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## Experimental Evaluation of the Effect of Antenna Parameters on the Reliability of Telemetry and Control Systems of Unmanned Aerial Vehicles under Radio-Electronic Warfare Conditions

### Abstract

This article examines the effect of antenna parameters on the reliability of unmanned aerial vehicle (UAV) telemetry and control systems under radio-electronic warfare conditions. The study aims to evaluate changes in key communication indicators when omni-directional, Patch, and Yagi antennas are used in combination with different telemetry modules. From both theoretical and applied perspectives, the analysis focuses on the influence of antenna gain, directivity, and radiation pattern on signal propagation quality and link stability.

For comparative evaluation, RFD900, LoRa 433 MHz, and NRF24L01 telemetry modules were selected, and their performance with corresponding antenna types was investigated at distances of 50 m, 100 m, and 150 m. The main evaluation metrics included RSSI, Path Loss, SNR, and Effective SNR. The graphical results presented in the study were generated on the basis of the obtained experimental and calculated data using the Python programming environment and the Matplotlib library. This allowed the communication trends to be visualized in a clear and consistent form.

The results show that, for all tested modules, increasing distance leads to a decrease in RSSI, an increase in Path Loss, and a deterioration in communication quality. At the same time, compared with omnidirectional antennas, Patch and especially Yagi antennas provide higher received signal levels, lower path loss, and more stable communication indicators under radio-electronic warfare conditions. Among the investigated modules, RFD900 demonstrated the most stable performance at longer distances, LoRa 433 MHz showed moderate stability, whereas NRF24L01 weakened more rapidly as distance increased. The obtained results confirm that antenna selection is a critical factor in the optimization of UAV communication systems operating in complex electromagnetic environments.

**Keywords:** *unmanned aerial vehicle, telemetry channel, antenna parameters, radio-electronic warfare, Path Loss, signal-to-noise ratio, Patch antenna, Yagi antenna, omni antenna*

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## Radioelektron müharibə şərtlərində pilotsuz uçuş aparatlarının telemetriya və idarəetmə sistemlərinin etibarlılığına anten parametrlərinin təsirinin eksperimental qiymətləndirilməsi

### Xülasə

Bu məqalədə antena parametrlərinin radioelektron müharibə şəraitində pilotsuz uçuş aparatının (PUA) telemetriya və idarəetmə sistemlərinin etibarlılığına təsiri araşdırılır. Tədqiqatın məqsədi çox yönlü, Patch və Yagi antenaları müxtəlif telemetriya modulları ilə birlikdə istifadə edildikdə əsas rabitə göstəricilərindəki dəyişiklikləri qiymətləndirməkdir.

Həm nəzəri, həm də tətbiqi nöqteyi-nəzərdən təhlil antenna qazancının, istiqamətləndiriciliyin və radiasiya modelinin siqnalın yayılma keyfiyyətinə və keçid sabitliyinə təsirində diqqət yetirir.

Müqayisəli qiymətləndirmə üçün RFD900, LoRa 433 MHz və NRF24L01 telemetriya modulları seçilmiş və onların müvafiq antena növləri ilə işləməsi 50 m, 100 m və 150 m məsafələrdə tədqiq edilmişdir. Əsas qiymətləndirmə ölçülərinə RSSI, Path Loss, SNR və Effective SNR daxildir. Tədqiqatda təqdim olunan qrafik nəticələr Python proqramlaşdırma mühitindən və Matplotlib kitabxanasından istifadə etməklə əldə edilmiş eksperimental və hesablanmış məlumatlar əsasında yaradılmışdır. Bu, ünsiyyət tendensiyalarını aydın və ardıcıl formada vizuallaşdırmağa imkan verdi. Nəticələr göstərir ki, bütün sınaqdan keçirilmiş modullar üçün məsafənin artması RSSI-nin azalmasına, Path Loss-un artmasına və rabitə keyfiyyətinin pisləşməsinə gətirib çıxarır. Eyni zamanda, çox yönlü antenalarla müqayisədə, Patch və xüsusilə Yagi antenaları daha yüksək qəbul edilmiş siqnal səviyyələri, daha az yol itkisi və radio-elektron müharibə şəraitində daha sabit rabitə göstəriciləri təmin edir. Tədqiq olunan modullar arasında RFD900 daha uzun məsafələrdə ən sabit performans nümayiş etdirdi, LoRa 433 MHz orta sabitlik göstərdi, NRF24L01 isə məsafə artdıqca daha sürətlə zəiflədi. Əldə edilən nəticələr antenanın seçilməsinin mürəkkəb elektromaqnit mühitlərində işləyən İHA rabitə sistemlərinin optimallaşdırılmasında kritik amil olduğunu təsdiqləyir.

*Açar sözlər:* pilotsuz uçuş aparatı, telemetriya kanalı, antena parametrləri, radioelektron müharibə, Yol itkisi, siqnal-küy nisbəti, Yamaq antenası, Yagi antenası, omni antenna

## Introduction

Unmanned aerial vehicles (UAVs) are now used extensively in both civilian and military applications, including surveillance, reconnaissance, border monitoring, search-and-rescue missions, and geodetic operations. As UAV missions become more complex, the performance requirements imposed on telemetry and control systems also increase. In this context, reliable real-time data transmission is essential for maintaining stable operation and ensuring the overall safety of the platform (Ağayev et al., 2025; Ağayev et al., 2025). The telemetry system is responsible for transmitting flight parameters, position data, battery status, and sensor outputs from the UAV to the ground control station. The control system, on the other hand, delivers operator commands to the aerial platform and ensures their execution. Any attenuation, delay, or interruption in these channels can directly degrade control accuracy and mission effectiveness (Rustamov et al., 2025; Rustamov et al., 2024).

One of the most critical factors affecting UAV communication performance is operation under radio-electronic warfare (REW) conditions. Electromagnetic interference, intentional jamming, and additional noise sources can reduce received signal strength, degrade the signal-to-noise ratio, and increase packet loss. These effects become especially significant in low-power telemetry modules, where communication reliability may deteriorate rapidly under hostile electromagnetic conditions (Ağayev et al., 2025; Rustamov et al., 2025; Rustamov et al., 2025; Rüstəmov et al., 2023).

Antenna characteristics are also a key element in the stability of telemetry and control links. Parameters such as gain, directivity, and radiation pattern directly influence signal propagation, reception quality, and resistance to interference. Because omni-directional, Patch, and Yagi antennas differ significantly in these characteristics, their effectiveness under REW conditions cannot be assumed to be the same. In particular, directional antennas may improve link robustness by concentrating radiation toward the intended direction and suppressing part of the external interference (Azizullayev & Nematzade, 2025; Rustamov et al., 2024; Rustamov et al., 2025).

This article examines how antenna parameters affect the reliability of UAV telemetry and control systems under radio-electronic warfare conditions. The analysis is based on experimental tests performed with several telemetry modules, including RFD900, LoRa 433 MHz, and NRF24L01, used together with omni, Patch, and Yagi antennas. The study compares changes in key communication indicators across these antenna-module combinations and identifies configurations that provide more

stable performance in complex electromagnetic environments (Azizullayev & Nematzade, 2025; Rustamov et al., 2025; Rüstamov et al., 2023; Rüstəmov et al., 2024).

### Research

In UAV telemetry and control systems, the antenna is a fundamental element of the communication channel, since it is directly involved in both signal transmission and reception. Its electrical and structural characteristics strongly influence communication range, signal quality, resistance to interference, and the overall reliability of the system. This becomes especially critical under radio-electronic warfare (REW) conditions, where the proper choice of antenna parameters can significantly improve link stability (Azizullayev & Nematzade, 2025; Rustamov et al., 2024). Communication performance is commonly assessed using several key parameters, namely Path Loss, RSSI, SNR, and Effective SNR. These indicators characterize, respectively, signal attenuation in the channel, received signal strength, the ratio of useful signal to noise, and the effective signal quality under interference. One of the key antenna characteristics is gain. Increasing antenna gain at the transmitter or receiver generally increases the received signal power and can therefore improve communication performance under the same propagation conditions (Azizullayev & Nematzade, 2025; Rüstəmov et al., 2024; Rustamov et al., 2025). The received signal power can be expressed as follows:

$$P_r = P_t + G_t + G_r - PL(d) \quad (1)$$

Here,  $P_r$  is the received signal power, dBm;  $P_t$  is the transmitted signal power, dBm;  $G_t$  and  $G_r$  are the gains of the transmitting and receiving antennas, respectively, dBi; and  $PL(d)$  is the path loss depending on distance, dB.

The directivity of an antenna characterizes the concentration of electromagnetic radiation in a given spatial direction. In directional antennas, radiation is primarily focused within the main lobe, resulting in a higher signal level along the intended transmission path. At the same time, signals and interference arriving from side and rear directions are attenuated relatively more strongly. This makes antenna directivity particularly important under radio-electronic warfare conditions.

The relationship between the effective area of the antenna and gain is expressed as follows:

$$A_e = \frac{G\lambda^2}{4\pi} \quad (2)$$

Here,  $A_e$  is the effective receiving area,  $\text{m}^2$ ;  $G$  is the linear gain of the antenna; and  $\lambda$  is the wavelength, m.

The relationship between wavelength and frequency is as follows:

$$\lambda = \frac{c}{f} \quad (3)$$

Here,  $c$  is the speed of light, m/s; and  $f$  is the signal frequency, Hz.

Antenna dimensions and performance characteristics depend strongly on the operating frequency. Even when the same antenna type is used across different frequency bands, its geometry, radiation pattern, and practical gain values must be adjusted for the target band to ensure efficient operation.

*Comparative characteristics of Patch, Yagi, and omni antennas.* Omni-directional, Patch, and Yagi antennas are among the most commonly used antenna types in UAV telemetry systems. Their performance differs mainly in terms of radiation pattern, gain, and application conditions (Azizullayev & Nematzade, 2025; Rustamov et al., 2024; Rustamov et al., 2025; Rustamov et al., 2025). Omni-directional antennas provide wide-area coverage and operational flexibility, although they generally offer lower gain and weaker interference selectivity. Patch antennas can provide more stable communication links due to their directional behavior, compact form, and moderate-to-high gain. Yagi antennas, by contrast, offer the highest directivity and gain among these types, which

improves long-range signal reception, but they require precise alignment during operation (Azizullayev & Nematzade, 2025; Rustamov et al., 2025; Rustamov et al., 2024).

The main comparative characteristics of these antenna types are presented in **Table 1** below.

**Table 1.**  
 Main comparative characteristics of antenna types

Antenna type	Typical gain, dBi	Radiation characteristic	Advantages	Limitations
Omni	2–5	Nearly 360°	Simple, flexible, wide coverage	Low gain, weak selectivity
Patch	6–9	Moderately directional	Compact, stable gain, better selectivity under REW conditions	Sensitive to angle
Yagi	9–14	Highly directional	Long distance, high reception level	Requires precise alignment

The selection of the antenna type should be based not only on the gain value, but also on the frequency of the applied telemetry module, the nature of motion, the test distance, and the characteristics of the electromagnetic environment.

*Main evaluation indicators of the telemetry channel.* The reliability of telemetry and control systems can be assessed using several core communication metrics. In the present study, Path Loss, RSSI, SNR, and Effective SNR were used as the main evaluation indicators (Rüstəmov et al., 2023; Rüstəmov et al., 2024; Rustamov et al., 2025).

The distance-dependent path loss can be given according to the logarithmic model as follows:

$$PL(d) = PL(d_0) + 10n \log_{10} \left( \frac{d}{d_0} \right) + X_{\sigma} \quad (4)$$

Here,  $PL(d_0)$  is the path loss at the reference distance, dB;  $n$  is the path loss exponent of the environment; and  $X_{\sigma}$  is the additional noise component characterizing shadowing and random variation.

According to the Friis approach, the free-space path loss is as follows:

$$PL_{FS}(d) = 32.44 + 20 \log_{10}(f_{MHz}) + 20 \log_{10}(d_{km}) \quad (5)$$

RSSI characterizes the power level of the received signal and is measured in dBm. In practice, RSSI and received signal power can be used in a similar sense:

$$RSSI \approx P_r \quad (6)$$

The signal-to-noise ratio is calculated as follows:

$$SNR = P_r - N \quad (7)$$

Here,  $N$  is the noise level, dBm.

Under radio-electronic warfare conditions, not only natural noise but also intentionally created interference must be taken into account. In this case, the effective signal-to-noise ratio is:

$$SNR_{eff} = P_r - (N + I_{REM}) \quad (8)$$

and, in simplified form:

$$SNR_{eff} = SNR - I_{REM} \quad (9)$$

It can be expressed in this form. Here,  $I_{REM}$  is the equivalent effect of radio-electronic interference in dB.

From the evaluation point of view, the following principle can be accepted: the higher the RSSI, the lower the  $PL$ , and the greater the  $SNR$  and  $SNR_{eff}$ , the higher the reliability of the telemetry channel is considered to be.

*Experimental setup and test methodology.* In order to evaluate the effect of antenna parameters on the reliability of telemetry and control systems, an experimental approach was adopted in a controlled laboratory-field test environment. In the study, three telemetry platforms representing different frequency bands were selected: RFD900, LoRa 433 MHz, and NRF24L01. These modules represent communication systems operating in the 900 MHz, 433 MHz, and 2.4 GHz bands, respectively.

For each module, omni, Patch, and Yagi antennas optimized for the corresponding frequency band were used. The tests were carried out at distances of 50 m, 100 m, and 150 m. At each distance, RSSI, calculated Path Loss, SNR, and Effective SNR values were recorded for each module-antenna combination. In order to ensure the comparability of measurements, the transmitter power, antenna placement, orientation, and test duration were kept as constant as possible.

The experimental setup consisted of the following elements:

- transmitting block: telemetry module + transmitting antenna;
- receiving block: ground terminal + receiving antenna;
- measurement and recording block: recording of RSSI, transmission quality, and packet stability indicators;
- additional interference source for modeling the REW effect.

In the tests, the noise level was accepted as constant depending on the environment, while for the REW scenario, a medium-level interference equivalent was applied. From a mathematical point of view, the relative reliability coefficient of the telemetry channel can be accepted as follows:

$$K_{rel} = \alpha \cdot \frac{SNR_{eff}}{SNR_{max}} + \beta \cdot \frac{RSSI - RSSI_{min}}{RSSI_{max} - RSSI_{min}} + \gamma \cdot \left(1 - \frac{PL}{PL_{max}}\right) \quad (10)$$

Here,  $\alpha$ ,  $\beta$ , and  $\gamma$  are weighting coefficients satisfying the condition  $\alpha + \beta + \gamma = 1$ .

In this work, for illustrative evaluation,

$$\alpha = 0.4, \beta = 0.3, \gamma = 0.3 \quad (11)$$

it can be accepted as follows:

*Analysis of comparative results.* The tables presented below are illustrative/example results and are intended to demonstrate the mathematical-analytical structure of the article. They should later be replaced with real measurements.

**Table 2.**  
 Measurement results for the RFD900 module with different antennas

Distance, m	Antenna	RSSI, dBm	PL, dB	SNR, dB	Effective SNR, dB
50	Omni	-68	88	22	15
50	Patch	-61	81	29	22
50	Yagi	-58	78	32	25
100	Omni	-76	96	14	7
100	Patch	-68	88	22	15
100	Yagi	-64	84	26	19
150	Omni	-84	104	6	-1
150	Patch	-75	95	15	8
150	Yagi	-70	90	20	13

**Table 3.**  
 Measurement results for the LoRa 433 MHz module with different antennas

Distance, m	Antenna	RSSI, dBm	PL, dB	SNR, dB	Effective SNR, Db
50	Omni	-71	85	19	13
50	Patch	-65	79	25	19
50	Yagi	-61	75	29	23
100	Omni	-79	93	11	5
100	Patch	-71	85	19	13
100	Yagi	-66	80	24	18
150	Omni	-87	101	3	-3
150	Patch	-78	92	12	6
150	Yagi	-72	86	18	12

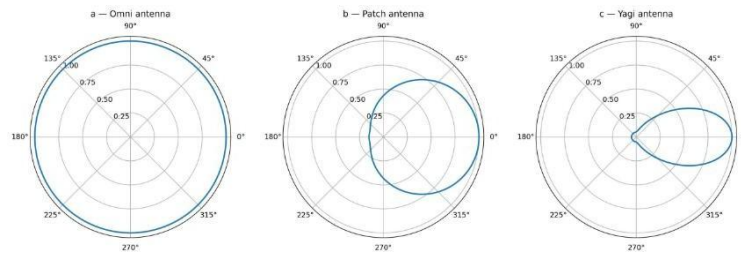
**Table 4.**  
 Measurement results for the NRF24L01 module with different antennas

Distance, m	Antenna	RSSI, dBm	PL, dB	SNR, dB	Effective SNR, dB
50	Omni	-74	92	16	9
50	Patch	-66	84	24	17
50	Yagi	-62	80	28	21
100	Omni	-82	100	8	1
100	Patch	-73	91	17	10
100	Yagi	-68	86	22	15
150	Omni	-90	108	0	-7
150	Patch	-80	98	10	3
150	Yagi	-74	92	16	9

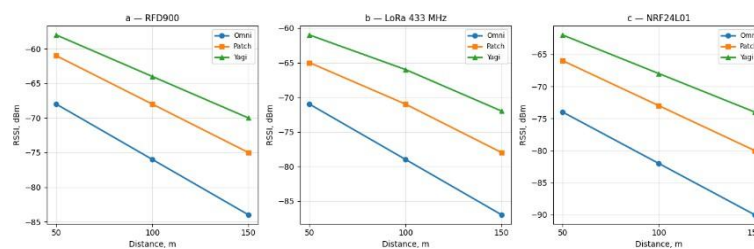
The tabulated results reveal a clear and consistent tendency for all tested modules: with increasing distance, RSSI decreases, Path Loss increases, and SNR deteriorates. Under REW conditions, the reduction in Effective SNR becomes even more pronounced, leading to a decline in communication reliability. Among the evaluated antenna types, the omnidirectional antenna produced the weakest results across all modules, primarily due to its relatively low gain and limited directivity. The Patch antenna provided more balanced performance at medium distances, whereas the Yagi antenna ensured the highest received signal level and the lowest Path Loss, especially at 100 m and 150 m. This confirms the superiority of directional antennas in maintaining link quality under REW conditions.

From the module perspective, the RFD900 demonstrated the most stable behavior at longer distances. The LoRa 433 MHz module also maintained moderate stability, likely due to the more favorable propagation properties of the lower-frequency band. In contrast, the NRF24L01 exhibited more rapid degradation as distance increased, which is consistent with the higher attenuation characteristics of the 2.4 GHz range. Therefore, antenna type should not be selected independently, but rather in conjunction with the operating frequency characteristics of the telemetry module.

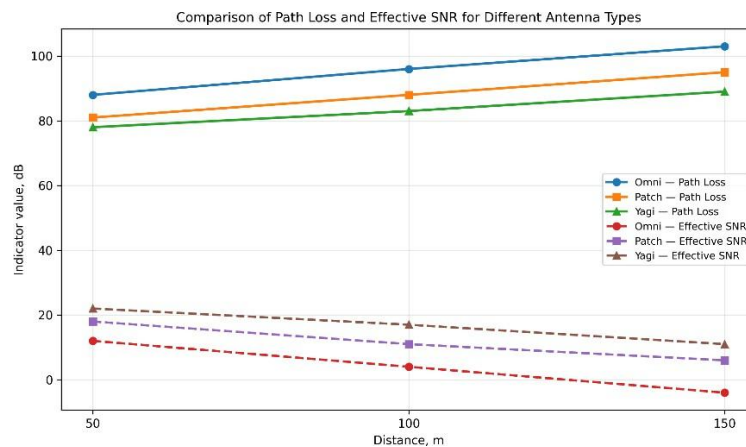
The graphs presented below illustrate the comparative changes in the main telemetry indicators for the RFD900, LoRa 433 MHz, and NRF24L01 modules, as well as the directivity characteristics of the Omni, Patch, and Yagi antennas.



**Figure 1.** Directivity patterns of Omni, Patch, and Yagi antennas



**Figure 2.** Comparative variation of distance-dependent RSSI indicators for the RFD900, LoRa 433 MHz, and NRF24L01 modules



**Figure 3.** Comparison of Path Loss and Effective SNR indicators for different antennas

The graphs presented above comparatively illustrate the effect of different antenna types and telemetry modules on communication indicators under radio-electronic warfare conditions. **Figure 2.1** shows the directivity patterns of the omni, Patch, and Yagi antennas, reflecting the differences in their radiation characteristics. In **Figure 2.2**, a decrease in RSSI is observed for the RFD900, LoRa 433 MHz, and NRF24L01 modules as the distance increases. **Figures 2.3 and 2.4** present the

comparison of Path Loss and Effective SNR indicators for different antennas. The analysis shows that, compared with the omni antenna, the Patch and especially the Yagi antennas provide a higher signal level, lower path loss, and a more favorable effective signal-to-noise ratio. This indicates that directional antennas are more efficient in improving the stability of telemetry and control systems.

### Conclusion

The conducted research and comparative tests confirmed that antenna parameters have a significant effect on the reliability of telemetry and control systems of unmanned aerial vehicles under radio-electronic warfare conditions. As a result of the evaluations carried out at distances of 50 m, 100 m, and 150 m, it was determined that, as the distance increases, RSSI decreases for all modules, Path Loss increases, and the SNR and Effective SNR indicators deteriorate. Nevertheless, the obtained results showed that, compared with the omni antenna, the Patch and especially the Yagi antennas provided a higher received signal level, lower path loss, and more stable communication indicators under REW conditions. Based on these results, it was determined that directional antennas are more advantageous in terms of protecting the telemetry channel.

During the tests, the RFD900 module showed relatively stable results at longer distances, the LoRa 433 MHz module demonstrated moderate stability, while in the NRF24L01 module attenuation was observed more rapidly in accordance with the high-frequency band. This shows that the selection of the antenna type should be evaluated together with the operating frequency of the module.

Thus, the purposeful selection and optimization of antenna parameters can be considered one of the main technical conditions for increasing the reliability of UAV communication systems under radio-electronic warfare conditions.

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