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SPATIAL SIGNAL PROCESSING IN MULTI-ANTENNA AND MULTI-USER WIRELESS COMMUNICATION SYSTEMS

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Abstract

This article analyzes the operating principles of multiple-input multiple-output (MIMO) and multi-user wireless communication systems. It examines spatial multiplexing, spatial diversity, separation of information streams, and electromagnetic radiation direction control. Particular attention is paid to the influence of phase and amplitude coordination on communication quality and network capacity.

Keywords: MIMO, multi-user communication, spatial multiplexing, spatial diversity, beamforming, electromagnetic radiation, phase control, 5G technology.

Introduction

The rapid development of modern wireless communication systems has created a need to increase data transmission rates, ensure communication reliability, and simultaneously serve a large number of users. The growing number of mobile devices, the expansion of digital services, the increasing volume of multimedia data, and the development of the Internet of Things (IoT) are further intensifying the demand for radio frequency resources. The limited availability of the existing frequency spectrum necessitates the development of new technological solutions to improve its utilization efficiency. Multi-antenna communication technologies play an important role in addressing these challenges [1]. In this technology,

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multiple antennas are used at both the transmitting and receiving devices, taking into account the spatial characteristics of the radio communication environment. Unlike conventional single-antenna systems, multi-antenna systems enable the simultaneous transmission of several independent data streams, improve resistance to signal fading, and enhance communication quality [2]. In multi-user communication systems, which represent an advanced form of multi-antenna technology, several subscribers can be served simultaneously using shared frequency and time resources. In this process, the spatial direction of the signal intended for each user is individually adjusted [3].

Coordinating the amplitude and phase of signals transmitted through the antennas plays an important role in this process. One of the key factors determining the efficiency of multi-antenna systems is the ability to control the direction of electromagnetic radiation. This approach makes it possible to concentrate energy in the desired direction, increase the power of the received signal, and limit radiation in unwanted directions. This not only improves communication quality but also helps reduce mutual electromagnetic interference between users. The main objective of this study is to investigate the operating principles of multi-antenna and multi-user wireless communication systems, analyze the mechanisms for controlling radiation direction, and determine their impact on communication efficiency.

In addition, the study aims to explore the potential applications of these technologies in modern mobile communication networks and smart city infrastructures.

Literature Review and Methodology

Scientific approaches aimed at improving multi-antenna communication systems primarily focus on utilizing the spatial capabilities of radio communication channels, increasing data transmission rates, and enhancing signal resistance to external interference.

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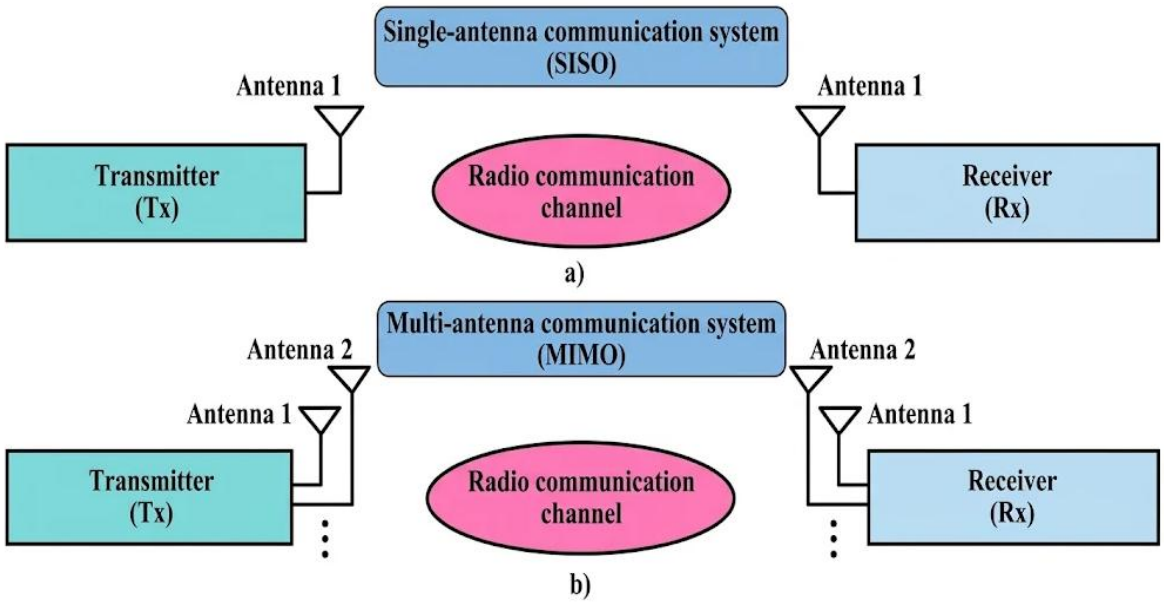


Fig.1. Structural diagram of single-antenna (SISO) and multi-antenna (MIMO) wireless communication systems

In this field, important research areas include comparing the technical capabilities of single-antenna and multi-antenna systems, determining the influence of the number of antennas on communication quality, and improving mechanisms for providing parallel services to multiple users. In single-antenna communication systems, data transmission is carried out through one transmitting antenna and one receiving antenna. In such systems, changes in the radio communication environment, multipath propagation, and electromagnetic interference directly affect signal quality. In multi-antenna systems, however, the use of different spatial propagation paths expands data transmission capabilities Fig.1.

In this context, spatial multiplexing and spatial diversity techniques are of particular importance. The former is used to increase data transmission rates, while the latter improves resistance to signal fading [4]. In multi-user systems, the main focus is on enabling multiple subscribers to share the same frequency

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and time resources. In this process, the spatial locations of users and the characteristics of radio communication channels are taken into account. By individually adjusting the direction of signals transmitted to each subscriber, data streams can be spatially separated [5]. However, the efficient operation of such systems requires signal coordination and the suppression of mutual interference. The research methodology is based on theoretical analysis, comparative assessment, a systematic approach, and scientific generalization.

First, the structures and operating mechanisms of single-antenna and multi-antenna systems were examined. Subsequently, the processes of spatial separation of data streams and control of electromagnetic radiation direction in multi-user communication systems were analyzed. During the analysis, the number of antennas, their relative positioning, phase and amplitude parameters, the state of the radio communication channel, and the spatial distribution of users were considered the main evaluation factors. Based on these approaches, the capabilities, technical limitations, and practical application characteristics of multi-antenna communication systems were summarized.

Results and Discussion

The analysis of the operating mechanisms of multi-antenna communication systems revealed that their main capability is associated with the use of multiple spatial propagation paths available in the radio communication environment. The presence of multiple antennas in transmitting and receiving devices makes it possible to generate and receive independent data streams. This process helps improve data transmission efficiency without expanding the system's frequency resources. In spatial multiplexing, several independent data streams are transmitted through different spatial channels within the same frequency band. The receiving device then processes the incoming signals and separates them into individual data streams [6].

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The efficiency of this method depends on the spatial channels being sufficiently distinct from one another. If the correlation between antennas is high, separating independent data streams becomes more difficult. Therefore, the proper selection of the antenna configuration is one of the key conditions determining the overall performance of the system. In multi-user systems, several subscribers can be served using the same time and frequency resources. In this process, each user's radio communication channel is evaluated separately, and a corresponding signal is generated for each user. As a result, the ability to use shared communication resources in parallel is enhanced.

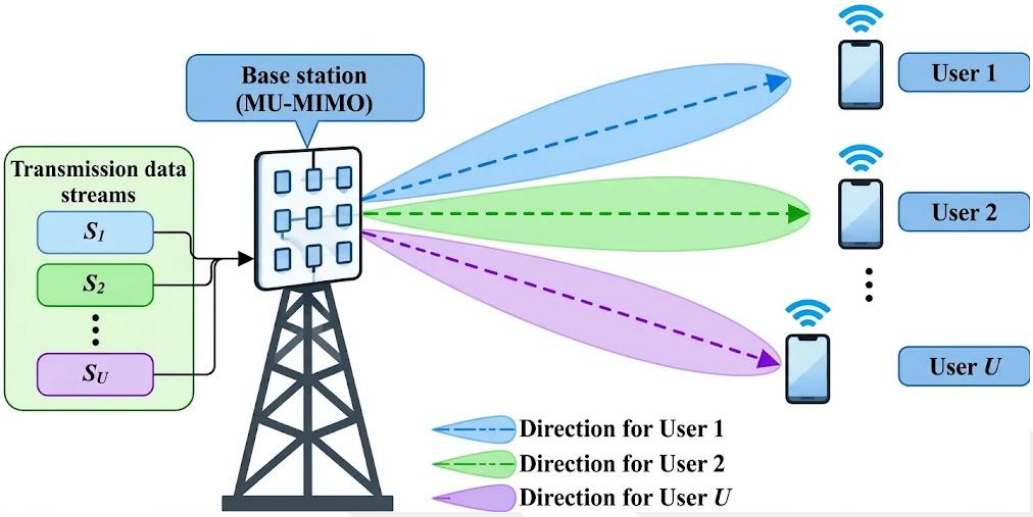


Fig.2. Principle of spatial separation of data streams and signa beamforming in a multi-user multi-antenna communication system

However, the relative positions of users, channel similarity, and mutual electromagnetic interactions affect the efficiency of this process. During beamforming, the phase and amplitude of signals transmitted by the antennas are adjusted according to a predetermined pattern. If the signals combine in phase at the location of the receiving device, constructive interference occurs [7]. As a result, the overall signal amplitude increases, improving reception conditions Fig.3.

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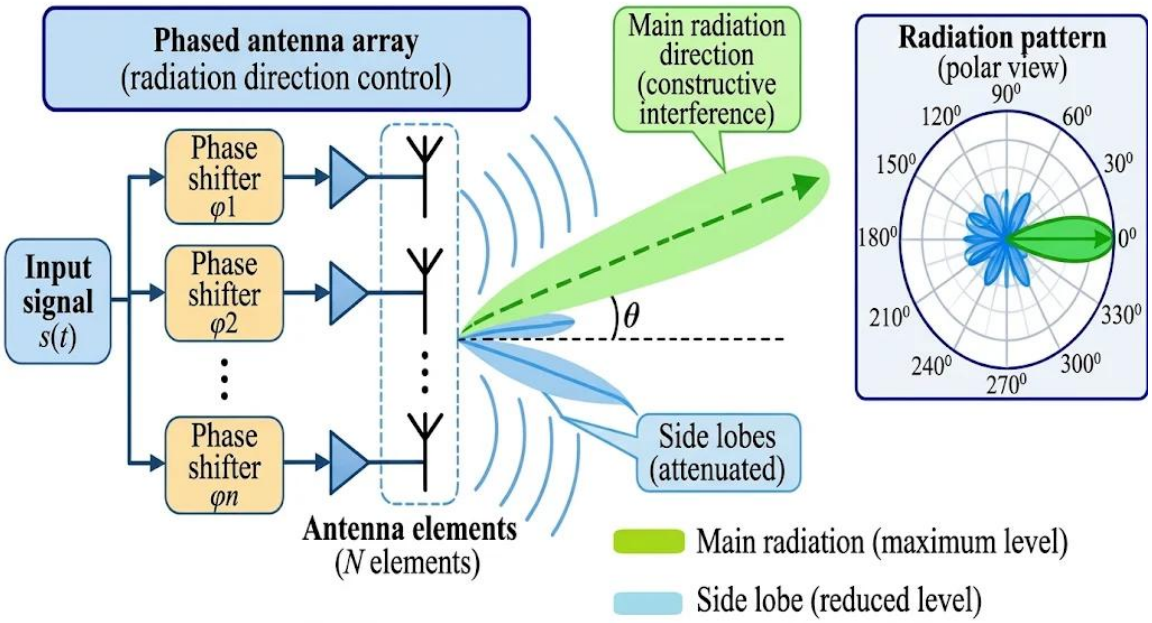


Fig.3. Schematic diagram of electronic control of electromagnetic radiation direction using a phased antenna array

In unwanted directions, the level of electromagnetic radiation can be reduced by coordinating the phase distribution of the signals. The number of antennas, the spacing between them, and the phase shift values play an important role in implementing this mechanism [8]. Incorrect selection of the spacing between antennas may adversely affect the formation of the radiation pattern. Furthermore, changes in the radio communication channel may necessitate readjustment of the previously established phase and amplitude parameters. Therefore, effective control requires continuous assessment of the channel conditions and updating signal parameters accordingly. The practical capabilities of multi-antenna communication systems are particularly evident in modern mobile communication networks. In fourth- and fifth-generation mobile communication systems, these technologies are used to achieve high data transmission rates, expand network capacity, and improve the quality of services

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provided to users [9]. In wireless local area networks, they also help improve the efficiency of simultaneous data exchange among multiple devices. Furthermore, these technologies have significant practical applications in wireless sensor networks, the Internet of Things (IoT), and smart city infrastructures. For example, vehicle tracking, video surveillance, remote monitoring, and automated control systems require continuous data exchange among numerous devices. Multi-antenna communication techniques expand the possibilities for efficient utilization of available radio frequency resources in such systems [10].

At the same time, certain limitations remain in the practical implementation of this technology. The use of a large number of antennas increases the structural complexity of transmitting and receiving devices. Spatial signal processing requires high computational capabilities, accurate channel state estimation, and rapid implementation of control processes. In particular, under conditions where users are mobile, frequent changes in the radio communication channel make the system adaptation process more complex. Thus, the efficiency of multi-antenna communication systems depends not only on the number of antennas but also on their relative positioning, the characteristics of the radio communication channel, signal processing capabilities, and the accuracy of beamforming. Taking these factors into account collectively is essential for the effective utilization of the system's technical capabilities.

Conclusion

The theoretical analyses conducted have demonstrated that multi-antenna and multi-user communication systems play an important role in expanding the technical capabilities of modern wireless communication networks. By utilizing the spatial characteristics of radio communication channels, these technologies enable the transmission of multiple independent data streams, improve communication reliability, and increase overall network capacity. The study also examined the impact of beamforming on communication quality. It was

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established that coordinating the phase and amplitude of signals makes it possible to concentrate electromagnetic energy in the desired direction, increase the power of the received signal, and limit radiation in unwanted directions.

Furthermore, it was determined that the efficiency of multi-antenna systems depends on the number of antennas, their spatial arrangement, the state of the radio communication channel, and the accuracy of signal processing. Therefore, optimizing antenna configurations, developing phase coordination techniques, and reducing inter-user interference are important tasks in improving these systems. Overall, the development of multi-antenna communication technologies provides an important scientific and practical foundation for creating high-speed, reliable wireless communication systems capable of serving multiple users.

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