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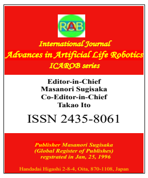

Research Article

Optimizing Antenna Configurations for Improved Drone Communication in Challenging Environments

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ABSTRACT

In recent years, the use of drones, also known as Unmanned Aerial Vehicles (UAVs), has experienced rapid growth across multiple industries, including agriculture, logistics, disaster management, and surveillance. The effectiveness of these UAVs is heavily dependent on reliable communication systems, particularly in challenging environments where signal strength and reliability are critical. This article explores the optimization of antenna configurations using MATLAB simulation tools to enhance the Signal-to-Noise Ratio (SNR), with a focus on the broader context of Internet of Things (IoT) integration. Considering the use of Energy per Bit to Noise Power Spectral Density Ratio (E/N) as a measurement technique commonly used in wireless communication systems to assess the quality of the received signal relative to the background noise, this paper evaluates and compares the quality of the received signals in SISO and SIMO systems.

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1. Introduction

Drones are poised to act a pivotal role in Emerging wireless connectivity, furnishing a positive approach to fulfill the growing requests of users. Their inherent Versatility, Resilience, enhanced direct visibility features or enhanced LOS, and potential to access the challenging regions, led to well-suited technologies to serve as aerial base stations. In this regard, several research has been conducted to measure the efficiency of appraisal and the allocation of resources in wireless networks that are powered by UAV. This survey article aims to comprehensively review the various algorithms and use cases driving drones' deployment. Lately, drones or UAVs usage has seen a remarkable increase throughout an extensive range of industries and uses, from capturing aerial photography to delivering packages. The Signal-to-Noise Ratio (SNR) is a crucial factor that affects drone networks' efficiency and output. In a communication system, the SNR shows the proportion of the desired signal to the undesired background noise. Optimal SNR level is a key factor for ensuring seamless and dependable communication between drones and ground control stations, facilitating precise data transmission

A strong SNR is essential for enabling effective drone operations, because it guarantees the caliber and reliability of the communication channels. This is particularly important in scenarios where drones are required to transmit critical information or receive commands from ground control in a reliable and timely manner. The optimization of the SNR is, therefore, a key focus area for researchers and developers working on improving the overall performance and capabilities of drone-based communication networks. By enhancing the SNR, drone operators can ensure more robust and efficient data transfer, ultimately unlocking the full potential of these versatile aerial platforms across various industries and applications. [1], [2]. Nevertheless, attaining a robust signal-to-noise ratio within drone networks poses multiple challenges [3]. Utilizing numerous drones nearby may lead to signal interference and degradation, impacting communication quality.

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Additionally, the drones' generated noise, known as ego-noise, can further influence the SNR. Effective and dependable drone-to-ground control station communication necessitates thoughtful deliberation and innovative strategies for enhancing the signal-to-noise ratio within drone networks. [4]. Recent research has focused on optimizing antenna configurations to improve the quality of drone communication in such challenging environments.

The research in [5] proposed an antenna offering 360° coverage and adaptive beam control for reliable drone-to-drone communication. While [6] introduced a structure for lunching a drone-centric antenna array, minimizing service time by optimizing drone spacing and positions. [7] experimentally evaluated antenna polarization and elevation effects, revealing that drone bodies can act as local scatterers, reducing cross-polarization discrimination and potentially doubling spectral efficiency. [8] developed a distributed solution for optimizing communication performance in UAV fleets by independently adjusting individual drone orientations based on local reception power information. These studies collectively demonstrate the importance of considering antenna configurations, polarization, elevation, and orientation in improving drone communication systems for various applications and environments.

At a specific location, the SNR can gauge the unwanted signal encountered by each drone. Various elements including Signal strength, antenna characteristics, drone location and height, ambient noise power spectral density, and path loss collectively shape the SNR. These factors hold significant importance in determining interference levels and are crucial for maintaining communication quality within drone networks [9]. Drones experience significant changes in signal-to-noise ratio based on their flying altitude. At higher altitudes, the signal quality diminishes due to the increased distance along the communication path. As altitude increases, signal loss is further exacerbated by atmospheric attenuation. The strength of the signal is influenced by the emission intensity and antenna characteristics of drones. Overcoming noise and interference requires optimal power levels, while signal coverage and directionality are influenced by antenna properties. The overall SNR is affected by background noise introduced by various sources' noise power spectral density. The maintenance of dependable communication in drone networks hinges on the careful consideration of these factors [4], [5], [6], [7], [8], [9]. In [9], [10], The domain of UAV supported communication in a smart sensor grid is explored by the writers. Their efforts are concentrated on creating a blueprint to assess the probability that terrestrial monitoring unit will be covered. Examining diffraction, frequency, and atmospheric attenuation, Raja's 2021 study estimates the distribution of links spreads among UAVs and terrestrial units in an enclosed area [11]. Authors in [12] proposed a novel multi-UAV communication paradigm with a focus on security. Multiple drones can communicate efficiently and securely using a wireless mesh network and cryptographic techniques in this model. Establishing secure data communication between drones and servers is crucial, as emphasized by the study. Within the field of drone communication, these academic works together provide significant contributions regarding the evaluation of coverage probability, propagation mechanisms, coordination among multiple UAVs, and security protocols [13], [14]. The data extraction process was conducted based on a Scopus document search, yielding a total of 2704 articles. To ensure the reliability and relevance of the data, conference proceedings were excluded from the search. The next step involved data cleaning, where the focus was limited to articles written in English. Further refinement was carried out by filtering the articles based on specific journals. The resulting article counts for each journal was as follows: IEEE Access (963 articles), Remote Sensing (321 articles), Sensors Switzerland (311 articles), IEEE Internet of Things Journal (294 articles), Sustainability Switzerland (231 articles), IEEE Transactions on Vehicular Technology (215 articles), and Wireless Personal Communications (125 articles). By narrowing down the dataset based on these journals, the research aims to gather valuable insights and trends in the respective fields.in the last stage of data cleaning process, only related articles that focused on SNR optimization, has been considered. Fig. 1 illustrates the importance of this topic based on the number of related documents published since 1996 till today.

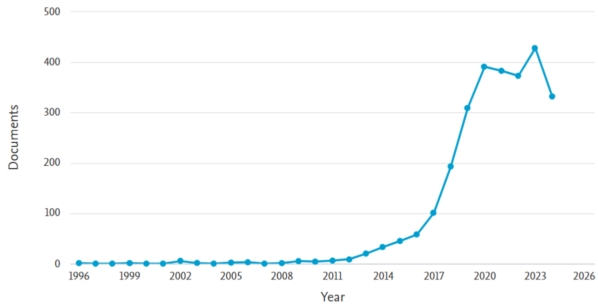


Fig. 1: Documents published per year

Recent research on optimizing drone communication focuses on enhancing air-to-ground (A2G) links and improving energy efficiency. [15] proposed an algorithm for selecting antenna patterns using beamforming to reduce sidelobe levels and optimize antenna array configurations. [16] present a dual optimization approach that simultaneously addresses UAV mobility and transmission power, resulting in enhanced energy efficiency and Air-to-Ground transmission reliability. [17] suggest using hybrid beamforming techniques to optimize UAV power consumption in wireless communication for disaster management scenarios. [18] addressed secure UAV communications by proposing a multi-objective optimization problem that maximizes secrecy rates and minimizes sidelobe levels and energy consumption. They introduced an enhanced multi-criteria Salp Swarm Algorithm to solve this complex problem. These studies collectively demonstrate advancements in antenna configurations, power optimization, and secure communication strategies for improved drone performance in challenging environments.

To aid in understanding the communication requirements of UAVs, Table 1 presents the key communication needs for Unmanned Aerial Vehicle (UAV) systems, categorized by data type and direction (downlink or uplink). The high data rate requirement for uplink might pose challenges in terms of bandwidth availability and power consumption. Table 1 succinctly provides an overview of these specifications. This tabulated reference efficiently outlines the essential facets of UAV communication, aiding readers in comprehending the vital information with ease. Table 1 presents a succinct and organized representation of the various communication requirements for UAVs, such as range, data rate, latency, and other relevant parameters. By consolidating this information into a tabular format, the text allows readers to quickly reference and comprehend the essential communication needs of UAVs, facilitating a better understanding of the underlying requirements and considerations in this domain. This table serves as a valuable resource for those involved in the deployment of UAV-based communication systems, as it provides a concise and easily digestible summary of the critical communication requirements that must be addressed to ensure the successful implementation and operation of these aerial platforms.

Table 1 Key Communication Needs for UAV Systems

Category	Throughput (Kbps)
System Alignment	Not applicable
Downlink /Uplink Control	$60 < DC, UC < 100$
Uplink App speed	Maximum of 50

An Analysis of the unique characteristics of various drone models is illustrated in [12], [19], [20], [21], [22] and the findings are structured in a table in Table 2.

Table 2 Distinctive Features of Drone Types [20], [21]

System Type	Weight	Payload	Flight Mechanism	Range	Flight Time (min)	Speed (Km/h)
Micro	16g	Not applicable	Poly-spin	50-80 m	6-8	Not applicable
Very Small	750g	Not applicable	static winged	2km	45	80
Small	3.3kg	4.9kg	Poly-spin	Not applicable	18	57.6
Medium	90kg	50kg	Poly-spin	Not applicable	180	100
Large	2223kg	1700kg	Poly-spin	1852km	1800	482

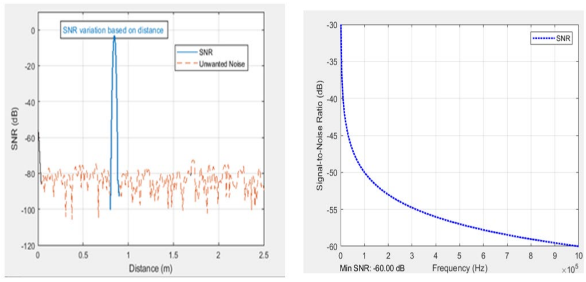
2. Methodology

2.1. SNR Analysis for Performance Assessment

The process of evaluating performance through Signal-to-Noise Ratio (SNR) strength involves exploring a series of key steps. It starts by looking at how SNR changes as the distance between the drone and the signal source increases, trying to determine the relationship between SNR and the drone's displacement. The investigation then expands to examining SNR variations across different operating frequencies, assessing how SNR levels fluctuate with varying frequencies and visualizing these patterns through graphs. Additionally, the team dives into the impact of noise on SNR levels at different operating frequencies, shedding light on how noise affects signal quality and SNR performance. Furthermore, they compare the Energy per Bit to Noise Power Spectral Density Ratio (E/N) between Single-Input Single-Output (SISO) and Single-Input Multiple-Output (SIMO) systems, which provides deeper insights into system reliability and performance metrics. Finally, the analysis explores how the Line-of-Sight (LOS) channels for Multiple-Input Multiple-Output (MIMO) systems stack up against SISO and SIMO setups, illuminating the SNR levels and operational efficiencies in LOS scenarios. Through these comprehensive evaluations, the team aims to gain a nuanced understanding of system performance based on SNR strength variations under diverse conditions and configurations. have surged in popularity, thanks to their autonomous capabilities, adaptability, and diverse array of uses. This section will conduct a thorough evaluation of drone performance. This talk will primarily center on examining a crucial Signal-to-Noise Ratio (SNR) metric. This metric will be used to assess and examine drone operations in-depth, providing insightful information about their overall efficacy. The comparison of signal power and noise power is reflected in the SNR, which is commonly expressed in dB. In the context of wireless communication, where data is transmitted between two points via a channel called a data link, this is an important consideration. This wireless transfer is known as a radio connection in the unmanned aviation community. Information exchanged between the aircraft's autopilot and the Ground Control Station (GCS) is facilitated by radio communication. This communication consists of two distinct links: the downlink, which is in charge of sending data from the aircraft to the GCS, and the uplink, which is in charge of sending data from the GCS to the aircraft. Equation (1) is utilized to compute the signal strength over the noise at the output of the system, which is a key factor for efficiency measurement of the communication links in drone-based operations. By analyzing and optimizing this SNR metric, researchers and practitioners can glean important understandings of the effectiveness and viability of drone-based communication systems, ultimately supporting the development and deployment of robust and efficient unmanned aerial platforms.

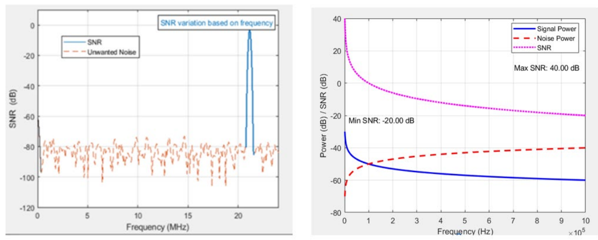
$$SNR = P_{signal} - P_{noise} \quad (1)$$

Power levels are commonly denoted in decibels per dBm. The minimum SNR required for a task determines a drone's operational radius with respect to a base station. Defining the maximum reachable distance while upholding the desired SNR is crucial. As the drone travels different distances during flight, the SNR varies and adjusts to reach the predetermined SNR. It should be highlighted that all the values in (1) have to be presented in dB. To illustrate this relationship, Fig. 2 illustrates a MATLAB-generated visualization model that demonstrates the impact of drone distance on the SNR_{dB}.



(a) (b)

Fig. 2 (a) SNR variation vs Drone's traveled distance [12], (b) SNR vs frequency of operation



(a) (b)

Fig. 3 (a)Effect of frequency of operation on SNR level [12], (b) SNR vs Frequency of Operation in presence of Noise

Fig.3 illustrates that the frequency of 22MHz is a promising operating frequency that can be resistive to the background noise.

2.2. Signal strength Improvement Techniques

The examination outlined in Fig. 3 provides perspectives on the importance of the SNR in influencing output quality. The determined threshold value for SNR is $-10\ dB$; Nevertheless, it is advisable to maintain a Signal-to-Noise Ratio exceeding $-20\ dB$ to achieve optimal output quality. The result depicts a gradual deterioration in signal power as the range extends, with the peak signal strength noted near the transmitter. This implies that the closeness to the transmitter is vital for upholding a robust and dependable signal. In light of the fixed parameters of a 2.4 GHz frequency cap, a 1 W power restriction, and a predetermined distance, it is evident that a stronger signal at 1 meter distance, 10 MHz frequency, and 1 W transmission power is required. This information highlights the importance of carefully managing the SNR in communication systems, particularly in scenarios where signal quality and reliability are critical factors, such as in drone-based operations. By understanding the relationship between SNR, range, and other relevant parameters, researchers and engineers can optimize the design and deployment of communication systems to ensure robust and consistent performance, even in challenging environments [11]. The higher signal quality observed near the transmitter is as a result of existence of several scatterers. These external factors have a tendency to diminish the signal power, particularly at longer distances. By increasing the communication path, the degradation in signal power can be observed. This occurs when the signal travels through the environment, while the noise from various sources remains relatively constant or even increases. The proximity to the transmitter is a critical factor in maintaining a strong and reliable signal. Closer proximity to the transmitter helps mitigate the impact of interference from external sources, resulting in a higher SNR and, consequently, better signal quality. This information highlights the importance of considering the spatial distribution of communication devices and the potential sources of interference when designing and deploying communication systems, particularly in environments with a high density of electronic devices or physical obstacles. By optimizing the placement and configuration of transmitters and receivers, the SNR can be maximized, leading to improved signal quality and overall communication performance.

2.3. SNR Boost through Array Gain in LOS Transmission

One method employed to enhance the dependability and excellence of wireless communication in situations of direct visibility propagation involves the utilization of array gain. To get the most from the array gain, large antenna arrays are commonly integrated into modern wireless communication systems [22], [23], [24]. By optimizing antenna configurations for improved drone communication in challenging environments, the reliability and effectiveness of medical drones can be enhanced [25]. A method utilized to enhance the dependability and quality of wireless communication in scenarios of line-of-sight propagation involves the implementation of array gain. Large antenna arrays are commonly integrated into modern wireless communication systems in order to take advantage of array gain. [15], [16]. Equations (2) and (3) are utilized to compute and compare the SNR for the SISO and SIMO scenarios, respectively.

$$SNR_{siso} = \frac{P_t G_t G_r \lambda^2}{4\pi d^2 N_0} \quad (2)$$

Where input power, gain at transmitter and receiver side, and input signal frequency are represented by P_t, G_t, G_r, and λ respectively. The d and N_0 present spatial gap between the transmitter and receiver, and the output noise power, respectively.

$$SNR_{siso} = \frac{P_t G_t \sum G_{ri} \lambda^2}{4\pi d^2 N_0} \quad (3)$$

Where G_{ri} is the gain of the i-th receiving antenna.

The Bit Error Rate (BER) vs E/N ratio has been displayed in a comparison format as a result of these computations. This method is frequently applied as a metric to measure the received signal power and the noise power impacting the transmission in a communication system.

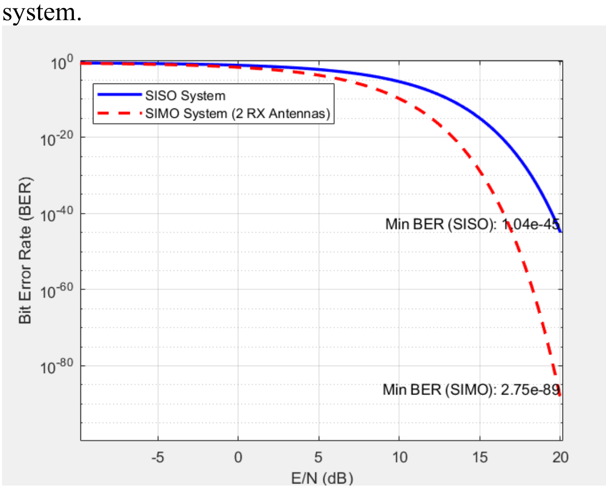


Fig. 4 Energy-to-Noise Ratios in SISO versus SIMO Systems

In the scenario under consideration, the transmitter and receiver are in direct Line-of-Sight (LOS) communication, allowing for a straightforward calculation of the system parameters. For the simulations, a four-element Uniform Linear Array (ULA) with half-wavelength spacing is utilized. The provided Fig. 4 illustrates the energy to noise ratio as a performance measurement technique for both SISO and SIMO systems. There is a notable enhancement of 6 dB in the curve. The primary cause of this gain is the coherent interaction between the components of the receive array and the received signals. Because the receiver is aware of the incoming signal path, it is possible to strategically align the receive array with respect to the transmitter, which improves the SNR. The coherence displayed by the received signals surrounding the receive array components can account for the observed gain. The spatial diversity that the receive array's multiple antennas provide is what causes this coherence. Several records for the transmitted signal, characterized by slight alterations in both amplitude and phase of each antenna. Concatenating these signals causes constructive interference, which raises the total power of the received signal. This occurrence underscores the advantages of utilizing a multi-antenna receiver array, enabling the system to effectively capture and utilize coherent signals, thereby enhancing signal robustness and subsequently improving Bit Error Rate (BER) performance. Bit Error

Rate (BER) performance for three distinct antenna configurations—Single-Input Single-Output (SISO), Multiple-Input Multiple-Output (MIMO), and SIMO—is compared in Fig. 5. Plotting the results against the Eb/No (energy per bit to noise power spectral density ratio) in decibels (dB), the performance is assessed over a Line-of-Sight (LOS) channel. A 4 × 4array is used in a MIMO setup; For peak performance, the elements need to be oriented in each other's direction. The BER curve can be computed as shown in Fig. 5.

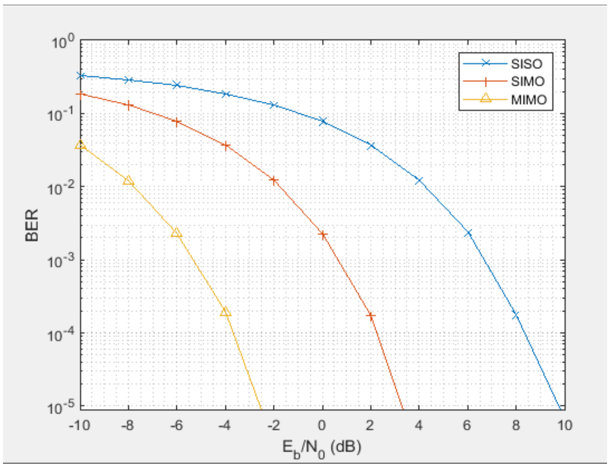


Fig. 5 MIMO LOS Channel vs SISO and SIMO LOS channel

As expected, the BER decreases as Eb/No increases for all three systems. This indicates that higher signal-to-noise ratios lead to better error performance. The MIMO system consistently exhibits the lowest BER across the entire Eb/No range. This illustrates the substantial benefit of employing numerous antennas for error rate reduction at both the transmitter and the receiver. The SIMO system shows improved performance compared to SISO, particularly at lower Eb/No values. This highlights the benefit of using multiple antennas at the receiver to combat channel impairments. The performance gains of MIMO over SIMO and SISO become more pronounced at higher Eb/No values. This suggests that MIMO systems can effectively exploit higher signal-to-noise conditions to achieve significantly lower error rates.

3. Conclusion

The importance of Drones in wireless networks is highlighted in this research paper, which also highlights the potential uses of UAVs, aerial base stations, and wireless network user services. By deploying UAV base stations, wireless network coverage and power can be significantly increased, facilitating communication in a variety of situations, including the distribution of vital public safety information. In addition, unmanned aerial vehicles (UAVs) exhibit potential for facilitating safe and economical mm-waves communication. Drones that are outfitted with cellular links necessitate real-time communication and ensure the communication integrity with terrestrial stations. The SIMO receive array's ability to receive coherent signals offers a way to point the array in the direction of the transmitter, which boosts the SNR. By using the receive array, a gain of 6 dB is obtained, as shown by the Bit Error Rate (BER) curve analysis, suggesting that the receiver is aware of the incoming signal path. These results demonstrate the benefits of using UAVs in wireless networks by highlighting how they can improve coverage, power, and communication capabilities. Improved SNR and overall system performance are a result of both the coherent nature of received signals and the capability to direct the receiving emissions into the transmitter. Overall, the results demonstrate the challenges associated with wireless communication systems, particularly regarding signal attenuation and noise interference. These factors can significantly impact the performance and reliability of communication links, especially over longer distances and at higher frequencies. The obtained results show the gain of 12dB or the increment of 6dB compared to the SIMO antenna.

Subsequent investigations may concentrate on streamlining UAV deployments, improving beamforming methods, and investigating new uses for UAVs in wireless networks. Improvements in safe, dependable, and effective wireless communication systems can be achieved by utilizing UAVs in these situations.

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