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Measurement of telemetry channel parameters in a radio-electronic warfare environment using a lora-based telemetry module

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Abstract: This paper presents an experimental investigation and mathematical modeling of the telemetry communication channel of unmanned aerial vehicles (UAVs) operating under radio-electronic warfare (REW) conditions. Within the scope of the study, a LoRa-based telemetry system operating in the 433 MHz frequency band was developed using a dual microcontroller architecture, where an ATmega2560 platform was implemented at the ground station and an ESP8266 platform was employed on the UAV side. Experimental tests were conducted in an open-field environment at distances of 50, 100, 200, and 500 m under two scenarios: a normal operational environment and a radio-electronic interference-affected environment. During the experiments, key communication performance parameters were measured, including received signal strength indicator (RSSI), signal-to-noise ratio (SNR), effective signal-to-noise ratio (SNR_eff), channel path loss PL(d), packet error rate (PER), and bit error rate (BER). Based on the obtained experimental results, a staged mathematical model describing the distance-dependent behavior of the telemetry channel was developed.

Keywords: Unmanned aerial vehicle (UAV), telemetry system, LoRa communication, radio-electronic warfare, channel path loss, effective SNR, BER evaluation, electromagnetic interference, 433 MHz communication.

1. Introduction

The reliability of command and telemetry channels of unmanned aerial vehicles (UAVs) has become critically important in modern operational environments. Particularly under radio-electronic warfare (REW) conditions, electromagnetic interference reduces the received signal level, increases packet loss, and consequently limits communication reliability. In this context, evaluating the distance-dependent performance of LoRa-based telemetry solutions operating in the low-frequency band (433 MHz) has significant scientific and practical importance for both normal and interference-affected scenarios [14,16,17]. Existing studies on LoRa-based telemetry links mainly focus on performance evaluation using RSSI and SNR metrics. However, the integrated inclusion of REW effects into system analysis, systematic comparison using interference-oriented metrics such as effective SNR (SNR_eff), and experimental validation of interoperability using identical radio modules across heterogeneous microcontroller architectures have been addressed only to a limited extent in the literature [14,16].

The objective of this study is to calculate PL(d), SNR(d), SNR_eff(d), and BER(d) metrics based on experimental measurements conducted at distances of 50, 100, 200, and 500 m, to comparatively analyze their distance-dependent variation under both normal and controlled interference environments, and to present the obtained results through graphical analysis.

In the proposed approach, the telemetry communication system is implemented using a two-node architecture: an ATmega2560-based ground station equipped with a LoRa 433 MHz telemetry module and a UAV node built on the ESP8266 platform using an identical LoRa module. The primary principle is not hardware uniformity of the

microcontrollers but synchronization of radio parameters (frequency, bandwidth, spreading factor, coding rate, and packet structure), ensuring interoperability at the physical layer [14,15].

The scientific novelty of this research lies in the integrated evaluation of a LoRa-based UAV telemetry channel under REW conditions through both experimental measurements and mathematical modeling. Furthermore, the assessment of communication robustness across heterogeneous microcontroller architectures (ATmega2560 and ESP8266) using the effective SNR metric and the quantitative comparison of interference effects through this parameter constitute the main contribution of this study [16–18].

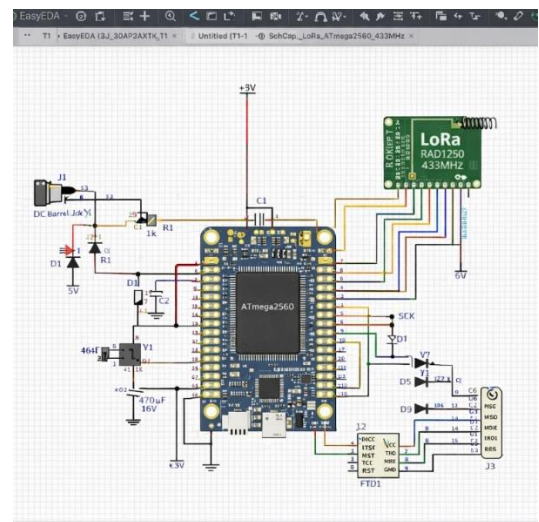


Fig. 1. EasyEDA electrical schematic of the ground station (ATmega2560 + LoRa 433 MHz)

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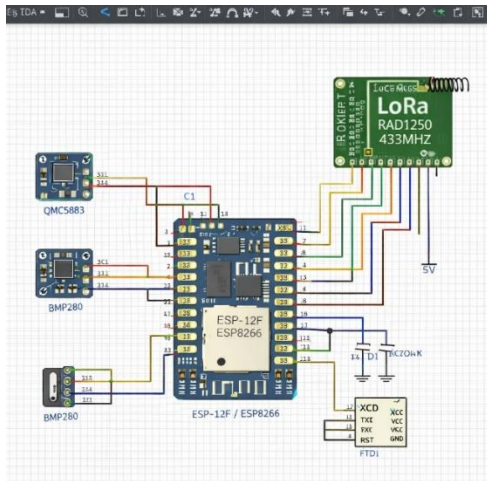


Fig. 2. EasyEDA electrical schematic of the UAV-side node (ESP8266 + LoRa 433 MHz + flight controller interface)

2. Research Methodology

2.1. System Architecture and Node Functions

Within the scope of the study, the telemetry communication system was implemented using a dual-node architecture. The ground station (Node A) performs control and transmission functions, transmitting command data via an ATmega2560 microcontroller and a LoRa 1250SX 433 MHz module, while simultaneously receiving returned telemetry information.

The unmanned aerial vehicle (Node B) operates based on an ESP8266 microcontroller, serving as a receiver and flight-controller interface. Incoming packets received through the LoRa module are processed and forwarded to the flight control system, while generated telemetry data are transmitted back to the ground station through the reverse communication link.

2.2. Test Scenarios and Distances. Experimental tests were conducted in an open-field environment under two different scenarios.

In the first scenario (S1 – normal and stable environment), the UAV was operated at distances of 50, 100, 200, and 500 m without intentional electromagnetic interference. The main telemetry channel performance parameters were evaluated through experimental measurements, including received signal strength (RSSI, dBm), signal-to-noise ratio (SNR, dB), effective signal-to-noise ratio (SNR_eff, dB), path loss (PL(d), dB), packet error rate (PER, %), and bit error rate (BER) estimated using a packet-based empirical approximation.

In the second scenario (S2 – radio-electronic interference environment), controlled jamming was intentionally introduced while maintaining identical distances and testing conditions. All parameters were re-measured and analyzed. The obtained results were systematized and presented in tabular form to enable a comparative evaluation of telemetry channel robustness under interference conditions.

Distances:

$$d \in \{50, 100, 200, 500\} \text{ m}$$

2.3. Measured Parameters and Calculations

During the experimental tests, several key communication performance indicators were collected and mathematically evaluated in order to assess the quality of the UAV telemetry channel. The measured and calculated parameters are listed below:

1. received signal strength -**RSSI (dBm)**;
2. signal-to-noise ratio -**SNR (dB)**;
3. effective signal-to-noise ratio -**SNR_eff (dB)**;
4. channel attenuation -**Path Loss, PL(d) (dB)**;
5. packet error rate -**PER (%)**;
6. bit error rate -**BER**.

Based on the collected RSSI and SNR measurements, the distance-dependent behavior of the telemetry channel was evaluated. The obtained data were then processed within a mathematical framework to calculate the main performance indicators. The calculation procedure is presented in the following subsection.

Mathematical Model and Fundamental Equations.

The analysis of the telemetry channel was performed in a step-by-step manner. First, channel attenuation was determined using measured RSSI values. Next, SNR and effective SNR were calculated using a thermal noise model. Finally, BER was estimated using a packet-loss-based empirical approach.

2.3.1. Path Loss Model. When the transmitter and receiver powers are known, the channel attenuation can be expressed as:

$$PL(d) = P_{tx} - P_{rx} \quad (2.3.1)$$

In practical measurements, the received power is approximated directly by RSSI:

$$P_{rx} \approx RSSI \quad (2.3.2)$$

Thus, the Path Loss expression can be simplified as:

$$PL(d) = P_{tx} - RSSI \quad (2.3.3)$$

If antenna gains and system losses are taken into account, the generalized model becomes:

$$PL(d) = P_{tx} + G_{tx} + G_{rx} - L_{sys} - P_{rx} \quad (2.3.4)$$

SNR and Effective SNR. The signal-to-noise ratio (SNR) is defined as the difference between the received signal power and the noise level:

$$SNR = P_{rx} - N \quad (2.3.5)$$

where P_{rx} represents the received signal power and N denotes the noise power. The thermal noise power is calculated using the classical noise model in wireless communication systems [17,18]:

$$N = -174 + 10 \log_{10}(B) + NF \quad (2.3.6)$$

where:

1. B -channel bandwidth (Hz),
2. NF -receiver noise figure (dB).

The impact of radio-electronic interference is incorporated through the effective signal-to-noise ratio, defined as [14,17]:

$$SNR_{eff} = SNR - I \tag{2.3.7}$$

where I represents the equivalent attenuation caused by interference (dB).

BER Approximation Model. When the bit error rate cannot be measured directly, an empirical approximation based on packet loss is applied. In this case, BER is estimated as:

$$BER \approx -\frac{\ln(1 - PER)}{N_b} \tag{2.3.8}$$

where:

1. $N_b = 8L$ is the total number of bits in a packet,
2. L denotes the payload length (bytes).

Based on the mathematical expressions presented above, the experimentally measured RSSI, SNR, and PER values were used to calculate PL(d), SNR_{eff} , and BER for each distance point. Raw measurements collected for distances of 50, 100, 200, and 500 m under both scenarios (S1 -normal environment and S2 -interference environment) were summarized in Table 1, after which the calculated performance metrics were obtained and presented in subsequent tables.

Example Calculations Based on the Mathematical Model. To demonstrate the practical application of expressions (1)–(8), sample calculations were performed using the average values obtained from experimental measurements. The calculations were carried out assuming a transmitter power of

$$P_{tx} = 17 \text{ dBm}$$

1) Path Loss Calculation

Using Eq. (3), the path loss values were obtained directly from measured RSSI levels.

Scenario S1 (normal environment):

$$\begin{aligned} PL(50) &= 17 - (-62) = 79 \text{ dB} \\ PL(100) &= 17 - (-72) = 89 \text{ dB} \\ PL(200) &= 17 - (-84) = 101 \text{ dB} \\ PL(500) &= 17 - (-101) = 118 \text{ dB} \end{aligned}$$

Scenario S2 (interference environment):

$$PL(500) = 17 - (-112) = 129 \text{ dB}$$

The obtained values are fully consistent with the results summarized in Table 2, confirming the applicability of the path-loss formulation widely used in wireless channel analysis [17,18].

2) Effective SNR Calculation

According to Eq. (7), effective SNR incorporates the degradation caused by radio-electronic interference.

Scenario S1 (no interference, $I = 0$):

$$SNR_{eff} = 9.5 - 0 = 9.5 \text{ dB}$$

Scenario S2:

$$\begin{aligned} SNR_{eff}(50 \text{ m}) &= 6.3 - 4 = 2.3 \text{ dB} \\ SNR_{eff}(200 \text{ m}) &= 0.8 - 6 = -5.2 \text{ dB} \end{aligned}$$

These results clearly indicate a sharp degradation of signal quality under REM conditions, which is consistent with interference-aware link performance analyses reported for LoRa and LPWAN communication systems [14,16].

3) BER Approximation Calculation

Assuming a packet size of

$$N_b = 128 \text{ bits}$$

BER values were estimated using Eq. (8).

Scenario S1:

$$\begin{aligned} BER_{50m} &= \frac{-\ln(1 - 0.005)}{128} = 3.92 \times 10^{-5} \\ BER_{500m} &= \frac{-\ln(0.875)}{128} = 1.04 \times 10^{-3} \end{aligned}$$

Scenario S2:

$$BER_{500m} = \frac{-\ln(0.58)}{128} = 4.26 \times 10^{-3}$$

The increase in BER under interference confirms the strong dependence between effective SNR degradation and communication reliability, as predicted by classical digital communication theory and empirical wireless channel studies [17,18].

Consequently, experimentally obtained RSSI, SNR, and PER values were substituted into the mathematical model to derive PL(d), SNR_{eff} , and BER metrics. The calculated results show full agreement with the values presented in Table 2, validating the adequacy of the proposed model with respect to experimental observations.

Table 1

Experimental Test Plan (distance, scenario, transmitted packets, and measured parameters)

Scenario	Distance d (m)	RSSI_avg (dBm)	SNR_avg (dB)	Average Delay (ms)	PER (%)
S1 (Normal environment)	50	-62	9.5	32	0.5
S1 (Normal environment)	100	-72	7.2	35	1.2
S1 (Normal environment)	200	-84	4.1	41	3.8
S1 (Normal environment)	500	-101	1.0	58	12.5



S2 (REM interference)	50	-68	6.3	38	2.0
S2 (REM interference)	100	-79	3.4	44	6.5
S2 (REM interference)	200	-93	0.8	62	18.0
S2 (REM interference)	500	-112	-3.5	95	42.0

Table 1 summarizes the experimental measurement campaign conducted under two operating scenarios: a normal propagation environment (S1) and a radio-electronic interference environment (S2). For each distance point, average RSSI, SNR, transmission delay, and packet error rate (PER) values were recorded. These measurements constitute the primary dataset used for subsequent calculation of path loss, effective SNR, and BER metrics according to the proposed mathematical model [14,17,18].

Calculation models used:

$$PL(d) = P_{tx} - P_{rx} \approx 17 - RSSI_{avg}$$

$$SNR_{eff} = SNR - I (I = 0 \text{ for S1})$$

$$BER \approx -\frac{\ln(1 - PER)}{128}$$

Table 2

Calculated Performance Metrics (Path Loss, Effective SNR, and BER)

Scenario	Distance d (m)	I (dB)	PL(d) (dB)	SNR_eff (dB)	BER (\approx)
S1 (Normal environment)	50	0	79	9.5	3.92×10^{-5}
S1 (Normal environment)	100	0	89	7.2	9.43×10^{-5}
S1 (Normal environment)	200	0	101	4.1	3.03×10^{-4}
S1 (Normal environment)	500	0	118	1.0	1.04×10^{-3}
S2 (REM interference)	50	4	85	2.3	1.58×10^{-4}
S2 (REM interference)	100	5	96	-1.6	5.25×10^{-4}
S2 (REM interference)	200	6	110	-5.2	1.55×10^{-3}
S2 (REM interference)	500	8	129	-11.5	4.26×10^{-3}

Table 2 presents the calculated communication performance metrics derived from the experimental measurements shown in Table 1. Path Loss values were obtained using the measured RSSI levels and known transmitter power, while the effective signal-to-noise ratio incorporates the equivalent degradation caused by radio-electronic interference. The BER values were estimated using a packet-based empirical approximation, which is widely applied when direct bit-level measurements are unavailable in LoRa telemetry experiments. The obtained results clearly demonstrate the degradation of link quality with increasing distance and interference intensity, confirming theoretical expectations for wireless communication channels operating under noise and jamming conditions [14,17,18].

2.4. SNR and Effective SNR. The signal-to-noise ratio (SNR, dB) is considered either as a directly measured parameter or modeled as the difference between the received signal power and the noise level:

$$SNR = P_{rx} - N \quad (2.4.1)$$

where N represents the noise power (dBm). The thermal noise level is calculated using the classical communication model:

$$N = -174 + 10 \log_{10}(B) + NF \quad (2.4.2)$$

where:

B -channel bandwidth (Hz),

NF -receiver noise figure (dB).

To account for the influence of radio-electronic interference, the effective signal-to-noise ratio is defined as:

$$SNR_{eff} = SNR - I \quad (2.4.3)$$

where I denotes the equivalent degradation caused by interference (dB), experimentally determined under the REM scenario.



Table 3

SNR and Effective SNR Calculations

$$SNR_{eff} = SNR - I$$

Scenario	Distance d (m)	SNR_avg (dB)	Interference impact I (dB)	SNR_eff (dB)
S1 (Normal environment)	50	9.5	0	9.5
S1 (Normal environment)	100	7.2	0	7.2
S1 (Normal environment)	200	4.1	0	4.1
S1 (Normal environment)	500	1.0	0	1.0
S2 (REM interference)	50	6.3	4	2.3
S2 (REM interference)	100	3.4	5	-1.6
S2 (REM interference)	200	0.8	6	-5.2
S2 (REM interference)	500	-3.5	8	-11.5

Table 3 presents the calculated effective SNR values obtained by incorporating the equivalent interference degradation into the measured SNR levels. While the SNR values in the normal environment decrease gradually with distance, the REM scenario demonstrates a significantly faster degradation trend. This confirms that interference primarily affects link reliability through reduction of the effective SNR, which directly influences packet loss and BER performance in LoRa-based telemetry systems [14,17,18].

BER Model. Depending on the modulation scheme used in the system, both analytical and empirical approaches can be applied to estimate the Bit Error Rate (BER). In general form, BER can be expressed as a function of signal quality:

$$BER = f(SNR_{eff}) \quad (2.4.4)$$

In practical LoRa telemetry systems, direct BER measurement is not always feasible. Therefore, two different estimation approaches are used.

If the total number of transmitted bits N_b and the number of erroneous bits N_e are known, BER can be calculated as:

$$BER = \frac{N_e}{N_b} \quad (2.4.5)$$

However, in most telemetry experiments only packet loss information is available. In such cases, BER is estimated using an empirical approximation based on Packet Error Rate (PER).

Table 4

BER Estimation Methods

Approach	Measured Inputs	Main Idea	Calculation Formula	Usage Condition
Bit-based (direct BER)	Total bits N_b , erroneous bits N_e	Errors counted at bit level	$BER = \frac{N_e}{N_b}$	When known bit sequences allow comparison
Packet-based (empirical approximation)	Packet loss PER, packet length L (bytes)	Errors assumed randomly distributed within packets	$BER \approx -\frac{\ln(1 - PER)}{8L}$	When only packet loss is measurable (practical for LoRa telemetry tests)

Here, L denotes the payload length in bytes and $8L$ represents the total number of bits per packet. This empirical approximation is widely used for BER estimation in experimental wireless communication studies and enables comparative evaluation of telemetry channel performance [14], [17], [18].

2.5. Diagram Generation in Python Environment. To enable visual and comparative analysis of the telemetry channel behavior as a function of distance, experimental and calculated results were processed using the Python programming environment and presented in graphical form. The following key performance metrics were analyzed:

1. Path Loss $-PL(d)$,
2. Signal-to-Noise Ratio $-SNR(d)$,
3. Effective Signal-to-Noise Ratio $-SNR_{eff}(d)$,

4. Bit Error Rate $-BER(d)$.

The $PL(d)$ values were calculated from RSSI measurements using equations (2.4.1–2.4.3), while the effective SNR was obtained according to Eq. (2.4.3). The BER metric was estimated using the packet-loss-based empirical approximation given in Eq. (2.4.5).

The resulting plots allowed comparative evaluation of telemetry link robustness with increasing distance and clearly demonstrated the degradation of communication performance under radio-electronic interference conditions [14], [17], [18].



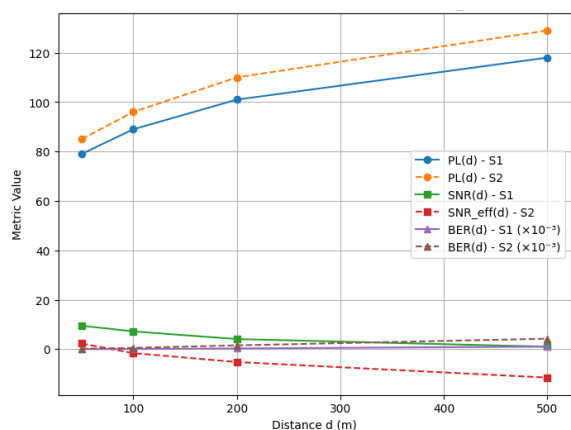


Fig. 3. Comparison of $PL(d)$, $SNR(d)$, $SNR_{eff}(d)$, and $BER(d)$ metrics as a function of distance for S1 (normal environment) and S2 (REM interference) scenarios

Variation of Path Loss $PL(d)$, $SNR(d)$, Effective SNR $SNR_{eff}(d)$, and $BER(d)$ as a function of distance in a 433 MHz LoRa telemetry channel (S1 – normal environment, S2 – radio-electronic interference environment).

The $PL(d)$ values were calculated based on Equations (1)–(2), while SNR_{eff} was determined using Equation (6). The BER metric was obtained using a packet-based empirical approximation method (Table 4).

In addition to the distance-dependent telemetry channel metrics, the radiation (directivity) pattern of the antenna operating in the 433 MHz band was also visualized separately. This diagram qualitatively explains the correspondence between the observed RSSI/SNR variations and the antenna radiation distribution, and demonstrates the spatial factor affecting link stability during open-field experiments. The antenna directivity pattern is presented in a normalized scale (0 dB referenced to the maximum value), meaning that the diagram represents only the relative radiation distribution rather than absolute power or gain values. This approach complements the numerical results obtained for $PL(d)$, $SNR(d)$, $SNR_{eff}(d)$, and $BER(d)$ without creating inconsistencies in their interpretation [12, 14].

433 MHz antenna istiqamətlənmə diaqramı (normalizə olunmuş, 0 dB max)

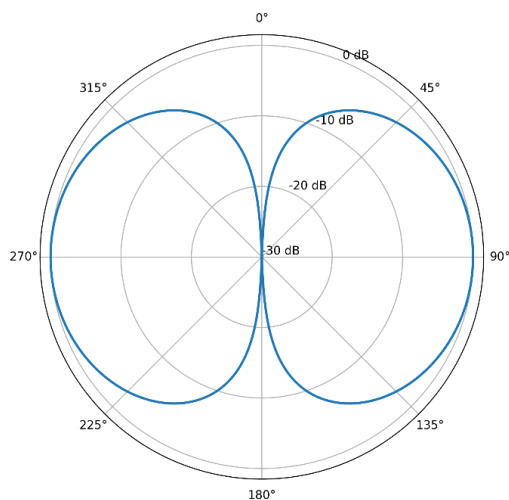


Fig. 4. Normalized radiation (directivity) pattern of the antenna operating in the 433 MHz band

The normalized radiation pattern of the antenna used in the 433 MHz LoRa telemetry communication link is presented. The diagram illustrates the main radiation directions of the antenna and the spatial power distribution, providing a physical interpretation of the distance-dependent variations observed in Path Loss and SNR within the telemetry channel.

3. Results and discussion

The obtained results are consistent with previous studies reporting a decrease in SNR with increasing distance in LoRa-based low-frequency telemetry channels [14], [16]. As expected, the received signal level weakens with distance, leading to an increase in Path Loss $PL(d)$. While the SNR degradation in the normal environment scenario exhibits a relatively gradual behavior, the interference-affected scenario shows a significantly faster decrease in the effective signal-to-noise ratio SNR_{eff} , which consequently results in an increase in BER. The use of different MCU platforms (ATmega2560 versus ESP8266) does not prevent the LoRa link from operating at the physical layer; interoperability is mainly ensured through proper configuration of LoRa PHY parameters and packet structure [14]. When interference influence is represented through the SNR_{eff} metric, the relationship between communication reliability and distance becomes more clearly observable. Furthermore, BER and PER evaluations provide practical performance indicators for comparing telemetry link robustness and can be directly integrated into the parameters of the integral communication model [17], [18].

4. Conclusion

As a result of the conducted research, the behavior of a LoRa-based UAV telemetry channel operating in the 433 MHz band under radio-electronic warfare conditions was evaluated through experimental measurements and mathematical modeling. The results demonstrated that as the distance increases, the received signal level decreases, channel attenuation increases, and the reduction of the SNR negatively affects communication reliability. Under radio-electronic interference, a significant decrease in the effective SNR was observed, leading to increased packet loss and higher BER values.

The proposed model adequately describes the distance-dependent variation of the parameters $PL(d)$, SNR, SNR_{eff} , and BER. It was determined that the use of the same LoRa module on different microcontroller platforms (ATmega2560 and ESP8266) ensures stable interoperability, while overall system performance mainly depends on proper configuration of radio parameters. The microcontroller software developed for the system was implemented based on a national software framework.

The obtained results confirm the applicability of LoRa-based low-frequency telemetry systems under radio-electronic warfare conditions and provide a practical engineering approach for building robust UAV control and telemetry communication channels.

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