Malaysian Journal of Computing, 8 (1): 1363-1374, 2023

eISSN: 2600-8238

AN IMPROVEMENT METHOD FOR MASSIVE MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) SYSTEM DEPLOYMENT

Lijun Han[1*], Ling Weay Ang[2] & Sellappan Palaniappan[3]

[1*,2, 3]*School of Information Technology, Malaysia University of Science & Technology, Petaling Jaya, Malaysia*

[1*]han.lijun@phd.must.edu.my, [2]dr.ang@must.edu.my, [3]sell@must.edu.my

ABSTRACT

This paper proposes a novel method for deploying massive multiple-input multiple-output (MIMO) systems, an essential component of next-generation wireless networks. The proposed method is designed to address the challenges of deploying MIMO systems in practical scenarios, including the selection of optimal antenna configurations and the need for efficient use of available resources. The method uses advanced machine learning techniques to optimize the deployment of MIMO systems, considering a variety of factors such as channel characteristics, interference, and network topology. The results of the systematic review show that the combination of channel coding technology and antenna diversity technology can significantly increase the capacity of 5G wireless communication systems, provide diversity and coding benefits for wireless transmission, and enable higher frequency band utilization than conventional single antenna systems. The proposed method has been shown to significantly improve the performance of MIMO systems in a variety of scenarios, making it a promising approach for the deployment of MIMO systems in future wireless networks.

Keywords*: High-Speed and High-Quality Wireless Data Transmission, Multiple Input Multiple Output (MIMO) Systems, Space Time Coding (STC), 5G Wireless communication Systems.*

Received for review: 16-1-2023; Accepted: 31-03-2023; Published: 10-4-2023
DOI: 10.24191/mjoc.v8i1.20280

1. Introduction

Multipath propagation is ubiquitous in wireless communication systems, causing signal fading and having a significant impact on signal transmission quality. MIMO technology was developed to combat the signal degradation caused by the "multipath effect" The MIMO communication system created by MIMO technology exploits the phenomenon of "multipath propagation" to its advantage. It can increase the received signal strength and data throughput.

In this study, MIMO and MMIMO technologies are introduced before examining the evolution of MIMO technology to illustrate its practical application. To improve the capacity of MIMO communication systems, it is important to study the definition of capacity and the parameters that determine it. To show and explain the relationship between the number of antennas and the capacity of MIMO channels, the capacity of MIMO channels is analyzed. Space-time coding is one of the three approaches to implement MIMO technology. Scientists and engineers have long sought and used powerful space-time codewords to make wireless data transmission faster and better.

2. Literature Review

2.1 MIMO & MMIMO

MIMO technology refers to the use of multiple antennas at the transmit and receive sites of a communications system to improve performance. This technique creates multiple independent channels between the transmitter and receiver, increasing the signal strength and data throughput of the received signal (Yang *et.al*. 2019). The arrangement of the antennas creates multiple separate channels between the transmitting and receiving sides, ensuring that the received signal from the receiving antenna does not have an excessive correlation. By using MIMO technology to create the MIMO communication system, “multipath propagation" is used, which can increase the signal strength and data throughput of the received signal.

Massive MIMO (MMIMO) is a type of MIMO technology that uses a large number of low-power antennas to improve system capacity. MMIMO technology also uses beamforming and multi-user transmission techniques to achieve high spatial concentration and eliminate user interference. MIMO technology has larger antenna arrays on both the transmitter and receiver than MIMO technology. The system capacity can be improved by using hundreds of low-power antennas, a dense scattering environment and active spatial multiplexing techniques. MMIMO technology uses both beamforming with a huge array gain and multi-user transmission with a very high spatial focus (Ngo *et al.*, 2017).

However, MMIMO requires many antennas, a complicated network environment, and powerful signal processing, making it challenging to implement.

2.2 Development of MIMO technology

The International Telecommunication Union (ITU) and the 3rd Generation Partnership Project (3GPP) have begun developing applicable standards for the use of MIMO technology in third-generation (3G) and B3G (beyond 3G) mobile communications. MIMO and related technologies are considered one of the most effective ways to increase system capacity and spectral efficiency. Bell Laboratories launched the world's first blast chip in October 2002, marking the beginning of the commercial implementation of MIMO technology. The LTE (Long Term Evolution) project, launched at the 3GPP conference in 2004, represents the transition from 3G to 4G (fourth-generation mobile communications) technology. It uses MIMO and OFDM (Orthogonal Frequency Division Multiplexing) as the only standards for the development of its wireless network. The wireless LAN standard IEEE802.11n and the wireless metropolitan area network standard IEEE802.16a (WiMAX) also use MIMO and OFDM technologies. At the same time, numerous manufacturers have developed MIMO chipsets. The field of wireless sensor networks (WSN) has been studied in depth by many researchers. For example, Ibrahim *et al.* (2022) proposed a structure that provides powerful routing conventions for WSNs in terms of essential utility, speed, equipment requirements, and conversion delay for WSNs compared to existing routing protocols.

MIMO technology is an essential component of communications technology. Since the network bandwidth is 28 GHz, which is about 20 times the 3G bandwidth, 4G technology provides faster communication transmission speed. With a number of 8 receive and transmit antennas and an average signal-to-noise ratio of 20dB, the maximum link capacity is 42bps/hz (Zhang, 2018), which is more than 40 times the capacity of a single antenna system. Therefore, MIMO technology has demonstrated its exceptional advantages in today's very limited wireless spectrum resources.

As a result of continued advances in recent years, MIMO technology has been incorporated into the 802.16e, 802.11n and 802.20 standards. MIMO technology has been used in the study of other wireless communication systems, such as ultra-wideband (UWB) and cognitive radio (CR) systems (Nayak, 2021).

By using many base station antennas, MIMO technology has achieved unmatched spectral efficiency and system capacity. It is widely regarded as the core technology of the physical layer of 5G transmission (the fifth generation of mobile communications). Compared to previous generations of mobile networks, 5G has ushered in the era of the Internet of Things and will meet the needs of the Internet of Things by bringing together a range of novel technologies, including Big Data, cloud computing and Artificial Intelligence. The average speed of the 4G network is 100 Mbps per second. The 5G network is 100 times faster than the 4G network. It has been improved to 10 Gbps. 5G cell phones are compatible with 5G networks as well as 4G, 3G and 2G networks. The Ministry of Industry and Information Technology reported that China had built the world's largest 5G mobile network in the first half of 2021. 5G uses a flexible new system architecture based on fundamental OFDMA and MIMO technologies to serve three application scenarios: Enhanced Mobile Broadband (embB), Ultra-High Reliable Low-Delay Communication (uRLLC), and Mass Machine Communication (mMTC) (Erunkulu *et al.*, 2021). Figure 1 illustrates the evolution of MIMO.

Figure 1. Development History of MIMO.

2.3 Implementation of MIMO Technology

MIMO technology is based on three technical means: beam forming (BF), spatial multiplexing (SM) and space-time coding (STC). In the current communication system, different technologies are selected according to the independent strength of the fading characteristics between the spatial sub-links in the environment and the multipath of the links. When the channel conditions are more complex and the system performance requirements are more comprehensive, the three technologies are often used in combination to develop strengths and avoid weaknesses. For example, in LTE, in order to make MIMO work well in different usage scenarios, 3GPP uses a combination of spatial multiplexing technology and space-time coding technology in the HSPA+ standard (enhanced high-speed packet access) (version R7), using 2*2. In 4G and 5G communication systems, the three technologies are comprehensively used in the communication system.

2.4 Space time coding（STC）

Space-time coding (STC) is a signal coding technology that uses antenna array processing technology to improve the performance of MIMO systems (Erunkulu *et al.*, 2021). Space-time coding and related MIMO signal processing technology have been widely used and rapidly developed in wireless communications.

Recent research in the field of information theory has shown that the use of antenna arrays with multiple elements at both ends of a wireless link constitutes a MIMO system that can significantly increase communication capacity (Gan *et al.*, 2020; Attarkashani *et al.*, 2019). Effective use of space-time coding requires the use of multiple antennas at both the transmitter and receiver, since space-time coding uses both time and space to create codewords. To improve the error performance of multi-antenna transmission, the error control coding, modulation, and transmission diversity are designed together, and the spatial transmission signal is combined with the two-dimensional temporal transmission signal.

The goal of space-time coding is to achieve the maximum diversity gain, maximum coding gain, maximum achievable capacity, and to have the simplest decoding algorithm. With the continuous development of information technology, 5G and beyond 5G need to support more user access (Khalil *et.al*, 2020). The 5G multi-antenna technology based on space-time coding technology can improve the diversity and gain of multi-antenna space and achieve higher communication throughput. Therefore, more and more researchers have carried out related research.

As a kind of spatial diversity, transmit diversity uses multiple antennas to repeat the transmitted signals on the transmitting side of the communication system, and uses one or more antennas to receive the signals on the receiving side (Minallah *et.al*, 2021). Multiple independent signal samples are combined to obtain the gain of transmit diversity. For MIMO channels with M transmit antennas and N receive antennas, in multiple parallel sub-channels between each pair of transmit and receive antennas, each signal channel drops in an uncorrelated mode. Then the signal samples on the receive side are independent, and the receive side combines these sample signals (Anouar & Larbi, 2019; Olaonipekun *et al.*, 2021; Ke *et al.*, 2021).

2.5 Classification of space-time codes

The signal is encoded in both the time and space domains, which integrates transmission diversity and coding and is therefore called space-time coding. The first is the layered space-time structure (BLAST) (Hao *et al.*, 2019).

Then, the space-time trellis code (STTC) is constructed by combining the traditional trellis code modulation (TCM) with a multi-antenna transmission system and extending it to a MIMO system. Then, space-time block coding (STBC) is developed based on the Alamouti scheme. These three space-time codes assume that the channel state is known at the receiver when it is decoded and that channel estimation is required at the receiver. In some environments, channel estimation at the receiver is very difficult, sometimes impossible. Therefore, the design of space-time coding without channel estimation is very important. This results in unitary space-time coding (USTC) and differential space-time coding (DSTC). Figure 2 shows the classification of space-time codes.

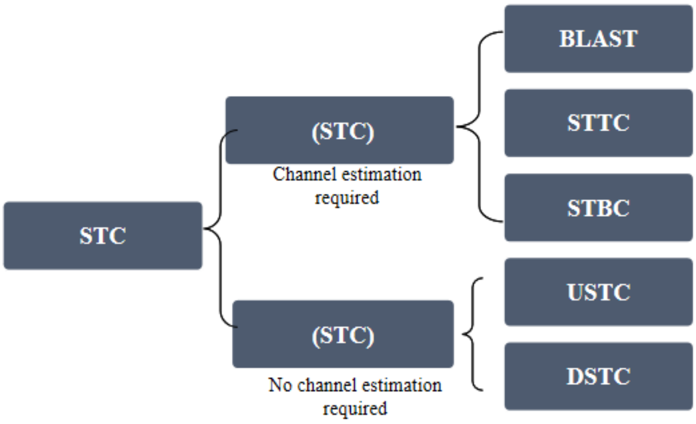

Figure 2. Classification of space-time codes.

Both 2.5G and 3G communications standards have built-in transmit and receive space-time diversity technology. Blast and STBC coding schemes have been adopted from 3G and have been widely studied and applied in practice (Huang et.al., 2022). STTC combined with OFDM technology has been applied in 4G.

2.1 STC In MIMO System

MIMO technology uses multiple antennas on both the transmit and receive sides to establish multiple communication links simultaneously. Its introduction has opened new avenues for improvement and flexibility in wireless communications. Massive MIMO, which uses large antenna groups, is an important component of 5G and improves spectral efficiency and network performance to achieve gigabit transmissions (Leevanshi *et al.,* 2021). The application of multiple antenna arrays in the MIMO system, which is supported by information-theoretic research, significantly increases the capacity of the communication system.

MIMO systems can be divided into two categories: Space Multiplexing and STC systems, depending on their ability to improve the transmission rate and diversity gain. STC is a signal coding type that improves MIMO performance by processing antenna groups (Bhamre & Gupta, 2019). STC and MIMO contribute significantly to improving the capacity, reliability, and performance of wireless communication systems and are used in various fields, including wireless local area networks, cellular networks, and satellite communication networks. Their development has also led to the emergence of beamforming and cooperative communication technologies, which continue to drive innovation in wireless communications.

3. Research Methodology

The flowchart shown in Figure 3 outlines the various phases of this study. It begins with the identification of research needs, where the researcher establishes the importance of the study and the problem it is intended to solve. This is followed by a review of the relevant literature on space-time coding (STC) technology and a theoretical model of the Massive Multiple Input Multiple Output (MIMO) system. The objective of this study is to investigate and analyze the potential of space-time coding (STC) technology in the context of the Massive MIMO system. The individual tasks are briefly described below:

Relate Space-Time Coding Technology to the MIMO System: this task involves investigating the connections and interactions between STC technology and the Massive MIMO system. The researcher may need to conduct a literature review and analysis to understand how STC technology can be applied to the MIMO system and the benefits it provides.

Analyze the basic characteristics of the Massive MIMO system: this task requires the researcher to study and analyze the basic characteristics and features of the Massive MIMO system, such as the antenna configuration, channel capacity, and signal processing algorithms. This analysis can help the researcher understand the system and its potential applications.

Calculation of the channel capacity limit of the Massive MIMO system: in this task, mathematical and statistical techniques are used to determine the maximum amount of information that can be transmitted over the wireless channel in the Massive MIMO system. This calculation can assist the researcher in evaluating the performance and capacity of the system. Find the design method for the space-time codeword: This task involves developing a technique to construct the space-time codeword, a type of code that can improve the performance of wireless communication systems. The researcher may need to develop new algorithms or modify existing ones to develop an effective method for constructing the space-time codeword.

The following phase is the development of STC, which includes the architecture and relevant techniques, research methods, and data collection for software development. In this phase, the STC prototype is created, which is then evaluated and tested to assess its effectiveness and efficiency. The study concludes with a comprehensive summary of the findings, their implications, and the contributions of the research. Overall, the flowchart serves as a guide for the researcher to maintain a systematic and logical approach to the research process and ensure that all necessary steps are taken to achieve the objectives of the study.

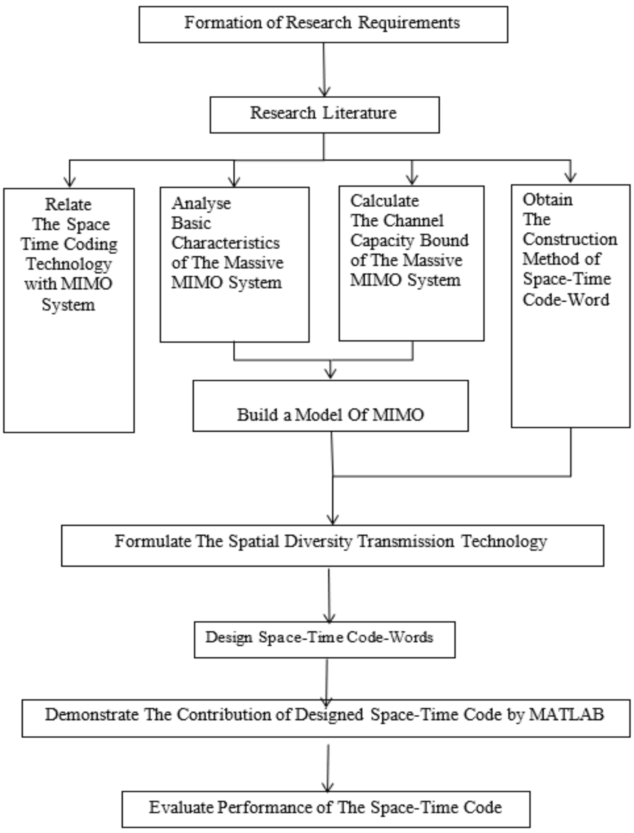

Figure 3. Research Flowchart.

4. Results and Discussion

Information theory has shown that MIMO technology improves the coverage and capacity of wireless communication systems, resulting in a better quality of service and higher transmission rates for user information. The maximum transmission rate that can be achieved by a communication system with the lowest error rate is called the system capacity, transmission rate, or throughput. It represents the limit of the maximum transmission capacity that a particular channel can provide. The channel capacity is the maximum transmission rate at which the bit error rate approaches zero, without taking into account delay and coding and decoding complexity.

To recover the transmitted signal from the received signal in a MIMO communication system, the measure of their degree of correlation is their average mutual information (entropy), which can be expressed as follows:

$$I(c,r)=\tilde{H}(r)-\tilde{H}(n) \tag{1}$$

where I is the operation symbol of the information quantity and $\tilde{H}$ is the operation symbol of the average information quantity.

If the channel parameter H and the transmitted signal power S_i are known, the Shannon capacity of the corresponding MIMO channel is the maximum mutual information between r and c, which can be expressed as:

$$C(H,S_i)=\max_{f(c)} I(c,r) \tag{2}$$

Where $f(c)$ is the probability density function of the transmitted signal c, $E[c^T c]\le S_i$, and T is the transpose operation symbol. According to information theory, only when the input variable c is Gaussian distribution, the micro entropy of Gaussian distribution is the largest, and mutual information can reach the maximum value (Gaussian random variable has the property of maximum entropy). Because two Gaussian variables are superimposed, the new variable is also Gaussian, and the mean-variance is linearly superimposed, so:

$$\begin{cases} \tilde{H}(r)=\dfrac{1}{2}\log_2 2\pi e({\sigma_c}^2+{\sigma_n}^2) \\ \tilde{H}(n)=\dfrac{1}{2}\log_2 2\pi e{\sigma_n}^2 \end{cases} \tag{3}$$

So:

$$\begin{aligned} I(c,r) &\le \frac{1}{2}\log_2 2\pi e(\sigma_c^{\,2} + \sigma_n^{\,2}) - \frac{1}{2}\log_2 2\pi e \sigma_n^{\,2} \\ &= \frac{1}{2}\log_2(1+\frac{\sigma_c^{\,2}}{\sigma_n^{\,2}}) \\ &= \frac{1}{2}\log_2(1+\frac{S_i}{N}) \end{aligned} \tag{4}$$

Where $\frac{S_i}{N}$ is signal to noise ratio (SNR), so the channel capacity of additive white Gaussian noise channel is:

$$C(H,S_i) = \max_{f(x)} I(c,r) = \frac{1}{2}\log_2(1+\frac{S_i}{N}) \tag{5}$$

In accordance with the sampling theorem, a signal is typically sampled at twice the bandwidth (2B), resulting in the famous Shannon formula (ergodic capacity). Refer to the following equation (6).

$$\begin{aligned} C &= 2B \times \max_{f(x)} I(c,r) = 2B \times \frac{1}{2}\log_2(1+\frac{S_i}{N}) \\ &= B\log_2(1+\frac{S_i}{N}) \end{aligned} \tag{6}$$

The unit is bit/（s·Hz）, which indicates the maximum amount of information that can be transmitted per second, and is also the maximum average information rate that can be transmitted by a single link SISO channel.

Generally, the MIMO channel is a quasi-static fading channel. Due to $r \in c^{N_R \times l}, c \in c^{N_T \times l}, H \in c^{N_R \times N_T}, n \in c^{N_R \times l}$, and assuming that the mean value of c is zero and the covariance is $E[c^T c] = Q$. If the noise *n* obeys the Gaussian distribution and the mean value is zero, that is, *n* ~ *N*（**0**， $\sigma_n^{\,2}$□I ）, then the received signal *r* is also a zero mean value, and its covariance matrix is:

$$E[r^T r] = HQH^T + I \tag{7}$$

Only when the transmitted signal *c* is Gaussian can *r* be Gaussian. In this way, the maximum mutual information entropy can be obtained, that is, under the additive white noise with bandwidth B and variance $\sigma_n^{\,2}$, the capacity of MIMO channel can be obtained by applying equations (4) and (6):

$$C = \max_{P(x)} I(x,y) = B\log_2 \left| I + \frac{HQH^T}{\sigma_n^{\,2}} \right| \tag{8}$$

The unit is $\sigma_n{}^2$. In essence, the capacity of this MIMO channel can only be reached under strict conditions. It only indicates the upper bound of the MIMO channel. Conversely, for the SISO system, the corresponding channel parameter H is reduced to a scalar, and equation (8) can be reduced to :

$$C = B\log_2\left(1+\frac{Q|H|^2}{\sigma_n{}^2}\right) = B\log_2\left(1+\frac{S_i}{\sigma_n{}^2}|H|^2\right) \tag{9}$$

It can be seen that equation (9) is a typical Shannon capacity formula, so the SISO system can be regarded as the simplest form of the MIMO system. In order to highlight the relationship between MIMO channel capacity and antenna number, using equation (8), the traversal capacity of $N_T \times N_R$ MIMO channel can be written as:

$$C_{N_T,N_R} = E\left[\log_2\left(\boldsymbol{I}_{N_R} + \left(\frac{Q}{\sigma_n{}^2}/N_T\right)\boldsymbol{HH}^T\right)\right] \quad (bit/s/Hz) \tag{10}$$

Where $\frac{Q}{\sigma_n{}^2}/N_T$ is the average signal-to-noise ratio of each transmitting antenna. Foschini and Gans' (1998) research shows that when N_T , N_R is very large, equation (10) is approximately:

$$C = \min\{N_T, N_R\}\log_2\left(\frac{Q}{\sigma_n{}^2}/2\right) \tag{11}$$

MIMO technology uses multiple antennas at both the transmitter and receiver to improve the performance of wireless communication systems. By transmitting multiple signals simultaneously, MIMO technology takes advantage of the spatial diversity of the wireless channel, resulting in higher data rates, higher reliability, and better overall system performance.

The capacity of a MIMO system is determined by the channel matrix, which is a mathematical representation of the wireless channel. The channel matrix is influenced by several factors, including the number of antennas, the channel environment, and the signal-to-noise ratio (SNR).

From the calculation above, it is mathematically shown that the capacity of a MIMO system increases linearly with the number of antennas used in the system as long as the channel matrix has full rank. This means that the capacity of a MIMO system increases proportionally with the number of antennas, which is why the relationship between the number of antennas and the MIMO channel capacity is often referred to as a linear relationship.

The linear relationship between the number of antennas and MIMO channel capacity has been demonstrated in various theoretical and experimental studies. For example, researchers have shown that by using multiple antennas, data rates can be achieved that are many times higher than in a system with a single antenna, and that the data rate increases linearly with the number of antennas.

In summary, the relationship between the number of antennas and MIMO channel capacity is a fundamental principle of MIMO technology. The linear relationship between the number of antennas and MIMO channel capacity has been shown to be true in both theoretical and experimental studies and provides the theoretical basis for the design and optimization of MIMO systems.

5. Conclusion

In this paper, we present a mathematical analysis showing a positive proportional relationship between the number of antennas and MIMO channel capacity, which provides a theoretical basis for improving the capacity of MIMO systems. Based on classical space-time codewords, researchers have developed various space-time codeword schemes with different performances, while engineers continuously design practical communication systems. By integrating multi-antenna technology, joint optimization of space-time coding, modulation, demodulation, and decoding can be achieved for specific communication applications. In addition, future work aims to explore new communication methods that can be combined with these technologies. However, in the current environment of high-speed mobile communications, accurate and efficient channel estimation remains a major challenge. Therefore, the research focus is also on developing efficient channel estimation methods, especially for large-scale MIMO communication systems.

Acknowledgement

The authors would like to thank their supervisor at the College of Science Malaysia for their assistance in conducting this study.

Fundings

This research is a self-findings project.

Author Contribution

Main author prepared the literature review. Co-author oversaw the article writing.

Conflicts of Interest

No conflicts of Interest.

References

Anouar, N., & Larbi, M. (2019). Space-time coding for MIMO wireless communication systems: A survey. *In 2019 International Conference on Wireless Networks and Mobile*

Communications (WINCOM) (pp. 1-6). IEEE. https://doi.org/10.1109/WINCOM.2019.8932991

Attarkashani, A., Abdipour, A., & Akbari, A. (2019). Space-time coding in MIMO communication systems. *In 2019 27th Iranian Conference on Electrical Engineering (ICEE)* (pp. 319-324). IEEE. https://doi.org/10.1109/IranianCEE.2019.8736135

Bhamre, S., & Gupta, R. (2019). Space-time coding for MIMO wireless communication systems: A review. *Wireless Personal Communications*, 106(2), 823-842. https://doi.org/10.1007/s11277-019-06411-5

Erunkulu, Femi & Adamu, Murtala & Lebekwe, Caspar & Mosalaosi, Modisa & Chuma, Joseph. (2021). 5G Mobile Communication Applications: A Survey and Comparison of Use Cases. *IEEE Access*. PP. 1-1. 10.1109/ACCESS.2021.3093213.

Foschini, G. J., & Gans, M. J. (1998). On limits of wireless communications in a fading environment when using multiple antennas. *Wireless Personal Communications*, 6(3), 311-335.

Gan, L., Liu, K., Huang, K., & Zhang, Y. (2020). Space-time coding for MIMO communications: A review. *Wireless Personal Communications*, 113(4), 2169-2202. https://doi.org/10.1007/s11277-020-07679-2

Huang, K., Xiao, Y., Liu, L., Li, Y., Song, Z., Wang, B., & Li, X. (2022). Integrated Spatial Modulation and STBC-VBLAST Design toward Efficient MIMO Transmission. *Sensors (Basel, Switzerland)*, 22(13), 4719. https://doi.org/10.3390/s22134719

Ibrahim, Maizatul Akmal and Awang, Norkhushaini (2022) An improvement of resource consumption in wireless sensor network (WSN) using compressive sensing / Maizatul Akmal Ibrahim and Norkhushaini Awang. *Malaysian Journal of Computing (MJoC)*, 7 (1): 11. pp. 1036-1046. ISSN 2600-8238

Ke, Y., Zhai, X., & Zhang, Q. (2021). Space-time coding for MIMO systems: A review. *In 2021 International Conference on Electronics, Communications and Control Engineering (ICECC)* (pp. 168-172). IEEE. https://doi.org/10.1109/ICECC52551.2021.9449283

Khalil, A., Minallah, N., Awan, M. A., Khan, H. U., Khan, A. S., & Rehman, A. U. (2020). On the performance of wireless video communication using iterative joint source channel decoding and transmitter diversity gain technique. *Wireless Communications and Mobile Computing*, *2020*, 1-16.

Leevanshi, S., Raghunathan, V., & Kulkarni, P. (2021). Massive MIMO for 5G: A review. *Journal of King Saud University-Computer and Information Sciences*, 33(2), 171-181. https://doi.org/10.1016/j.jksuci.2019.12.001

Minallah, S., Salam, M. A., & Qayyum, A. (2021). Transmit diversity techniques in MIMO communication: A review. *In 2021 4th International Conference on Information and Computation Technology (ICICT)* (pp. 81-87). IEEE. https://doi.org/10.1109/ICICT51268.2021.9376582

Nayak, A. K. (2021). *MIMO Techniques in Mobile Communication*. In Handbook of Research on 5G Networks and Advancements in Computing, Electronics, and Electrical Engineering (pp. 38-49). IGI Global.

Ngo, H., Ashikhmin, A., Yang, H., Larsson, E., & Marzetta, T. (2017). Cell-Free Massive MIMO Versus Small Cells. *IEEE Transactions On Wireless Communications*, *16*(3), 1834-1850. doi: 10.1109/twc.2017.2655515

Olaonipekun, O., Gacanin, H., & Seetharam, A. (2021). MIMO space-time coding schemes for 5G and beyond: A review. In 2021 IEEE Wireless Communications and Networking Conference (WCNC) (pp. 1-6). *IEEE*. https://doi.org/10.1109/WCNC.2021.9453754

Yang, S., Yin, D., Song, X., Dong, X., Manogaran, G., Mastorakis, G., & Batalla, J. M. (2019). Security situation assessment for massive MIMO systems for 5G communications. *Future Generation Computer Systems*, *98*, 25-34.

Zhang L. (2018). Analysis on the development prospect of 4G-5G mobile communication technology, *Digital technology and applications*, 36 (12): 15-16.