for multiple antenna arrays including conventional MIMO (8 × 8) and large scale (16 × 16, 18 × 18, 20 × 20) multiple antenna systems with fully correlated (that is correlation at both transmitter and receiver) MIMO channel.

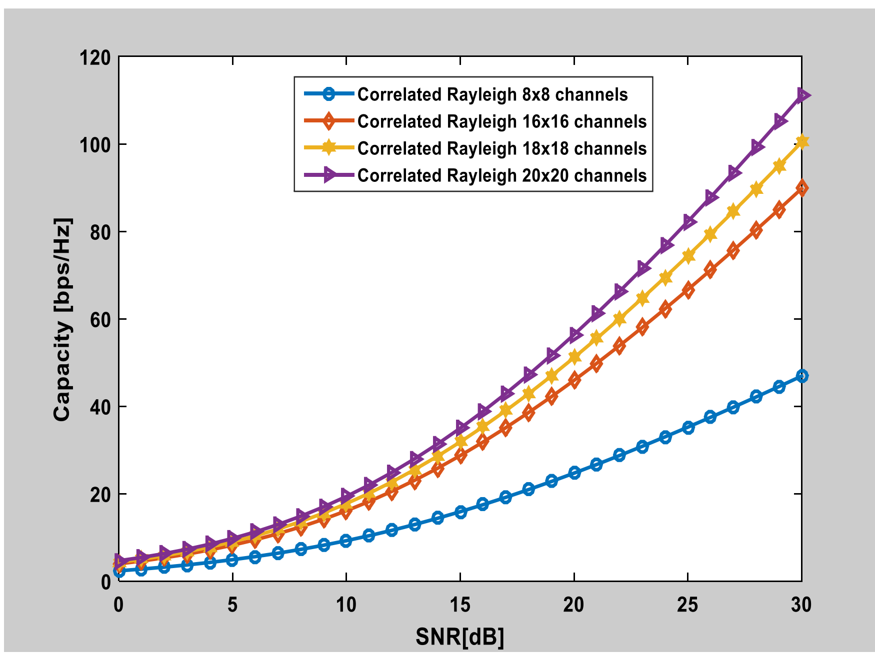

Fig. 3 Ergodic capacity of correlated channel

The numerical value of the ergodic capacity of the correlated channel for each antenna arrangement at SNR of 30 dB is 46.87 bps/Hz for 8 × 8, 89.69 bps/Hz for 16 × 16, 100.4 bps/Hz for 18 × 18, and 111 bps/Hz for 20 × 20 respectively.

4.2 BER Performance Analysis

The capacity of the system is simulated in this subsection in terms of BER when MS sends data to BS. The essence of this section is based on the fact in multimedia applications, where users are demanding high data rate and high capacity, BER performance is valuable parameter to determine efficiency or effectiveness of a multiple antenna system [15]. In Fig. 4, a massive MIMO with varying MS terminals and 20 BS antennas is considered, while in Fig. 5, the number of BS antenna (M) is 32 and the number of mobile station antennas (N) was 8, 16, and 20. The MS size N = 2, 4, 6, 8, 10. In this case, the channel is correlated Rayleigh fading.

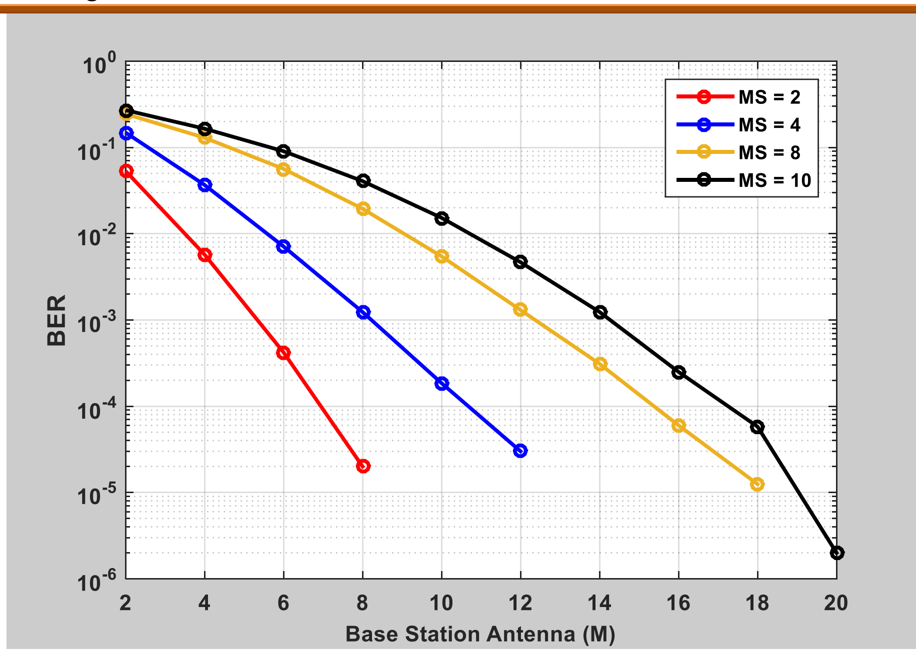

Fig. 4 BER performance of massive MIMO with (M = 20)

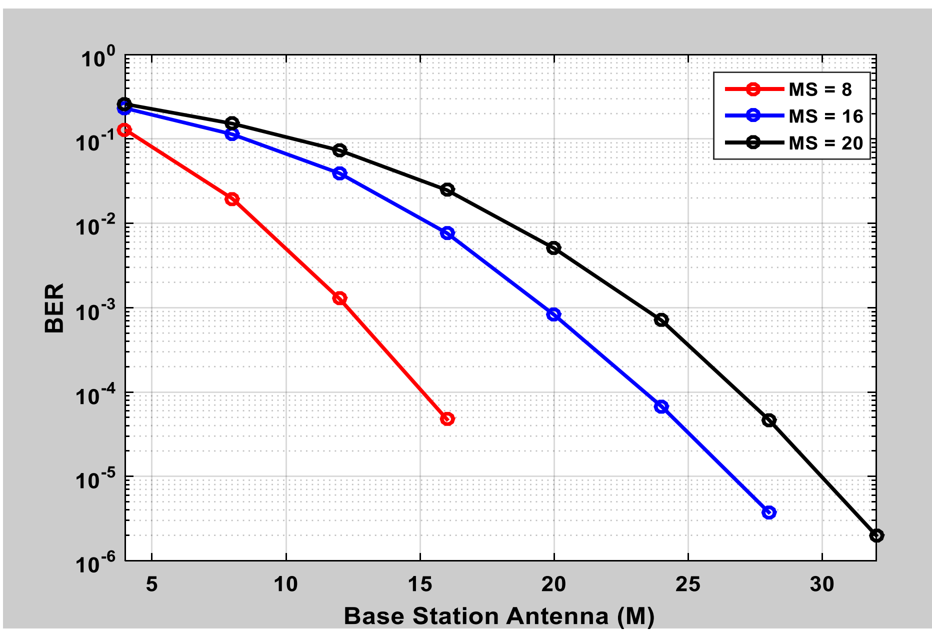

Fig. 5 BER performance of massive MIMO with (M = 32)

Actually, looking at Fig. 4, it is obvious that the BER performance improves as the antenna array configurations increases. BER performance when 2 mobile stations are sending data to base station with 20 antennas was 2e-05. Thus, for 4, 8, and 10 mobile stations, the BERs were 3e-05, 1.25e-05, and 2e-06 respectively. Also, in Fig. 5, with M now 32, the BER for N = 8, 16, and 20 was 4.75e-05, 3.75e-06, and 2e-06 respectively. Generally, Fig. 4 and 5 reveal that even though the channel is correlated, the performance of the system is still improved as the mobile station transmits the base station with increasing number of antennas.

4.3 Comparison of Uncorrelated and Correlated Ergodic Capacities

In this section, a scenario in which the ergodic capacity of the multiple antenna system is evaluated considering when the channel is not correlated and when it is correlated is presented. The results of the simulations are shown in Fig. 6 and 7. Table 1 shows the numerical performance of the channel capacity in each case.

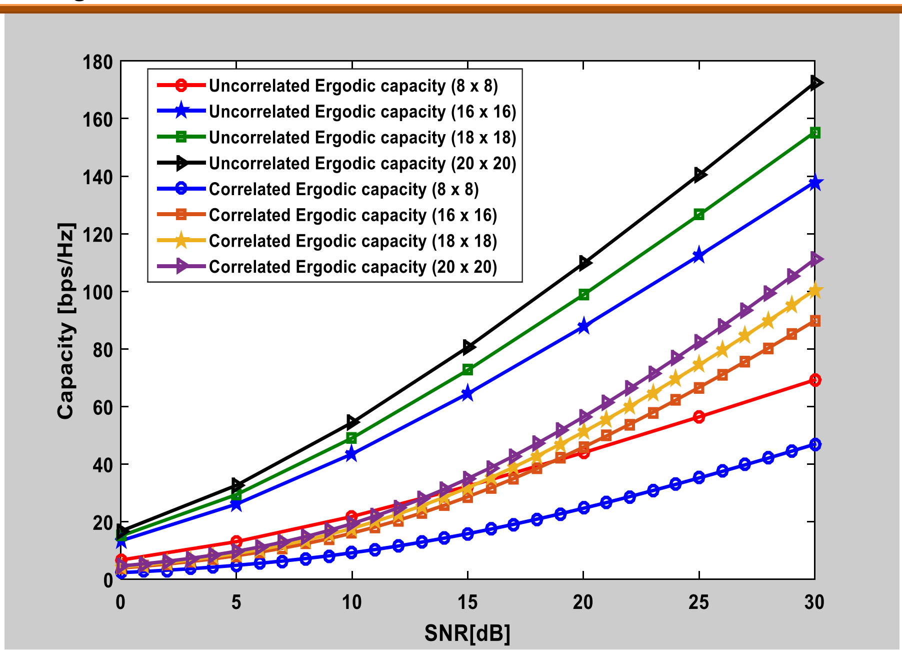

Figure 4.10 Comparison of capacity (for M = N= 8, 16, 18, 20)

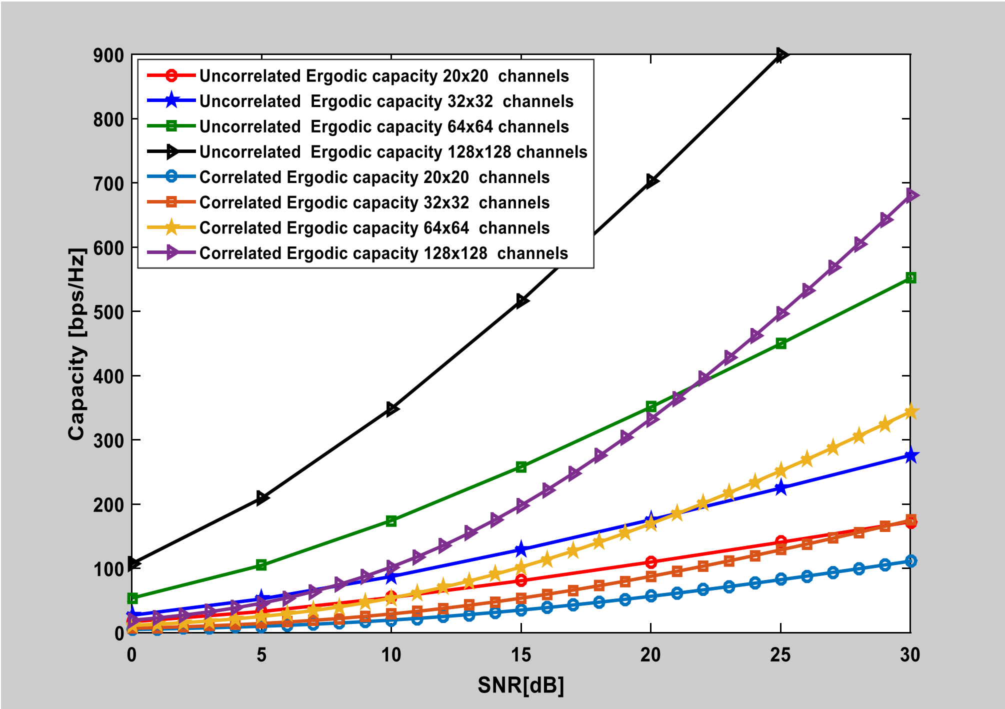

Figure 4.11 Comparison of capacity (for M = N= 20, 32, 64, 128)

Table 1 Performance comparison of uncorrelated and correlated ergodic capacity

Antenna Array (M × N)	Uncorrelated ergodic capacity	Correlated ergodic capacity
M = N = 8	69.31 bps/Hz	46.87 bps/Hz
M = N = 16	138.1 bps/Hz	89.69 bps/Hz
M = N = 18	155.1 bps/Hz	100.4 bps/Hz
M = N = 20	172.4 bps/Hz	111 bps/Hz
M = N = 32	275.8 bps/Hz	174.7 bps/Hz
M = N = 64	551.3 bps/Hz	343.5 bps/Hz
M = N = 128	898.9 bps/Hz	680.2 bps/Hz

Table 1 has shown the numerical results of the ergodic capacity for conventional multiple antenna (8X8 MIMO) system and large scale multiple antenna (massive MIMO) for uncorrelated and correlated channel for different SNRs, which was varied from 5 dB steps from 0 dB to 30 dB. Looking at the table, it is obvious that a significant reduction of capacity is achieved with highly correlated channels. Though the uncorrelated capacity was higher than the correlated capacity, it should be noted that in the uncorrelated channel where independent and identical distributed (i.i.d.) Rayleigh channel is assumed, this scenario is not valid in a realistic channel where some correlations exist between antenna elements [16]. The mean square error is significantly minimized in correlated channels [3]. Furthermore, for performance assessment and improvement of multiple antenna system, the knowledge of channel correlation is critical [17].

5. CONCLUSION

Large scale multiple-input multiple-output (massive MIMO) is regarded as a critical technology to meet high data rate demand in multimedia application. The proposed large scale multiple antenna scheme has been implemented to improve the capacity performance of wireless communication system in multimedia applications such as in the latest 5G network considering both the common idealistic assumption of channels to be uncorrelated and the realistic scenario of correlated channel. In order to study the capacity performance of the proposed system employing massive multiple antenna arrays considering a more realistic channel scenario, correlation was taken into account and the capacity of system was observed to reduce such that for, say M = N = 20, the capacity was 172.4 bps/Hz for uncorrelated channel and 111 bps/Hz for correlated capacity. However, the ergodic capacity of correlated channel provides more realistic scenario about the channel than uncorrelated channel. Furthermore, a scenario whereby mobile stations with varying number antennas transmit data to base station was of a given fixed number of antennas was considered. The performance of the receive diversity in terms of BER revealed that improved capacity can be achieved even under correlation.

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