DOI: 10.54254/2755-2721/6/20230803

Analysis of increasing channel capacity of MIMO communication system by vortex electromagnetic wave

Jierui Jiang

SWJTU-Leeds Joint School, Southwest Jiaotong University, 999 Xi an Road, Chengdu, Sichuan, 611756, China

3045106048@qq.com

Abstract. Multiple-input and multiple-output (MIMO) communication technology which depends on multipath reflection can bring more efficient use of spectrum and higher channel capacity without expanding the bandwidth. This technology has been widely used in 5G communication system these days. However, under some circumstances which are lack of multipath reflection, the performance of traditional MIMO communication is not satisfying. Therefore, some researchers have pointed out that the technology of vortex electromagnetic wave can improve this situation efficiently. This article has done some researches on analyzing the channel capacity in traditional MIMO system and the MIMO system with vortex electromagnetic wave. Firstly, the spatial channel geometry model has been established with a 4-antenna transmit array and a 25-antenna receiving array in a three-dimensional rectangular coordinate system. In order to obtain the total channel capacity, the Los channel fading matrix should be calculated through calculating the distances between each two transmit and receiving antennas. After that the water filling algorithm has been used to decide the power allocation method to each subchannel to get the maximum capacity of the system. Finally, the relationship between maximum channel capacities and the signal-noise ratio (SNR) can be plotted as a line chart. The experiment first compared the capacities with and without the vortex electromagnetic wave of MIMO communication system under different SNR and found that the adding of vortex electromagnetic wave can increase the capacity efficiently. Next the influences of some variables to the channel capacity include the height of transmit antenna array, the distance between each two nearby transmit antenna elements and the variable Q which can change the phase complexity of wavefront have been discussed.

Keywords: MIMO, capacity, vortex electromagnetic wave

1. Introduction

Nowadays, with the increasing demand for the quality and efficiency of communication, communication technology is also making rapid progress. In order to adapt to the needs of users, each generation of communication system changes dramatically. The first generation of communication technology (1G) came out in the 1980s, which is a kind of voice service that uses analog signals. The transmitting speed of it reaches 2.4 Kbps. In the following decades, 2G, 3G and 4G technologies were introduced which all contains nonnegligible improvement of technology [1]. This kind of technological advance has effectively improved the user experience.

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Until now, the fifth-generation communication technology (5G) has been widely used in people's lives. Comparing to 4G, 5G offers more improvements than any previous generation of communication technology. Researches on 5G technology have pointed out that this technology can make the communication network contains features include high speed, wide coverage, low power consumption and low latency [2]. To achieve this goal, traditional single-channel communication cannot satisfy. Therefore, the Multiple Input and Multiple Output (MIMO) communication technology has been used. This kind of communication system can improve the capacity and spectrum utilization of the communication system exponentially [3]. To analyze the total channel capacity of MIMO system, the spatial channel fading coefficients of all subchannels should be calculated. Based on this, the capacity of each subchannel can be obtained [4][5]. In order to get the maximum channel capacity, the power allocation of each subchannel should be calculated by water filling algorithm, which can increase the power allocation to the high-quality channel and reduce or cancel the power allocation to the low-quality channel [6]. After the channel power allocation has been decided, the maximum channel capacity can be obtained.

This kind of technology can be widely used in some mobile communication devices such as mobile phones and tablets. Some researchers have worked on it and proved that MIMO compact antennas can be well used in mobile phones [7]. This kind of technology depends on multipath reflection, which means in the complex environment such as city, the communication of MIMO system can perform well. However, in some circumstances that there is no obstacle between transmit antennas and receiving antennas, which means in the Line-of-Sight (LoS) situation, it is lack of multipath. In this situation, the quality of MIMO communication system is not satisfying comparing to the quality in the None Line-of-Sight (NLoS) [8]. Luckily, some researchers have pointed out that the technology of vortex electromagnetic wave can efficiently improve this problem. In essence, this technology can change the orbital angular momentum which can bring more complex orthogonality and vorticity [9] [10]. This kind of technology can decrease the correlation between subchannels, which means the whole channel can carry more information. Therefore, the channel capacity can be increased.

This article has done some research on the channel capacity of MIMO communication system. Additionally, the capacities with and without vortex electromagnetic wave in MIMO system have been analyzed and compared. In the Modeling and Analysis part, the geometry model of MIMO communication system has been established and the spatial channel fading matrix has been calculated. Then according to the water filling algorithm, the power allocation to each subchannel has been decided and the maximum capacity of the system has been obtained. Finally, the technology of vortex electromagnetic wave has been added and the channel capacity has been calculated again. In the simulation and conclusion part, the capacities of the systems with and without vortex have been compared. The line charts which have shown the capacity changes with the increase of SNR under two situations have been plotted. Additionally, some variables include the height of transmit antenna array, the distance between each two nearby transmit antenna elements and the variable which can change the phase complexity of wavefront have been changed and the effects to the capacity have been analyzed.

2. Modeling and analysis

2.1. Geometric model establishment

In this model, the whole system is a Multiple-input and Multiple-output (MIMO) communication system with four transmit antennas in a straight line and 25 receiving antennas form as a 5x5 square. the whole system has been considered in a Three Cartesian coordinates in Figure 1.

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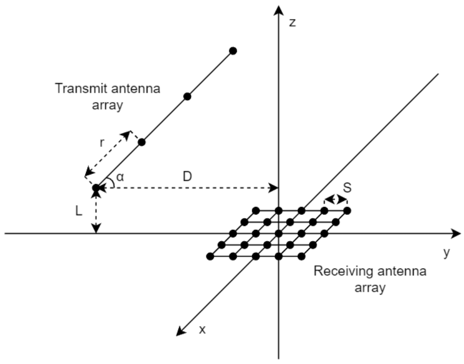

Figure 1. Antenna spatial location model.

The transmit antennas are on a straight line in y-z plane in the coordinate, and the receiving antenna square has been places in x-y plane in the coordinate. The distance between each two nearby antenna elements is equal in both transmit and receiving antenna arrays. The distance between each two transmit antennas equals to r, and the distance between each two nearby receiving antennas equals to S. The distance between the farthest transmit antenna and the z axis has been set as D, and the height of that antenna is set as L. The angle between the transmitting antenna array and the receiving antenna array plane is α.

In order to calculate the distances between each transmit and receiving antenna elements, each antenna should be numbered. In Fig. 1, the transmit antennas from left to right can be numbered as 1 to 4. For the receiving antenna array, the order can be described as Figure 2. This figure is the top view of the coordinate system.

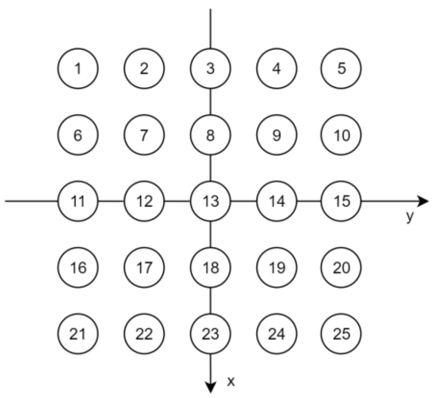

Figure 2. The numbers of receiving antennas.

Next is to match the coordinates and the numbers of antennas. For transmit antennas, the first one's coordinate can be described as $(0, -D, L)$. The coordinate of n_{th} transmit antenna can be described as (X_n, Y_n, Z_n). The distance between each nearby antennas and the angle α has been set. Therefore, the coordinate can be calculated as

$$\begin{cases} X_n = 0 \\ Y_n = -D + r \cdot \cos(\alpha) \\ Z_n = L + r \cdot \sin(\alpha) \end{cases} \tag{1}$$

After the coordinates of transmit antennas have been calculated, the coordinates of receiving antennas should be considered. The distance between each two nearby receiving antennas is set as S. Therefore, the side length of receiving antenna array square equals to 4S. The x and y axis of all receiving antenna elements can be included in two sets:

$$\begin{cases} x \in \{-2S, -S, 0, S, 2S\} \\ y \in \{-2S, -S, 0, S, 2S\} \end{cases} \tag{2}$$

Therefore, the coordinates of n_{th} receiving antenna can be calculated by using two nested for loops.

Next step is to calculate the distances between each transmit antenna and receiving antenna. Here the distance between m_{th} transmit antenna and n_{th} receiving antenna can be calculated as Figure 3.

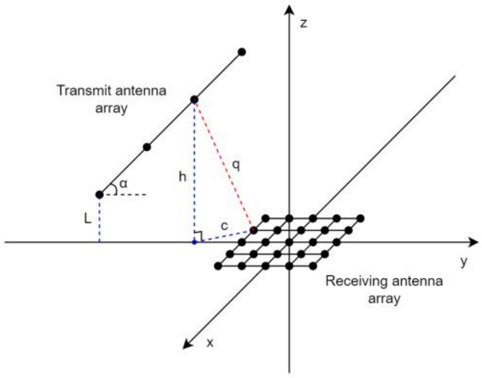

Figure 3. The distance between transmit and receiving antennas.

The height h of m_{th} transmit antenna can be calculated as the height of the first transmit antenna L add the height difference between these two antennas.

$$h = L + (m-1) \cdot r \cdot sin(\alpha) \tag{3}$$

Following from the Pythagorean theorem, the base side of the right triangle c can be calculated as:

$$c = \sqrt{(x_{rt} - x_{rr})^2 + (y_{rt} - y_{rr})^2} \tag{4}$$

In formula (4), x_{rt} and x_{rr} are the x-coordinates of m_{th} transmit and n_{th} receiving antennas, and y_{rt} and y_{rr} are the y-coordinates of m_{th} transmit and n_{th} receiving antennas.

Therefore, the distance q can be calculated as:

$$q = \sqrt{h^2 + c^2} \tag{5}$$

In the model there exist 4 transmit antennas and 25 receiving antennas. Therefore, the distances between each two transmit and receiving antennas can be expressed as a 25*4 size matrix:

$$Q = \begin{bmatrix} q_{1,1} & \cdots & q_{1,4} \\ \vdots & \ddots & \vdots \\ q_{25,1} & \cdots & q_{25,4} \end{bmatrix} \tag{5}$$

2.2. Channel model establishment

2.2.1. Traditional MIMO channel capacity calculation. Because there is no obstruction between transmit antenna array and receiving antenna square, it can be considered as a Line of Sight (LoS) model. Therefore, in the process of the signal passing through the wireless channel, its fading envelope follows Rayleigh distribution. The LoS channel fading matrix can be calculated through the distances.

$$H(m,n) = \frac{\beta \cdot wl \cdot e^{\left(-i \cdot \frac{2\pi}{wl} \cdot Q(m,n)\right)}}{4\pi \cdot Q(m,n)} \tag{6}$$

In formula (6), $H(m,n)$ is the spatial channel fading coefficient from m_{th} transmit antenna to n_{th} receiving antenna, β means the antenna gain, wl is the wavelength of the electromagnetic wave and

$\mathrm{Q(m,n)}$ is the distance between $\mathrm{m_{th}}$ transmit antenna and $\mathrm{n_{th}}$ receiving antenna. Therefore, H has been obtained as a 25*4 size channel fading coefficient matrix.

$$H = \begin{bmatrix} h_{1,1} & \cdots & h_{1,4} \\ \vdots & \ddots & \vdots \\ h_{25,1} & \cdots & h_{25,4} \end{bmatrix} \tag{7}$$

This model is a MIMO communication system with 4 transmit antennas and 25 receiving antennas. Therefore, the transmit signal in each period can be expressed as a 4*1 size column vector $\mathrm{rt} = [\mathrm{rt_1\ rt_2\ rt_3\ rt_4}]^{\mathrm{T}}$, and the receiving signal in each period can be expressed as a 25*1 size column vector $\mathrm{rr} = [\mathrm{rr_1\ rr_2\ rr_3\ ...\ rr_{25}}]^{\mathrm{T}}$. In these two vectors, $\mathrm{rt_m}$ and $\mathrm{rr_n}$ express the data transmit from $\mathrm{m_{th}}$ transmit antenna and received by $\mathrm{n_{th}}$ receiving antenna. Therefore, the covariance of the sent signal can be expressed as:

$$R_{xx} = E\{xx^H\} \tag{8}$$

The transmitting power can be calculated as:

$$P = tr(R_{xx}) \tag{9}$$

The noise in channel also can be expressed as a 25*1 size column vector $\mathrm{n} = [\mathrm{n_1\ n_2\ n_3\ ...\ n_{25}}]^{\mathrm{T}}$ which follows a cyclic symmetric Gaussian distribution. Additionally, it doesn't correlate with the transmitting signal. Therefore, the covariance of the sent signal can be expressed as:

$$R_{nn} = E\{nn^H\} = \sigma^2 I_{n_R} \tag{10}$$

In formula (10), the mean value of vector n has been set to 0, and the power of noise has been considered as σ^2.

The receiving signal in this model can be expressed as $\mathrm{y = Hx + n}$ while H is the channel fading coefficient matrix, x is the transmit signal and n is the noise. Therefore, the covariance of the receiving signal can be expressed as:

$$R_{yy} = E\{yy^H\} = HR_{xx}H^H + \sigma^2 I_{n_R} \tag{11}$$

Because the transmit, receiving and noise signals all follow Gaussian distribution, the general formula of information capacity can be obtained. According to the sampling theorem, the sampling frequency must not less than double bandwidth of signal. Therefore, the sampling frequency has been set to double bandwidth and the MIMO channel capacity can be calculated as:

$$C = Blog_2\left\{det\left[I_{n_R} + \frac{HR_{xx}H^H}{\sigma^2}\right]\right\}\ bit/s \tag{12}$$

Because MIMO communication system include a lot of channels, the original channel fading matrix is complicated. Therefore, the matrix needed to be simplified. According to matrix theory, the channel fading matrix can be decomposed by singular value decomposition which can help to calculate the capacity easier. According to the singular value decomposition theory, the channel fading matrix can be written as:

$$H = UDV^H \tag{13}$$

In formula (13), H is a $\mathrm{n_T \times n_R}$ size channel fading matrix, and D is a diagonal matrix in the same size. Besides, U and V are the unitary matrixes in $\mathrm{n_T \times n_T}$ and $\mathrm{n_R \times n_R}$ sizes. Put this in to formula $\mathrm{y = Hx + n}$, and plug the result into formula (12), the capacity can be calculated as:

$$C = B\sum_{i=1}^{r} log_2\left(1 + \frac{\lambda_i P_T}{\sigma^2 n_T}\right)\ bit/s \tag{14}$$

In formula (14), λ_i is the singular value of HH^H in formula (12). Making further simplification, the final formula of capacity can be expressed as:

$$C = Bmlog_2\left(1+\frac{P_T}{\sigma^2}\right)\ bit/s \tag{15}$$

In formula (15), m equals to min (n_T, n_R). Next step is to determine the power allocation P_T for each subchannel. The water filling algorithm is needed to allocate power according to the communication quality of each channel. If the channel communication quality is poor, it will be allocated with less or even no power.

To judge if the channel should be allocated how much power, the water level should be calculated. Water filling algorithm can make the capacity as large as possible, and the capacity after water filling can be expressed as:

$$C = \sum_{f=1}^{Nc} log_2\left(1+\frac{P_f}{\sigma^2}h_i\right) \tag{16}$$

In formula (16), P_f is the transmit power at frequency f, h_i is the gain for each subchannel, Nc is the total number of subchannels, and σ is the noise power. Besides, the total power should satisfy that the sum of the power allocated to all subchannels should not larger than the total apportionable power.

Then the Lagrange multiplier method can be used to calculate the value of water level.

$$\mathcal{L} = \sum_{f=1}^{N_c} log2(1+\frac{P_f h_i}{\sigma^2}) + \alpha(\sum_{f=1}^{N_c} P_f - P) \tag{17}$$

Setting $\frac{\partial\mathcal{L}}{\partial P_f} = 0 \forall f$ and $\frac{\partial\mathcal{L}}{\partial\alpha} = 0$, the power allocation can be expressed as:

$$P_f = \left(\frac{1}{\alpha}-\frac{\sigma^2}{h_i}\right)^+ \tag{18}$$

In this formula, $\frac{1}{\alpha}$ can be considered as the 'water level' of the water filling system. The equation satisfies for all f so that the total allocated power P_{total} can be expressed as:

$$P_{total} = \sum_{f=1}^{N_c}\left(\frac{1}{\alpha}-\frac{\sigma^2}{h_i}\right)^+ \tag{19}$$

In formulas (17) and (18), $(\frac{1}{\alpha}-\frac{\sigma^2}{{h_i}^2})^+$ means max $\{0, (\frac{1}{\alpha}-\frac{\sigma^2}{{h_i}^2})\}$.

After the water level has been obtained, it can be used to judge if the quality of signal in each subchannel is good enough. If the value of $\frac{1}{\alpha}-\frac{\sigma^2}{h_i}$ of a subchannel is negative, this one will not be allocated any power. Therefore, the power allocation condition can maximize the channel capacity.

2.2.2. Introducing vortex electromagnetic wave. MIMO communication system rely on multipath. If the multipath is not enough, the vortex electromagnetic wave can be introduced to further enlarge the channel capacity. As a new mechanism, vortex electromagnetic wave can carry infinite kinds of Orbital Angular Momentum (OAM) at the same frequency, and each OAM mode is orthogonal to each other [11]. Using this orthogonality, the vortex electromagnetic wave is used as the carrier of information transmission in wireless communication, which can realize the multichannel transmission at the same frequency and enlarge the transmitting channel capacity [12].

In the algorithm, each entry in the channel fading matrix needs to be multiplied by a coefficient. Due to the different spatial positions of the four transmitting antennas, the spatial azimuths between them and the receiving antennas are different (Fig. 4). Therefore, four transmit antennas correspond to four different coefficients.

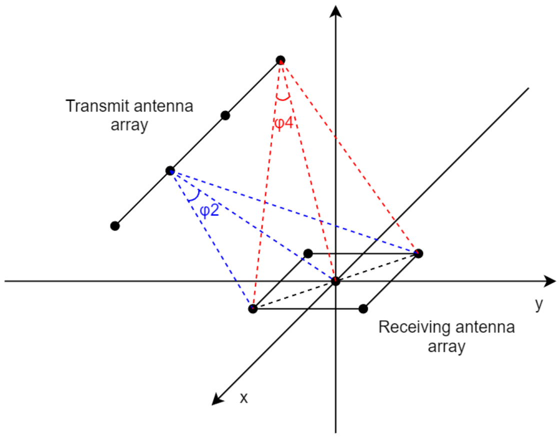

Figure 4. Azimuths in space of transmit antennas.

According to the values of four spatial azimuths, the coefficients which should be multiplied into the channel fading matrix can be calculated as:

$$\varepsilon = \frac{1}{\sqrt{Q}} \frac{sin\left(\frac{Q\varphi\Delta L}{2}\right)}{sin\left(\frac{\varphi\Delta L}{2}\right)} e^{-j\left(L_f^n + \Delta L\frac{Q-1}{2}\right)} \tag{20}$$

In formula (20), ε is the coefficient which should be multiplied into the channel fading matrix. The value of Q can decide the phase complexity of wavefront. The values of L_f^n and ΔL are determined by the nature of the special antenna that emits the vortex electromagnetic wave.

After the coefficient ε has been calculated for each transmit antenna, it should be multiplied into the LoS channel fading matrix. In the channel fading matrix, each column represents a different transmit antenna. Therefore, each column should be multiplied with corresponding coefficient ε_m, with the m means the number of transmit antenna. The final channel matrix with the addition of vortex electromagnetic wave performs as formula (21).

$$H = \begin{bmatrix} \varepsilon_1 h_{1,1} & \cdots & \varepsilon_4 h_{1,4} \\ \vdots & \ddots & \vdots \\ \varepsilon_1 h_{25,1} & \cdots & \varepsilon_4 h_{25,4} \end{bmatrix} \tag{21}$$

After multiplying four coefficients into the fading matrix, the new channel capacity can be calculated by formulas (12) to (19) with water filling power allocation. The results can be compared with the results without vortex electromagnetic wave.

3. Simulation

In this article, a 4-transmit antenna and 25-receiving antenna MIMO communication system has been established. The research has firstly simulated the channel capacity under the circumstance with and without vortex electromagnetic wave under different Signal-Noise Rates (SNR). The range of SNR is the integers from 1 to 20 in dB. The other constants are set in the following table:

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Table 1. Parameters of the experiment.

Parameter	Value	Unit
Wavelength (wl)	$1x10^{11}$	m
The height of transmit antenna array	0.5	m
The distance between transmit antenna array and receiving antenna array	0.5	m
The distance between the transmit antenna elements	0.012 (4*wl)	m
The distance between the receiving antenna elements	0.012 (4*wl)	m
Transmit antenna tilt Angle	Pi/4	
The power of noise	$1x10^{-2}$	dB
The bandwidth	1	bit
The gain of antenna	500	
The multiple of amplifier	1	

The results of capacities with and without vortex electromagnetic wave has been compared and a chart has been plotted in Figure 5.

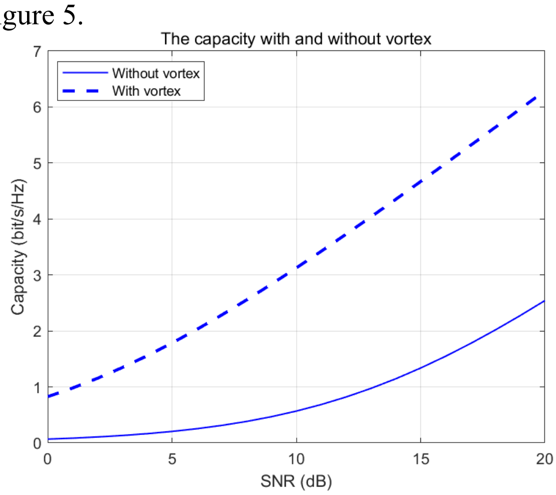

Figure 5. The capacity with and without vortex electromagnetic wave.

It is obvious that under other conditions are equal, the channel capacity with vortex electromagnetic wave is larger than the one without this technology. It has proved that vortex electromagnetic wave can improve the capacity of MIMO communication system.

Next is to change the height of transmit antenna array. This is to change the distance between the transmit antenna array and the receiving antenna array, which will change the degree of signal attenuation. This will directly affect the channel capacity of the network. Without other conditions changing, the heights of transmit antenna array have been changed into 0.5m, 1m, 1.5m and 2m. The chart has been plotted with 8 lines express the capacity with and without vortex electromagnetic wave under different height of transmit antenna array respectively. The chart has been shown in Figure 6.

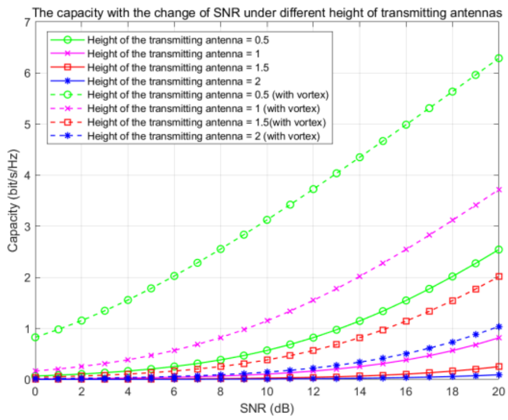

Figure 6. The capacity under different height of transmitting antennas.

In this chart, the dotted lines have expressed the capacities of network with vortex electromagnetic wave and the solid lines have expressed the capacities of network without vortex electromagnetic technology. It is obvious that in both two situations, with the increase of the distance between transmit and receiving antenna arrays, the total capacity decreases. Additionally, this chart has shown again that the vortex technology can increase the total capacity in MIMO communication system.

After have taken the consideration of the influence from the distance between transmit and receiving antenna arrays, the influence from the distance between each transmit antenna element will be taken consideration. With the same other conditions, the distances between each transmit antenna element have been set into 2, 4, 8 and 16 times the wavelength of electromagnetic wave. The chart has been plotted with 8 lines express the capacities with and without vortex electromagnetic wave under different distances between transmit antenna respectively. The chart has been shown in Figure 7.

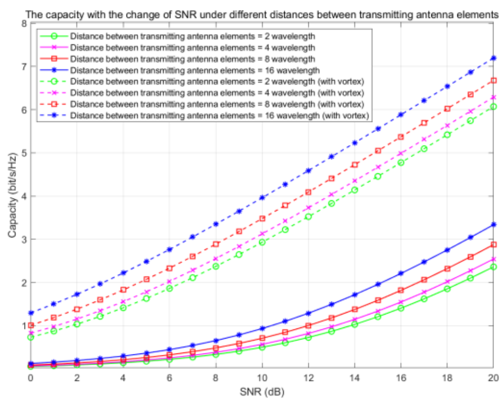

Figure 7. The capacity under different distances between transmit antenna elements.

This chart has shown that the channel capacity of MIMO communication system will be greatly increased by vortex electromagnetic wave. What is more, with the increase of the distance between each two nearby transmit antennas, the capacity increases. It is because increasing the distance between antenna elements not only can increase the SNR but also it can decrease the correlation between signals transmitted by two adjacent antennas.

The last variable is the change of phase complexity of wavefront, which is decided by variable Q in the vortex calculation formula. With the same other conditions, the values of Q have been set into 1, 2, 3 and 4 to express different phase complexities of wavefront. The chart has been plotted with 8 lines express the capacities with and without vortex electromagnetic wave under different values of Q. The chart has been shown in Figure 8.

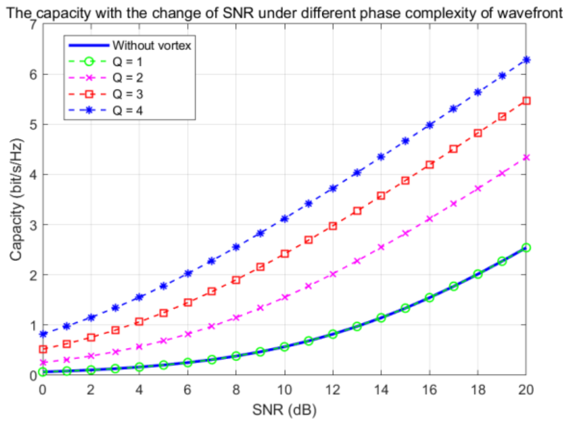

Figure 8. The capacity under different phase complexity of wavefront.

From the chart it is obvious that while Q equals to 1, the phase complexity of wavefront has not been changed with the addition of vortex technology. Therefore, the capacity will not change when Q equals to 1. With the increase of Q, the phase of wavefront becomes more complicated. This will cause the amount of information increases, which will increase the capacity of network.

4. Conclusion

In this article the capacity under different SNR has been simulated in different situations. After obtained the greatest power allocation method by using water filling algorithm, the capacity of the network with and without vortex electromagnetic wave. Additionally, the other variables include the height of transmit antenna array, the distance between each transmit antenna element and the phase complexity of wavefront in transmitting signal.

During the process of experiment, the three-dimensional geometric coordinate system has been established first. After the locations of transmit and receiving antenna arrays have been determined, the water filling algorithm has been used to increase the capacity of the MIMO communication network. Firstly, the channel capacities of a traditional MIMO communication system under different signal-noise ratios. The range of SNR has been set from 1 to 20. The simulation has proved that with the increase of SNR, the capacity of this MIMO communication system will increase. Next the vortex electromagnetic wave has been added and the capacities under different SNRs have been calculated again with a new channel fading matrix. The result of simulation has shown that the vortex technology can help to increase the capacity of MIMO communication system. What is more, the experiment also researched the influence to the capacity from the change of the height of transmit antenna array, the distance between each two nearby transmit antenna elements and the phase complexity of wavefront of the signal. The results of the simulations have shown three conclusions. Firstly, the conclusion relates to the effects from the different height of transmit antenna array. With the decrease of transmit antenna height, the capacity will increase. No matter with and without the vortex electromagnetic wave, the difference of height of transmit antenna array have brought marked changes to the total capacity. While the height equals to 4 m, the capacity of the channel with vortex electromagnetic wave is ten times that of the traditional MIMO channel. However, while the height changes to 1 m, this multiple relation becomes to two times, which means with the decrease of height, the advantage of vortex electromagnetic wave is diminishing. Secondly, the conclusion relates to the different distances between each two nearby transmit antenna elements. With the increase of the distance between each two nearby transmit antenna elements, the correlation of signals from different transmitting antennas is reduced, which can increase the capacity. From the chart, it is obvious that with the increase of the distance between each two transmit antenna elements, the capacity with vortex electromagnetic wave is always about twice the capacity of the traditional MIMO channel, which means this variable does not affect the optimization degree of vortex electromagnetic wave for MIMO channel. Thirdly, the conclusion relates to the different phase complexity of wavefront. With the increase of Q, the phase of wavefront has become more complicated, which can increase the capacity. It is obvious that with the change of variable Q, the capacity in traditional MIMO channel does not change. It is because Q only affects the value of coefficient ε which has been multiplied in the channel fading matrix to express the influence of vortex electromagnetic wave. With the increase of Q from 1 to 4, the channel capacity increases obviously with the increase of phase complexity of wavefront. While Q equals to 4, the total capacity is more than two times of the one while Q equals to 1.

The experiment has proved that no matter under any circumstance, the vortex electromagnetic wave can increase the capacity of MIMO communication system. In the future this technology can be used in some situations which lack of multipath or need to enhance the signal. Through this technology, the communication in the future will be faster and more efficient. However, the experiment is just theatrical without any physical prove, which might mean some settings of experimental parameters are not very realistic. Therefore, I would be interested in doing some experiments with real antennas in the future to further prove the conclusion and use this technique in a real situation.

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