The application and development of electromagnetic waves in wireless communication technology

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Abstract. Electromagnetic waves played the cornerstone role of the modern wireless communication facilitating the efficient transmission of information across a large distance. This essay delves into the development and application of electromagnetic waves in wireless communication, with a specific emphasize on improvements in 5G technology and the emerging landscape of 6G. The analysis concludes the key areas such as wave propagation characteristics, antenna design, and signal processing techniques, they all having the same target to enhancing the communication performance. By doing an examination of literature existed and the research finding recently, this essay provides an in-depth analysis of the theoretical foundations and technological advancement that may help propel the evolution of wireless communications. The study focuses on how important that the enhancing transmission efficiency and signal reliability is. At the same time, it tackles main challenge for example the path loss and multi-path effects. Additionally, this essay will talk about the future directions of wireless communication which cover the AI-driven optimization and cutting-edge antenna technology, this will help sketch the contours of the prospects for the next generation of wireless communication.

Keywords: Electromagnetic wave, wireless communication, 5G, 6G, antenna design.

1. Introduction

1.1. Back ground of wireless communication and development of wireless

Wireless communication has experienced a substantial evolution. From the earliest radio transmission to new-generation high-speed mobile networks. The genesis of wireless communication can be traced back to 1880 which is when the photophone was discovered by Alexander Graham Bell and Charles Sumner Tainter. After few years, in 1888 Heinrich Hertz proved their existence of radio waves used in wireless telegraph system, and Guglielmo Marconi began developing it in 1894. With the research achievements of these great scientists have paved the way for practical applications such as radio broadcasting, satellite communication, and mobile phones [1]. As the time progresses, continuous breakthroughs in signal modulation, spectrum utilization strategies, and antenna engineering have not only improved the performance of wireless communication systems, but also lead to the explosive development of wireless networks, allow it to spread to every nook and cranny of modern life.

In recent years, the demand for high speed, low latency communication grow rapidly, mostly fuelled by applications for example: VR, AR and cloud gaming, which has driven the development of the fifth-generation network (5G) and emerging sixth-generation network (6G) [2]. 5G technology uses higher frequency bands, particularly the millimetre-wave spectrum which have the range of 30GHz -300GHz. As the higher frequencies offer, the larger amount of band width. This will cause 5G technology reach ultra-high data rates of up to 20Gbps. At the same time, 6G research focuses on the THz spectrum which have a range of 0.1THz to 10THz. These extremely high frequency bands offer a super-giant amount of band width, which enabling potentially much higher data rates compare to 5G. While 5G improve the efficient of wireless communication in modern life, 6G aims to let the signal penetration and expand coverage to remote areas.

1.2. literature review and research progress

Lots of research have examined the role of electromagnetic waves in wireless communication, concentrating on technologies for example, multiple-input multiple-output (MIMO), beamforming and orthogonal frequency-division multiplexing (OFDM) to improve data transmission efficiency. The key technique of MIMO is that it uses multiple antennas at transmitters and receivers, and spatial multiplexing can let a lot of data streams be transmitted over different spatial channels at the same time, each antenna receives a version of the transmitted signal that has travelled along the different path. The signals will be combined after received, and the receiver can detect the path which experiences fading or effected by interference, and those which get faded will be from another paths that is still be in good condition. This enhances reliability against fading and interference [3]. Beamforming can concentrate the energy in specific orientation by adjusting the phase and amplitude of the signals. OFDM converts high speed data streams into low-speed sub data streams for subcarriers and transmission. What is more is the improvements of the design antenna and refined channel modelling. All these above causes the performance of the network is significantly optimized.

The technologies which 5G mainly uses is MIMO and beamforming, these technologies will optimize signal propagation in high-frequency bands, and that the aim of 6G study is to surmount limitations by integrating AI base on signal processing and reconfigurable intelligent surfaces. Algorithms can be learned by machine which enable real time channel prediction and real time adaptive transmission adjustments, and reconfigurable intelligent surfaces can reconfigure the wireless environment to improve the efficiency of signal [4]. These innovative stuffs are expected to boost spectral efficiency, minimize interference, and improve overall network reliability.

At the beginning, the motivation of this study is to find what electromagnetic wave can do in wireless communication system, especially in the next generation of it. Solving the key challenges like path loss, multipath fading, and power consumption [5]. And this research uses the structured approach, starting from the analysis of the wave propagation features then extending to practical applications in 5G and 6G networks. This study also researches how to optimize the strategies to improve network performance and reliability.

2. Methodology

2.1. fundamental theories

Electromagnetic waves propagate is governed by Maxwell's equations. It is a set of 4 complicated equations, these equations describe how electric and magnetic fields propagate interact, and how they are influenced by objects [6]. These principles are needed to understand, and it essential for optimizing wireless communication systems.

The first equation is the Gauss's Law for electricity is $\nabla \cdot E = \frac{\rho}{\varepsilon_0}$ and this state that electric charges create electric fields. And the total electric flux through a closed surface is proportional to the charge enclosed.

The second equation is also Gauss's Law but it is for magnetism, can be written as $\nabla B = 0$. And this state that there are no magnetic field monopoles, while magnetic field lines always form closed loops. Additionally, the net magnetic flux through a closed surface is zero for all time.

The third equation is the Faraday's Law of induction, which look like this $\nabla \times E = -\frac{\partial B}{\partial t}$ this equation describes a changing magnetic field includes and electric field. At the same time is the basis for electric generators and transformers.

The fourth equation is the ampere's law, but there is a correction done by Maxwell. The version after the correction is like this $\nabla \times H = \frac{\partial B}{\partial t} + J$. And this equation shows a magnetic field is generated by electric current and changing electric fields. The correction by maxwell led to the prediction of electromagnetic waves.

The key propagation features include three parts, which is path loss, multipath effects and doppler shift. The path loss is a kind of signal attenuation cause by serval reasons such as when the distance between the transmitter and receiver are long, sometime even can be effect by the environment factors. When the signal is propagated, as the time pass the signal strength will be gradually weaken. And there is a free-space path loss formula which can be written as (1), it can be used in many situations as a tool to estimate the signal loss. Where, L is the loss in decibels, which shows the logarithmic unit used to quantify the ratio of the power of signal. f is the frequency, and the unit of it is megahertz, and the distance d have a unit as kilometer [1].

$$L = 32.45 + 20\,log_{10}\,f + 20\,log_{10}\,d \tag{1}$$

Multipath effect is a kind of phenomenon will happen while the transmitted signal experience several situations during the propagation, mainly experiences reflections, diffractions and scattering during the propagation. In modern city environments, it is filled with a large amount of architecture, such as tall buildings, bridges, and many kinds of man-made obstacles, the signal will always be bounced off these surfaces several times because the surface of these things are huge and flat, it's constructed by metal and steel, which can reflect wireless signals. The consequence caused by these is that lots of copies of the original signal, and each one of them have different path, and delay of these "copies" have different delays, and it arrive the receiver at different time. The components of multiple signals will interfere with other; this will cause to signal distortion [3].

When transmitter and receiver are having relative motion, the frequency of the received signal will be changed. And this is called doppler shift. In wireless communication systems, while the users are using vehicles or moving, the device are moving in a constant motion, and the doppler shift will be a key factor. Let's give an example, when the user is moving to the base station, the frequency that send by the device will be lower than the frequency received by the station. But it will be completely opposite when the user is moving away from the station. And this is going to cause negative effect for signal which is transmitted by device [2]. How people deal with this problem? Scientist lower the effect of the doppler shift by using the high technology and processing algorithms in wireless communication, and these will help to adapt the changing frequencies and keep reliable communication.

2.2. Modelling and implementation

MIMO and OFDM are used a signal processing technologies which will help to solve these challenges.

2.2.1. MIMO

Multiple input and multiple output can be written as MIMO, this technology use multiple antennas at transmitters and receivers, and spatial multiplexing can let a lot of data streams be transmitted over different spatial channels at the same time, each antenna receives a version of the transmitted signal that has travelled along the different path. The signals will be combined after received, and the receiver can detect the path which experiences fading or effected by interference, and those which get faded will be from another paths that is still be in good condition [5]. This enhances reliability against fading and interference. Beamforming can concentrate the energy in specific orientation by adjusting the phase and amplitude of the signals.

2.2.2. OFDM

Orthogonal frequency division multiplexing has an abbreviation as OFDM, this make the whole frequency band in to lots of pieces, and it is called orthogonal subcarriers. These things are closely spaced and also orthogonal to each other, and this means that interference does not exist between them. These data will be modulated and transmitted on all these subcarriers at the same time [3].

3. Applications in wireless communication

The technology of electromagnetic wave is widely applied in 5G networks, internet of things, remote sensing and space communication.

For wireless communication, the one that use the most is about the network stuff, and the latest technology and used for most people is the 5G network. 5G networks needs to be high data rates and low latency, so the frequency and the type of the wave is important. It uses mm wave with frequency from 24GHz to 100GHz [1]. But at the same time, it can be easily affected by the high path loss, and it also cannot pass the obstacles easily. Then beamforming and MIMO technologies are needed to make sure the wireless communication reliable.

Wireless communication is widely used in internet of things devices; it is always work in low-power and wide-area networks. These technologies are use in long range and narrow band-internet of things. These things use sub-GHz frequencies which is lower than 1GHz, and this make sure that the power used is very low and the range of the communication is very long [3]. Some examples that use this technology is agriculture, the automatic industrial and some other things.

Electromagnetic waves are also used in remote sensing applications, like some radar things, and satellite communication use in MIMO, this technology will help detect and monitor things which in long distances. In the space communication, electromagnetic waves can travel for a long distance [5].

4. Results and disscussion

4.1. Data sources and evaluation

There is some key information which is needed in the essay after, and it is mainly three things, the signal to noise ratio which have an abbreviation signal-to-noise ratio (SNR), bit-error-rate (BER) and the channel capacity.

The SNR is a unit which can shows the signal quality, the definition of it is the ratio between the power of the signal and the power of the noise, as the SNR become higher the signal has a better quality [7]. $BER = \frac{number\ of\ incorrect\ bits}{total\ number\ of\ bits\ transmitted}$ if the BER is low the better quality of signal is [8]. Channel capacity is the highest data rate which can be reach in a communication channel, and it have a unit which is bit per second it always written as bps, but some time it has another unit which is bits per seconds per hertz which is bps/Hz [9].

4.2. performance analysis of MIMO and OFDM system

From Table 1, the data shows that MIMO and OFDM technologies have remarkably improve the data transmission in high frequency band the key finding include two points which is the spectral efficiency through spatial multiplexing and robustness against multipath fading. The increased spectral efficiency through spatial multiplexing. But how to achieve it? It can be done by transmitting multiple data streams simultaneously, and the MIMO and OFDM system which is mentioned before can help to transmit higher data rates, and it does not need more band width at the same time. For 2×2 MIMO system it has a capacity about 5.2bps/Hz, but compare to the larger ones with 4×4 MIMO system will have channel capacity about 8.5bps/Hz [10]. The use of OFDM is to improve the stability against the multipath fading, OFDM achieve this goal by sperate the signal into multiple subcarriers, each of these subcarriers will experience the flat fading [11]. And this will decrease the impact of fading and improves the reliability at the same time. MIMO and OFDM system can help reduce the bit-error rate (BER= (number of incorrect bits)/ (total number of bits transmitted)) value in a very noisy place by using spatial diversity to transmit unnecessary repeated copies of the data in several paths. When the MIMO system have a 2×2 it will have a BER of 1.2×10^{-3} at an SNR of 10dB, but when it became to 4×4 the BER become to 4.5×10^{-4} at the same SNR [12].

Table 1. MIMO system performance

Size of the MIIO	Channel capacity in bps/Hz	BER when SNR equals to 10dB
2*2	5.2	1.2×10^{-3}
4*4	8.5	4.5×10^{-4}
8*8	12.7	1.1×10^{-4}

4.3. Antenna design and signal coverage

The design of the antenna has a vital function which can help improve the wireless communication. It has already shown that signal coverage and interference reduction can be optimized by beamforming technology and adaptive array antennas technology. But how this technology can help optimize wireless communication?

The basic principle of Adaptive array antennas is using several antenna elements to change the radiation pattern at all time to response to changing signal condition. And this will increase the area of the signal covered and the signal will not be interfered that much in the city environment [13]. Fig.1 shows how the beamforming technology works.

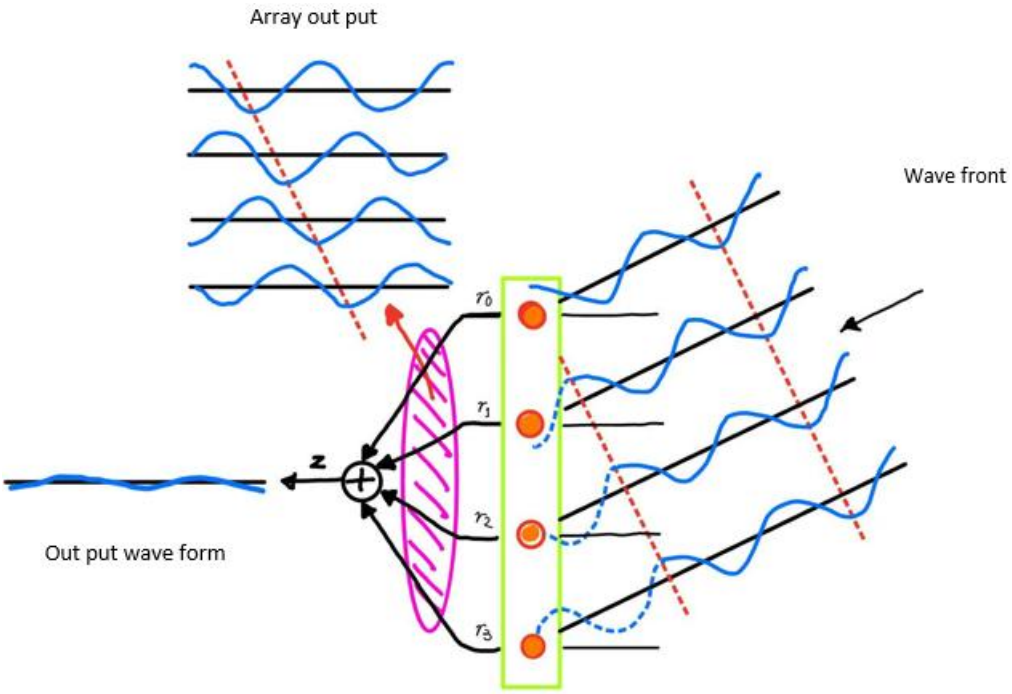

Figure 1. Beamforming technology workflow diagram

The beamforming technology, this technology is a kind of technique which can transmit the signal in a specific direction and optimize the signal strength and reduce the interference in signal processing. In the 5G networks. The problem of high pass loss and poor penetration of the mmWave frequencies can be solve by gathering the mmWave signals to users which is call beamforming [14].

4.4. The challenges and how to improve

After all this research, there are three main limitations which are the strict condition of experiment, the penetration problem of the signal and the amount of energy of consumption.

There are so many limitations for experiment, when doing the high frequency experiment needs the high-quality hardware which is so expensive and most of people cannot afford for the hardware. For example, the machine creates the mmWave and the machine that can generates THz signal, these are the most important hardware in the experiment and they are so expensive to borrow from others, let alone buy a new one [17]. This will make only a few people can do experiment research in this area. This might slow down the speed of the exploration in this area.

The problem of the penetration of the signal will be exist since the large architectures have been built. In urban city there are some things for example the tall buildings, cars and other obstacle that will bounce or even block the mmWave and THz signal. There is also the path loss problem from the signal itself. And this will lead to the unstable connection of the device and the length the signal can transmit. So, the signal will not be that reliable in the city. And these are the big challenges of the wireless communication in crowded city [15].

There is a very serious problem for base station of wireless communication which is that it uses too much energy. At the same time IOT devices have the same challenge, especially the place with a lot of people using a lot of devices that connected to the station.

So, the first thing is going to be invented is the AI driven wireless communication. Basically, is the AI algorithms will be take control of the system, and this is going to improve the ability of signal processing, cause AI can think the solution of almost every situation when there is a problem. This will improve the allocation of resource, and the efficiency of the future networks.

The second and the last one is the IOT technology combine with the smart city, which means the wireless communication will be embedded into IOT technology and the smart city. Which means there will be loads of new applications making life a lot easier, for example the automatic vehicles, and some cars driven by the AI which already exist which is the base of this future technology. Limitations and future

The design of the antenna has a vital function which can help improve the wireless communication. It has already shown that signal coverage and interference reduction can be optimized by beamforming technology and adaptive array antennas technology. But how this technology can help optimize wireless communication?

5. Conclusion

If The basis of how 5G develop rapidly is the electromagnetic wave. At the same time, it is being as the ground work and gives 6G technology a bright future. In the essay, it thoroughly researched some key parts, for example the propagation of the electromagnetic wave, MIMO and OFDM technology, and how antennas should be design. All of these things will help improve the quality of the signal, and also will make the wireless communication progressing better. All these play an important role in the wireless communication. But at the same time there are still lots of serious problems will make the wireless communication unreliable and unstable, these problems are waiting to be solve, and lots of people are working hard to try to solve these problems. It is believed that as wireless communications keep develops whether the IOT or space communication, even other diverse fields will be experienced a huge leap and breakthrough of technology. It must bring people more surprise and huge changes in people’s life.

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