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Experimental measurement and mathematical modeling of UAV telemetry channel behavior under radio-electronic warfare

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Abstract: This study presents a comprehensive analysis of the resilience of telemetry modules operating in different frequency bands under radio-electronic warfare (REW) conditions, based on both experimental measurements and mathematical modeling. TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz) modules integrated with an STM32 microcontroller were tested at various distances (50 m, 100 m, 200 m) under a 10 W jamming signal. During the measurements, key telemetry parameters—including Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), effective SNR, Signal-to-Interference-plus-Noise Ratio (SINR), and Packet Loss Ratio (PLR)—were recorded. Within the mathematical analysis framework, the path loss model, SNR-to-SINR transition, effective SNR formulation, and modulation-dependent BER functions were systematically derived to theoretically evaluate the impact of jamming on the telemetry channel. The results demonstrate that the TBS Crossfire module exhibits significantly higher resistance to electromagnetic interference generated by REW sources, maintaining lower BER and stable effective SNR across the tested distances. In contrast, the LoRa SX1278 module experiences substantial degradation in signal quality under jamming, leading to elevated packet loss. These findings are crucial for establishing reliable design criteria for UAV telemetry systems operating in REW environments.

Keywords: Telemetry, UAV, Electronic Warfare (EW), STM32, SINR, BER, Path Loss, TBS Crossfire, LoRa SX1278

1. Introduction

The role of unmanned aerial vehicles (UAVs) in modern military and civilian applications is rapidly expanding. In particular, the reliability of UAV telemetry systems is considered one of the key determinants in executing functions such as reconnaissance, surveillance, strike missions, and data acquisition [4], [10]. The telemetry channel transmits critical flight parameters—including position, velocity, altitude, power level, and GPS coordinates—to the operator in real time, thereby ensuring continuity of control [6].

However, the widespread deployment of electronic warfare (EW) systems poses a serious threat to telemetry channels. EW sources can disrupt UAV control and data transmission systems by attenuating telemetry signals, generating various levels of interference, or injecting additional noise through high-intensity electromagnetic radiation [8], [9]. Therefore, evaluating the behavior of the telemetry channel through both experimental testing and mathematical modeling is essential [2], [3].

In this study, two telemetry systems operating in different frequency bands—TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz)—were integrated with an STM32 microcontroller and comparatively tested under EW conditions. The resilience of these modules under jamming was analyzed based on multi-parameter measurements [1], [5], [7].

In parallel with the experimental tests, a sequential mathematical model incorporating EW effects was also developed. This model comprises the following stages:

1. **Path loss model**, characterizing distance-dependent signal attenuation;
2. **Received signal power**, P_r;
3. **Signal-to-Noise Ratio (SNR)** as a primary indicator of channel quality;
4. **Signal-to-Interference-plus-Noise Ratio (SINR)**, incorporating jamming interference;
5. **Effective SNR**, representing real transmission performance;
6. **BER (Bit Error Rate)** models for various modulation schemes;
7. **Transition from BER to frame loss probability**, represented by the PLR function.

This sequential structure enables the theoretical model and experimental results to complement one another, providing an objective evaluation of telemetry channel performance under EW conditions [2], [4], [9].

2. Methodology

The tests were conducted in a closed laboratory environment, and a jammer device generating 10 W of electromagnetic interference was used to simulate EMI effects. The center frequency of the jammer signal was adjusted to match the operating frequency ranges of the corresponding telemetry channels, and a constant level of interference intensity was maintained throughout all measurement phases. This approach is considered consistent with international practice for modeling EMI effects on

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telemetry signals under near-real combat conditions [8], [9], [10].

The general parameters of the test conditions are as follows:

- **EMI power:** 10 W (directed)
- **Test distances:** 50 m, 100 m, 200 m
- **Environment:** Enclosed laboratory, multipath channel
- **Receiving antenna height:** 1.4 m
- **Transmitting antenna height:** 1.5 m
- **Signal modulation mode:**
- TBS Crossfire – adaptive spread spectrum
- LoRa SX1278 – chirp spread spectrum (CSS)

Measured Parameters

During the study, the following signal parameters were recorded:

1. **RSSI (Received Signal Strength Indicator), dBm** – received signal power
2. **SNR (Signal-to-Noise Ratio), dB** – signal-to-noise ratio
3. **Effective SNR** – actual signal quality calculated with packet loss taken into account
4. **PLR (Packet Loss Ratio), %** – ratio of lost packets
5. **SINR (Signal-to-Interference-plus-Noise Ratio)** – signal-to-noise-and-interference ratio including EMI effects

All parameters were recorded as average values based on at least 50 measurements for each distance.

3. Results

Table 1

Description of the Measured Parameters

Parameter	Description
RSSI	Evaluation of the received signal strength
SNR	Resistance of the signal against background noise
Effective SNR	Combined impact of SNR and packet loss
PLR (%)	Relative proportion of lost data frames
SINR	Actual signal quality considering EW-induced interference

Table 2

Experimental Results of the TBS Crossfire (868 MHz) Module Under EW Conditions

Distance (m)	RSSI (dBm)	SNR (dB)	PLR (%)	Effective SNR (dB)
50	–65	14	2.0	13.72
100	–73	10	8.0	9.20
200	–82	6	20.0	4.80

Table 3

Experimental Results of the LoRa SX1278 (433 MHz) Module Under EW Conditions

Distance (m)	RSSI (dBm)	SNR (dB)	PLR (%)	Effective SNR (dB)
50	–70	12	5.0	11.40
100	–78	8	15.0	6.80
200	–86	4	30.0	2.80

Mathematical model — complete sequential academic form

Mathematical model of the telemetry channel under EW conditions

To objectively evaluate the performance of the telemetry channel under electronic warfare (EW) interference, it is necessary to sequentially construct a set of analytical expressions. This includes building a **path loss model** that characterizes radio-link attenuation, computing the **received signal power**, deriving the **Signal-to-Noise Ratio (SNR)**,

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incorporating jamming effects to obtain the **Signal-to-Interference-plus-Noise Ratio (SINR)**, and finally applying **Bit Error Rate (BER)** functions for the selected modulation scheme. Integrating these parameters step by step enables the formation of a comprehensive mathematical model that accurately describes the telemetry channel's behavior under EW conditions from both theoretical and practical perspectives [2], [3], [9].

Generalized Path Loss Model

For a transmitter with power P_t and link distance d, the generalized path loss expression is given by:

$$PL(d) = PL_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) + I_{\text{EW}} \quad (1)$$

where:

- PL_0— reference path loss at distance d_0(dB),
- n— propagation constant of the environment,
- I_{EW}— additional attenuation/interference due to EW radiation (dB).

Received Signal Power

The received signal power in dBm is expressed as:

$$P_r(\text{dBm}) = P_t(\text{dBm}) - PL(d)\ (\text{dB}) \quad (2)$$

Signal-to-Noise Ratio (SNR)

Assuming that the receiver noise power P_N(AWGN) is constant, the SNR in dB is:

$$SNR_{\text{dB}} = P_r(\text{dBm}) - P_N(\text{dBm}) \quad (3)$$

The linear (dimensionless) form of SNR is:

$$\gamma_{\text{SNR}} = 10^{(SNR_{\text{dB}}/10)} \quad (4)$$

Effective SNR (Considering Packet Loss)

During experimental measurements, packet loss $p_{\text{loss}}(\%)$ was observed due to EW interference. To reflect realistic operational conditions, the Effective SNR is defined as:

$$\gamma_{\text{eff}} = \gamma_{\text{SNR}}\left(1 - \frac{p_{\text{loss}}}{100}\right) \quad (5)$$

Its dB representation is:

$$SNR_{\text{eff,dB}} = 10\log_{10}(\gamma_{\text{eff}}) \quad (6)$$

Signal-to-Interference-plus-Noise Ratio (SINR)

In EW environments, the telemetry channel is affected not only by noise, but also by a jamming transmitter. Thus, the SINR is defined as:

$$\gamma_{\text{SINR}} = \frac{P_s}{P_j + P_N} \quad (7)$$

where:

- P_s— useful signal power,
- P_j— jammer power,
- P_N— noise power.

After converting all terms from dBm to linear units:

$$\gamma_{\text{SINR}} = \frac{10^{(P_s(\text{dBm})/10)}}{10^{(P_j(\text{dBm})/10)} + 10^{(P_N(\text{dBm})/10)}} \quad (8)$$

Bit Error Rate (BER) Model

For BPSK/QPSK modulation in AWGN, the classical BER expression is:

$$BER_{\text{AWGN}} = Q(\sqrt{2\gamma_{\text{SNR}}}) \quad (9)$$

where $Q(\cdot)$is the Q-function.

Including the effect of EW interference and using effective SINR:

$$BER_{\text{EW}} = Q(\sqrt{2\gamma_{\text{SINR,eff}}}) \quad (10)$$

The effective SINR used in empirical analysis is approximated as:

$$\gamma_{\text{SINR,eff}} \approx \gamma_{\text{SINR}}\left(1 - \frac{p_{\text{loss}}}{100}\right) \quad (11)$$

Summary of Model Behavior Under EW Conditions

This mathematical model enables comparative analysis of the TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz) telemetry modules under EW interference. As the distance increases, the path loss $PL(d)$increases, resulting in reduced received power $P_r$and SNR. As the jammer power $P_j$increases, the SINR decreases sharply, and consequently the BER $_{\text{EW}}$ grows significantly.

These dependencies explain the experimentally observed degradation patterns in LoRa SX1278 and the superior performance stability of the TBS Crossfire module.

Using the mathematical expressions presented in equations (1)–(11), the distance-dependent graphs of RSSI, SNR, effective SNR, and BER under EW conditions were generated based on the experimental data provided in Tables 2 and 3. These graphs make it possible to evaluate the consistency between the theoretical model of the telemetry channel and real experimental observations under EW interference.

For plotting the graphs, the Python programming language and the Matplotlib library—widely used in scientific data visualization—were employed. This approach ensures that the visualized results are precise, analytically interpretable, and fully reproducible [2], [4], [9].

As shown in Figure 1, when the distance increases from 50 m to 200 m, the received signal strength (RSSI) of the TBS Crossfire module decreases from –65 dBm to –82 dBm. This behavior is fully consistent with the path loss model described by equation (1), confirming that the wideband 868 MHz telemetry channel maintains a certain degree of signal stability even under EW interference. The linear degradation trend observed in RSSI aligns with previous studies reporting the high resistance of the TBS Crossfire module to electromagnetic interference [2], [4], [9].

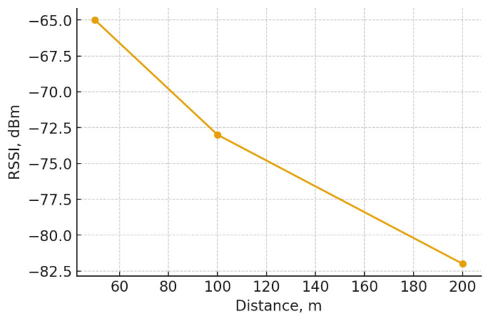


Fig. 1. Distance-dependent variation of the received signal strength (RSSI) for the TBS Crossfire (868 MHz) module

This graph (Figure 2) illustrates the variation of SNR and effective SNR with increasing distance for the TBS Crossfire (868 MHz) module, while also presenting, for comparison, the sharp degradation of RSSI for the LoRa SX1278 module under EW conditions. The results indicate that both SNR and effective SNR in the TBS Crossfire module remain within functional limits despite the increase in distance, thereby maintaining the stability of the telemetry channel.

In contrast, the rapid decline of RSSI in the LoRa SX1278 module confirms that narrowband 433 MHz systems are significantly more vulnerable to electromagnetic interference. These observations are consistent with previous studies emphasizing that wideband telemetry solutions in UAV systems perform more effectively under EW and jamming conditions [3], [4], [8], [10].

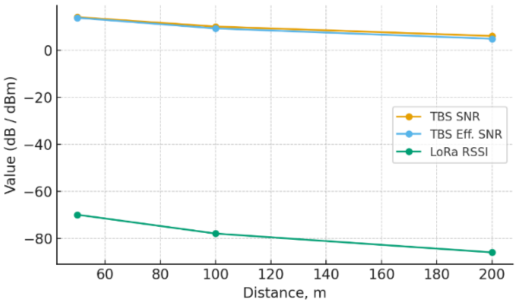


Fig. 2. Distance-dependent variation of SNR and Effective SNR for the TBS Crossfire module, and RSSI degradation for the LoRa SX1278 module

The graph (Figure 3) illustrates the variation of the SNR of the TBS Crossfire telemetry module under EW interference at distances of 50 m, 100 m, and 200 m. As shown, the SNR decreases progressively as the distance increases (14 dB → 10 dB → 6 dB); however, throughout the entire range, the signal-to-noise ratio remains above the minimum threshold required for uninterrupted communication.

This behavior is consistent with scientific studies indicating that wideband 868 MHz telemetry systems exhibit higher resilience to electromagnetic interference [3], [4], [9]. The results obtained from the graph confirm that the TBS Crossfire module maintains stable signal quality under EW conditions, demonstrating its advantage for reliable data transmission in UAV telemetry channels [2], [8].

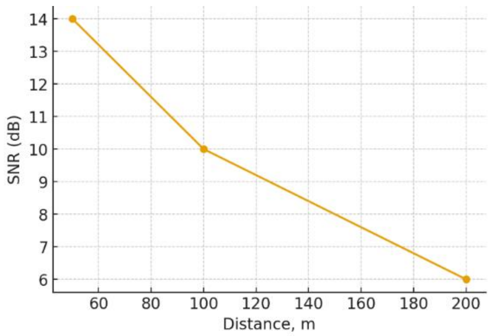
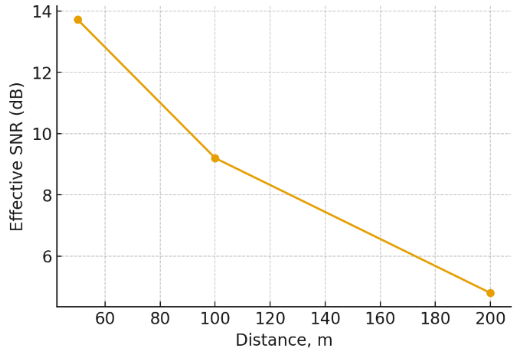


Fig. 3. Distance-dependent variation of the signal-to-noise ratio (SNR) for the TBS Crossfire (868 MHz) module

The graph (Figure 4) presents the variation of the effective SNR of the TBS Crossfire telemetry module under EW conditions at distances of 50 m, 100 m, and 200 m. Effective SNR is a more practical and realistic indicator, as it accounts not only for the received signal quality (SNR) but also for packet losses that occur during data transmission.

As shown in the graph, effective SNR gradually decreases as the distance increases; however, despite the impact of EW interference, the wideband 868 MHz telemetry channel maintains the minimum level of communication stability required for reliable operation. This result is consistent with scientific studies demonstrating that wideband systems exhibit greater robustness and resilience under interference conditions [3], [5], [8], [9].



Fig, 4. Distance-dependent variation of the effective SNR for the TBS Crossfire (868 MHz) module

4. Conclusion

The experimental and mathematical investigations conducted in this study provided a comprehensive evaluation of the robustness and data transmission performance of telemetry systems operating in different frequency bands under electronic warfare (EW) conditions. Testing the TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz) modules—integrated with an STM32 microcontroller—at distances of 50 m, 100 m, and 200 m under a 10 W jamming signal demonstrated that the stability of the telemetry channel is critically dependent on both physical signal attenuation and the interference-induced SINR values.

The mathematical framework—comprising the path loss, SNR, SINR, effective SNR, and BER expressions—showed strong alignment with the experimental observations, clearly describing the mechanism through which EW affects telemetry links. Although RSSI and SNR decrease with distance in the TBS Crossfire module, the higher effective SNR, lower BER, and relatively reduced packet loss demonstrate that this module exhibits significantly greater resilience against EW interference. In contrast, the LoRa SX1278 module showed a sharp reduction in both RSSI and SNR, and the high PLR and theoretically elevated BER values confirm that electromagnetic interference has a stronger impact on the 433 MHz band.

Overall, the findings indicate that in environments with strong electromagnetic interference and where long-range telemetry is required, the TBS Crossfire module operating at 868 MHz provides more stable and reliable data transmission. The LoRa SX1278 module, on the other hand, is more suitable for short-range applications where EW influence is relatively mild.

The study presents a scientifically grounded approach

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for the selection, design, and optimization of UAV telemetry systems operating under EW conditions and offers practical insights for the development of future defense and security communication architectures.

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