Volume: 15 Issue: 04 Pages: 6063 - 6068 (2023) ISSN: 0975-0290

Capacity Analysis of Multiple Antenna Wireless System under Different Array and Channel Configurations

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ABSTRACT

This paper has presented capacity analysis of multiple antenna wireless system under different array and channel configurations. In this study, the dimension of conventional multiple input multiple output (MIMO) system was extended to large scale MIMO. The capacity of MIMO system was considered over spatially correlated Rayleigh channel. The parameters of interests used for the system analysis are the channel capacity (measured in terms of data transfer rate) in bit per second/ hertz (bps/Hz), signal to noise ratio (SNR) in dB, spacing between the antennas, and the number of antenna elements. A MATLAB model was developed for the system for the purpose of simulation analysis to examine channel capacity performances under different antenna arrangement and channel configurations. Simulation results revealed that the capacity of the system increases as the number of antennas at both transmit and receive ends increases. Generally, the uncorrelated channel provided better capacity than correlated channel in all cases. However, the capacity of the correlated channel offers more practical results than uncorrelated channel.

Keywords – **Antenna, Capacity, Correlated channel, MIMO, Wireless system**

Date of Submission: October 17, 2023 Date of Acceptance: December 25, 2023

I. INTRODUCTION

Recent development of mobile technology tends toward the use of multiple antennas at transmit and receive ends of the wireless systems. This provides faster data and reliable link for data transmission to each user on the network and is actualized by implementing an algorithm to improve channel capacity with multiple antennas to provide: increase channel capacity, reliability of data of communication between devices, improved spectral efficiency at low cost, since multiple antennas system capacity increases directly as the number of antennas, using large scale will further enhanced system capacity, and high speed wireless communication network to facilitate wide range of application without increasing bandwidth or transmitted power is provided by multiple antennas technology.

Despite the fact that previous studies regarding the use of multiple antenna system for channel capacity improvement have largely be considered in order to solve the problem of low data rate as s result limited bandwidth, the design have been largely limited to neglecting the effect of correlation. Thus, according to Naser et al. [1], vast majority of the studies on large scale multiple antenna systems have assumed the channels to be uncorrelated and this concept is very idealistic.

In this paper, the objective is to evaluate the performance of wireless system with varying transmit and receive antenna configuration including different channel models –uncorrelated and correlated Rayleigh.

II. LITERATURE REVIEW

There are several studies regarding capacity improvement. The optimal subset of transmit antenna elements from a set of antennas was selected considering channel amplitude and correlation [2]. Wang et al. [3] studied the transmission of wireless traffic generated by multimedia applications over massive multiple input multiple output (MIMO) wireless networks. The study first considered the receive diversity gain and examined it for wireless massive MIMO. It was revealed that the number of antennas and the spacing of antenna in the rectangular antenna array have an obvious effect on massive MIMO wireless communication system performance. Considering the mutual coupling effect, an effective capacity with QoS statistical exponent constraint was determined for multimedia wireless massive MIMO systems. The overall receive diversity gain regarding the number of antennas was investigated. It was observed that for a given number of independent incident paths; overall receive diversity gain initially increased as the number of antennas increased to less than 180 for antenna spacing greater than half wavelength (0.5λ). However, with number of antennas greater than 180, which is antenna spacing less

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than 0.5λ, the gain of the receive diversity decreased with as the number of antennas increased. The maximum of the overall receive diversity gain was achieved at number of antennas equal to 180 with spacing of antennas maintained at 0.5λ. The authors recommended the use of more efficient precoding technique to improve the multimedia performance of massive MIMO wireless systems taking into account the QoS statistical component constraints and mutual coupling. Fankunle et al. [4] employed genetic algorithm (GA) based optimization to improve the BER performance of massive MIMO system. The employed GA selects the optimal signal needed for efficient transmission. The system was configured for different number of antenna arrays, which included 2×2, 4×4, 8×8 and 16×16. These various configurations were used to study BER performance of the massive MIMO system. The system used Space Time Block Code (STBC) for encoding and decoding. The modulation was done over Rayleigh channel using filter bank multicarrier-offset quadrature amplitude modulation (FBMC-OQAM) such that simulations were conducted for 4-FBMC-OQAM, 16-FBMC-OQAM and 64-FBMC-OQAM order. The evaluation of the BER performance was analyzed for GA optimized and non-GA optimized (normal coded) massive MIMO systems. Simulation results showed that BER gradually reduced as the antenna number increases, but increased as the modulation order increased. The comparison of the optimized massive MIMO with the normal coded massive MIMO revealed that the GA optimized system provided better BER performance. Kumar et al. [5] characterised the performance requirements of MIMO system for 5G wireless standard in terms of capacity, spectral efficiency, data rate, energy efficiency, and average throughput of cell. The study presented a potential cellular architecture of 5G network designed with separate indoor and outdoor possibilities for massive MIMO technology using a distributed antenna system. A brief overview of MIMO wireless system considering receiver design, channel models, capacity, coding, and performance limits was presented. Simulation showed that the massive MIMO system could provide significant improve capacity, with increase in data throughput and link range without being dependent on the increasing power of transmitter or bandwidth. Kusuma et al. [6] implemented the problem of maximizing the capacity of MIMO system with water filling algorithm using the singular value decomposition (SVD) of the received signal which was composed of a set of parallel sub channels. MATLAB was used to simulate the effect of MIMO system capacity with Rayleigh fading channel. The simulation results indicated that the performance of the MIMO system improves with the number of transmitting and receiving antennas in terms of capacity and bit error rate (BER). The study observed the variation in the capacity of MIMO system with the number of transmit and receive antennas and also observed the variations in the statistical parameters of the diagonal matrix obtained by singular value decomposition of the MIMO system. The variation of bit error rate with signal to noise ratio (SNR) for different cases of transmit and receive antennas are also observed.

III. SYSTEM MODEL

Figure 1 shows an arrangement of a base station (BS) with multiple antennas (M) and mobile station (MS) with multiple receive antennas (N).The arrangement is such that M number of antennas serves N number of mobile terminals. It is assumed that

i. The same signal is simultaneously transmitted by all BS antenna
ii. Spacing of antennas from one another is based on wavelength distance
iii. The same time and frequency resources are shared among N antennas of mobile terminals.
iv. There is equal power spread for all transmit antennas.
v. Channel of narrow-band time invariant.
vi. The channel state is perfect.

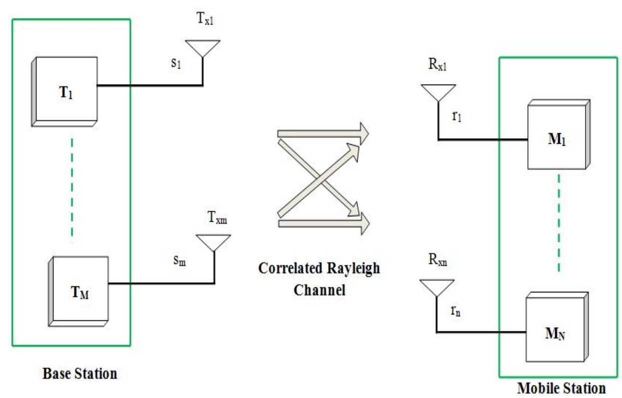

Fig. 1 System model

In a MIMO system, the relationship between the received vector symbol (signal) and the transmitted vector symbol (signal) is defined by:

$$r = Hs + \sigma \quad (1)$$

where r is the received vector symbol, s transmitted the vector symbol, H is the channel gain, and σ is the additive white Gaussian noise (AWGN) vector of mobile terminal, The matrix of the channel H is defined by:

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N} \\ \vdots & \vdots & \cdots & \vdots \\ h_{M,1} & h_{M,2} & \cdots & h_{M,N} \end{bmatrix} \quad (2)$$

Given a Rayleigh channel matrix, every input to Rayleigh channel matrix may be described by [4]:

$$h_{i,j} = \alpha + j\beta$$
$$h_{i,j} = |h_{i,j}| e^{j\phi_{i,j}} \quad (3)$$

where α and β are randomly distributed variables and $|h_{i,j}|$ stands for a Rayleigh distributed random variables,

$h_{i,j}$ is the element of the channel matrix for ith transmit antenna and jth receive antenna with $i = \{1, 2, 3, 5, 4, \cdots, T_x\}$ and $j = \{1, 2, 3, 4, 5, \cdots, R_x\}$. The system model is further represented in terms of Eq. (1) as shown in Fig. 2.

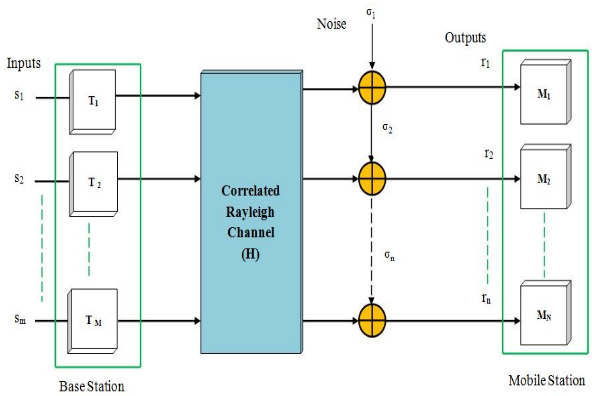

Fig. 2 System model with channel matrix and noise

A. MIMO Channel Capacity

Considering the multiple antenna system with T_x antennas at the BS and Rx receive antennas such that $T_x>1$ and $R_x>1$ in which for a given transmission time interval (TTI), only one active mobile terminal M is scheduled to receive a transmitted signal from mth transmit antenna. Thus, Eq. (1) can be described by:

$$r_n = \sqrt{\rho} H_{m,n} s_m + \sigma_n \tag{4}$$

where r_n is thenth antenna received signal, s_m is the mth transmitted signal, σ_n is the nth receive signal channel noise, ρ is a scalar that stands for the normalized transmitted signal (i.e. summing of the total power of the transmitted signal to unity), and $H_{m,n}$ is the $T_{xm} \times R_{xn}$ channel matrix of the MIMO system. The capacity of the MIMO system with m transmit antennas and n receive antennas in bit per second per hertz (bps/Hz) is defined by [12]:

$$C = \log_2\left[\det\left(I_{Tx} + \frac{1}{\sigma_n^2} H R_T H^*\right)\right] \tag{5}$$

where I_{Tx} is an identity matrix, H^* is the transpose-conjugate of H, and R_T is the transmitted covariance indicating power allocated to the transmit signal and it is expressed by:

$$R_T = \frac{P}{T_x} \times I_{Tx} \tag{6}$$

where P is transmit signal power. Putting Eq. (6) into Eq. (5), the expression for the channel capacity becomes:

$$C = \log_2\left[\det\left(I_{Tx} + \frac{P}{T_x \sigma_n^2} \times I_{Tx} \times HH^*\right)\right] \tag{7}$$

If $T_x \gg R_x$ for the case of large scale MIMO, then $HH^* = T_x \times I_{Tx}$ and putting this into Eq. (7) yields:

$$C = \log_2\left[\det\left(I_{Tx} + \frac{P}{\sigma_n^2} \times I_{Tx}\right)\right] \tag{8}$$

According to Omer et al. [7]:

$$\left(I_{Tx} + \frac{P}{\sigma_n^2} I_{Tx}\right) = \left(1 + \frac{P}{\sigma_n^2}\right)^N \tag{9}$$

Putting Eq. (9) into Eq. (10), the capacity of MIMO channel can be defined by:

$$C = N\log_2\left(1 + \frac{P}{\sigma_n^2}\right) \tag{10}$$

Eq. (10) can be written for Tx>>Rx as given by [8]:

$$C = \min(M, N)\log_2\left(1 + \frac{P}{\sigma_n^2}\right) \tag{11}$$

Thus, it can be seen from Eq. (11) that MIMO channel capacity directly increases as both transmit and receive antennas increases though the transmit power and channel bandwidth do not increase [7].

Considering the channel ergodic capacity, which is the statistical average of the mutual information taking place, the channel capacity is re-defined. Since MIMO channels are random, the channel capacity is also random. With the total average of the information rate over dispersion channel matrix elements, the MIMO channel ergodic capacity can be described by [8, 7]:

$$C = E\left\{\sum_{i=1}^{m} \log_2\left(1 + \frac{P}{T_x \sigma_n^2} \lambda_i\right)\right\} \tag{12}$$

where λ_i denotes the eigenvalues of HH^*. Hence, the channel ergodic capacity when the total power allocated is equally assigned to all transmit antenna is defined by Eq. (12). The CSI is not known at the transmit side. And because the capacity of the channel is not improved at all by the availability of CSI [9], this paper has assumed that all transmit antennas are allocated with equal total transmit power.

B. Simulation Parameters

The parameters used for the simulations conducted in this paper are defined in this section. These parameters are for micro strip antennas designed and implemented for MIMO system. Number of BS antennas (Tx) is $2 \le Tx \le 20$, Number of mobile station antennas (or receive antennas) (Rx) is ≤ 20, signal to noise ratio (SNR) is 35, 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.

Volume: 15 Issue: 04 Pages: 6063 – 6068 (2023) ISSN: 0975-0290

IV. SIMULATION RESULTS

The simulation results in this section show the ergodic capacities for various antenna elements with MIMO channel. The SNR was 35dB. Simulations were initially conducted considering correlated Rayleigh MIMO channels as shown in Fig. 3 to 5. The next simulations were performed for uncorrelated Fig. 6 to 8. The statistical plots of the comparisons of the capacities for correlated and uncorrelated channel models are shown in Fig. 9 to 11.

A. *Correlated Channel MIMO System*

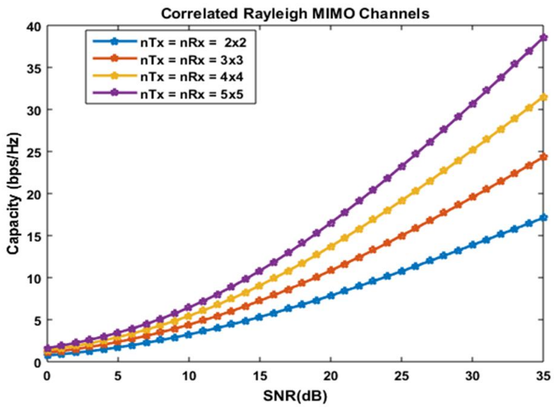

Fig. 3 Correlated Rayleigh MIMO system (2x2 – 5x5)

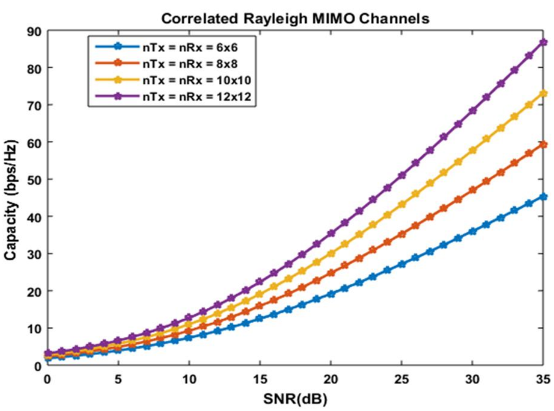

Fig. 4 Correlated Rayleigh MIMO system (6x6 – 12x12)

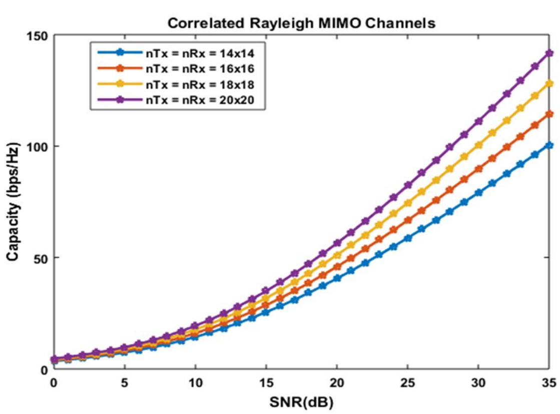

Fig. 5 Correlated Rayleigh MIMO system (14x14 –20x20)

As shown in Fig. 3 to 5, it can be seen that the correlated channel capacity increases as the number of antennas increases on both ends of the communication link (transmit and receive ends). The channel capacity was initially 17.1 bps/Hz for number of transmit antennas (nTx) and number of receive antennas (nRx) equal to 2 respectively in Fig. 3. With the antenna array increased to 5×5, the capacity of the system increases to 38.54 bps/Hz. Then in Fig. 4, the capacity of the channel increased from 45.35 bps/Hz for nTx = nRx = 6 to 86.86 bps/Hz for nTx = nRx = 12. Similarly, further increase in number of antennas resulted in much more increase in the channel capacity from 100.6 bps/Hz to 141.8 bps/Hz for nTx = nRx = 14 and nTx = nRx = 20 respectively.

B. *Uncorrelated Channel MIMO System*

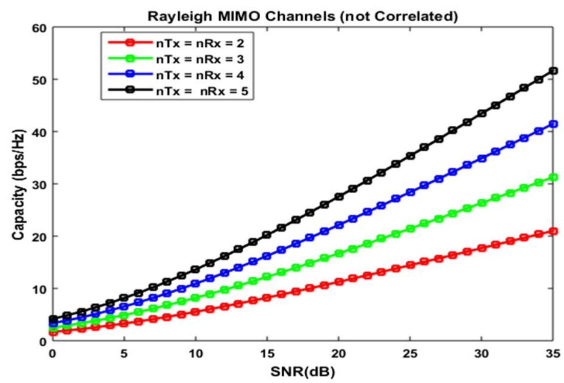

Fig. 6 Uncorrelated Rayleigh MIMO system (2x2 – 5x5)

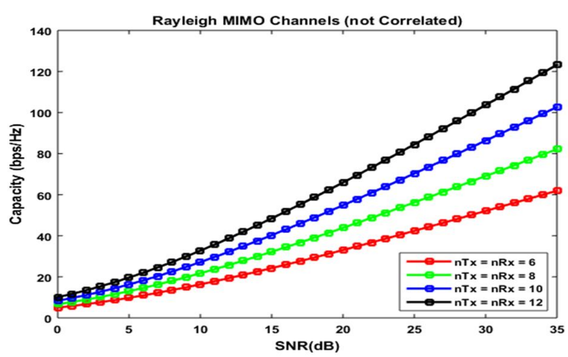

Fig. 7 Uncorrelated Rayleigh MIMO system (2x2 – 5x5)

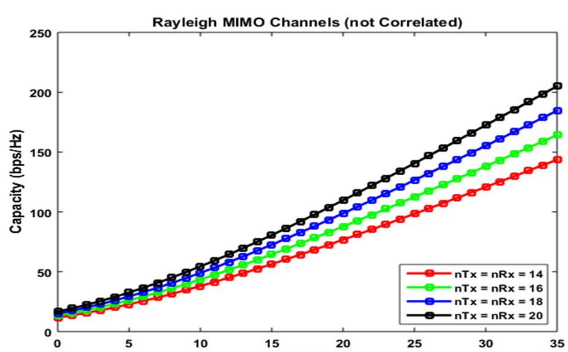

Fig. 8 Uncorrelated Rayleigh MIMO system (14x14-20x20)

Figures 6 to 8 revealed the performance characteristics of uncorrelated MIMO channel. For uncorrelated MIMO channels of the 2×2 to 5×5 antenna arrangement, it was observed that the capacity of the system increased from 21 bps/Hz to 51.64 bps/Hz as shown in Fig. 6. Similarly, in Fig. 7 and 8 the channel capacity of the system increased from 61.92 bps/Hz to 123.2 bps/Hz for nTx = nRx =6 to 12 and nTx = nRx = 14 to 20 respectively.

C. Comparison of Channel Capacities

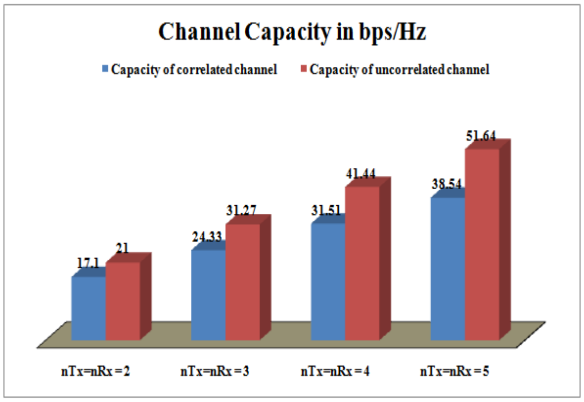

Fig. 9 Comparison of correlated and uncorrelated channel capacity (2×2 - 5×5)

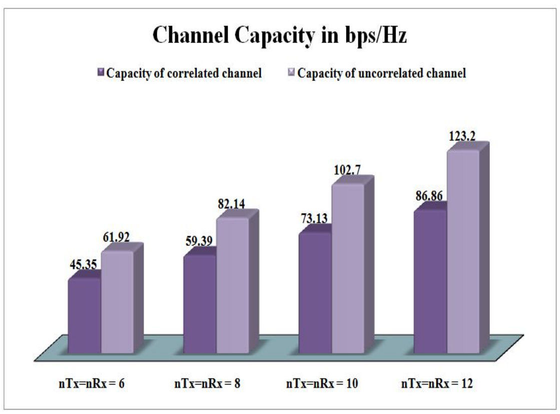

Fig. 10 Comparison of correlated and uncorrelated channel capacity (6×6 - 12×12)

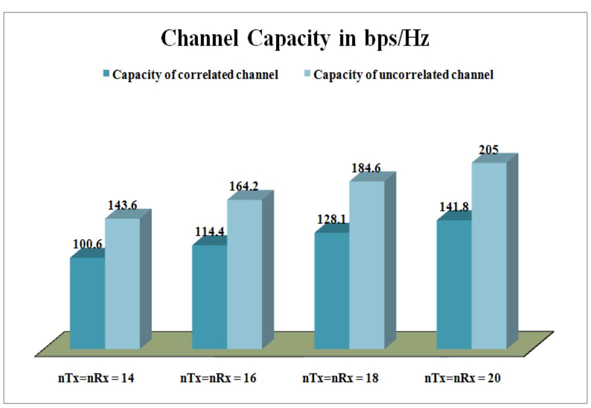

Fig. 11 Comparison of correlated and uncorrelated channel capacity (14×14 - 20×20)

Figures 9 to 11 show the comparison of the numerical performances of the MIMO system for various antenna arrangements and channel configurations (correlated and uncorrelated) in terms of channel capacities. It can be seen looking at the figures that significant reduction of capacity is recorded with the channel largely correlated as the SNR is varied from 0 dB to 35 dB at every 5 dB interval. That is, the uncorrelated channel configurations yielded better capacities than the correlated channels. Despite the fact that the higher capacity was achieved with uncorrelated channel model than with correlated channel model, it is worthy of note that in uncorrelated channel, independent and identical distributed (i.i.d) Rayleigh channel is assumed. This assumption does not hold in a realistic channel where correlation actually does exist between antenna elements [10]. Also, in correlated channels mean square error (MSE) is significantly minimized (Naser et al., 2021). Besides, the knowledge of channel correlation is important for the performance assessment and improvement of MIMO system [11].

V. CONCLUSION

The analysis of the capacities of different MIMO antenna arrangement under different channel configurations – correlation and uncorrelated channels, has been presented. The results from the simulation analyses revealed that increasing the number of antenna elements from conventional MIMO system to large scale MIMO can increase that rate in which data is transmitted over wireless channel. The capacity of the MIMO system was examined considering correlated channels in order to reflect or take into consideration a more realistic channel scenario. Though, the comparison analysis of the numerical values of the channel capacities indicated that uncorrelated channel model yields better capacity than correlated channel model, this gain comes with a cost that uncorrelated effect is not valid in practical scenario.

ACKNOWLEDGEMENTS

Authors acknowledge the management of the Chukwuemeka Odumegwu Ojukwu University for the enabling environment to conduct this study.

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