

ADAPTIVE MULTI-BAND DMR-BASED SYSTEM FOR DATA TRANSMISSION IN CIVIL DEFENCE MONITORING AND ALERTING

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The continuity of national civil defence warning systems requires resilient backup communication channels that remain operational under crisis conditions, including long-term evolution (LTE) outages and intentional interference. This work presents the design and evaluation of a narrowband digital mobile radio (DMR)-based backup system employing a novel multi-band software-defined radio (SDR) transceiver architecture. Unlike conventional fixed-band implementations, the proposed prototype integrates five parallel radio frequency (RF) chains (150 MHz, 430 MHz, 868 MHz, 1.2 GHz, and 2.4 GHz), each equipped with dedicated filtering and antennas, thereby enabling rapid band switching without hardware replacement. Experimental point-to-point tests over a 6 km line-of-sight link, combined with Monte Carlo interference simulations, demonstrate frequency-dependent performance trends and validate the resilience benefits of multi-band operation. A methodological contribution of this study is the equalization of effective isotropic radiated power (EIRP) across all channels using calibrated attenuators, which allows for fair cross-band comparison of metrics such as received signal strength indicator (RSSI), bit error rate (BER), and packet delivery ratio. The results confirm that very high frequency and ultra high frequency bands remain the most reliable foundation for long-range telemetry, while higher frequencies serve as auxiliary reserves. The proposed SDR-based multi-band approach enhances system survivability by enabling dynamic adaptation to spectrum congestion or electronic countermeasures, offering a practical and cost-efficient foundation for nationwide deployment of backup siren control networks.

Keywords: *Civil defence warning systems, backup communication channel, digital mobile radio (DMR), interference resilience, multi-band communication, narrowband telemetry, software-defined radio (SDR).*

1. INTRODUCTION

Ensuring the continuity of public warning systems during emergencies critically depends on resilient communications between the central control server and distributed siren controllers. As long as the primary long-term evolution (LTE) infrastructure is susceptible to disruption, a fully autonomous, radio-based backup network is necessary to ensure two-way command and status exchange with acceptable delays even under crisis conditions.

This article synthesizes system requirements, technology options, and an implementation scenario for a national-scale ultra high frequency (UHF) backup solution in Latvia, focusing on digital mobile radio (DMR) and terrestrial trunked radio (TETRA) as leading candidates.

Recent research on resilient communications for emergency services, critical infrastructure, and public safety has converged around three interrelated themes: (i) the application of software-defined radios (SDR) and digital mobile radio (DMR) systems in mission-critical networks, (ii) multi-band or frequency-agile communications systems (often employing cognitive radio, multi-waveform architectures or narrowband fallback links), and (iii) interference mitigation and adaptive channel or spectrum selection for robustness in degraded or contested environments.

Representative publications from 2019 to 2024 include several relevant studies. Rabbi (2025) proposed integrating a DMR trunking system into emergency grid control, demonstrating feasibility for critical infrastructure management [1]. ETSI TR 102 445 Technical Report (2023) outlined standards for emergency communications resilience [2]. Li et al. (2021) examined 5G new radio (NR) for public-safety mission-critical com-

munications (MCC) [3], while Wang et al. (2023) described hybrid emergency communication networks integrating narrowband and broadband solutions [4]. The study [5] explored narrowband interference mitigation using Welch algorithms, and Khadr et al. (2022) developed jamming-resilient multi-channel transmission for cognitive radio Internet-of-Things (IoT) networks [6]. Combes and Proutière (2014) provided theoretical foundations for dynamic channel selection [7], and the survey by Aygur et al. (2025) summarised narrowband interference mitigation methods [8]. Relevant contributions by V. Popov and A. Shevchenko include an analysis of standards and norms of electromagnetic irradiation levels in wireless communication systems (2019) [9]; a study on the electromagnetic compatibility of WiFi networks (2020) [10]; and an examination of EMC issues in GSM-R systems (2019) [11].

Despite these advances, most studies focus on LTE fallback or mesh networks rather than narrowband DMR/SDR architectures. No quantitative assessment of frequency-dependent link performance (PER, jitter) under equalized EIRP conditions has been documented. The present work fills this gap by providing empirical measurements and Monte Carlo modelling for a narrowband, multi-band DMR-based SDR telemetry system, demonstrating its robustness and adaptability for civil-defence backup communication.

Technology Selection Criteria are as follows:

- Functional objective: provide an independent, two-way backup channel between the central server and siren controllers that automatically assumes service when LTE is unavailable, with acceptable delays of seconds to tens of

seconds for small command/telemetry payloads.

- Topology and logic: Central server → central UHF controller → siren controllers over UHF, with automatic failover from LTE to UHF and return upon restoration.
- Radio domain: UHF band 300MHz–3GHz, with link distances up to ~64 km in line-of-sight conditions using elevated, appropriately selected antennas and, where needed, repeaters.
- Interfaces and manageability: RS-232, GPIO, and Audio/PTT at the UHF controller; Ethernet/LTE backhaul to the server; remote configuration, diagnostics, and logging via SNMP, MQTT, and HTTPS.
- Security and ruggedization: end-to-end encryption (preferably AES-256), device authentication, electromagnetic immunity, IP65+ enclosure rating, -30 °C...+60 °C operation, ≤95 % RH (non-condensing), DIN-rail/wall mount, 24 VDC with UPS.
- Interoperability: compatibility with professional terminals (e.g., Motorola, Kenwood) to enable standardized modulation and protocols, as well as possible operational access in emergencies.

A suitable backup network must be operator-independent and fully under institutional control, excluding reliance on public 4G/5G or subscription satellite services for the primary path in crisis scenarios. The solution must support two-way IP-capable transport (or IP packet carriage) with low-volume payloads and predictable latency while remaining robust to interference or deliberate jamming through appropriate physical-layer and cryptographic measures. Industrial-grade hardware meeting IP65,

extended temperature, EMC, and 24 VDC power/UPS requirements is mandatory for long-term field deployment.

Analogue FM links are simple and broadly interoperable, but lack native encryption, offer limited spectral efficiency, and provide only kilobit-class data rates via audio modems, making them a suboptimal baseline for secure control at scale. In contrast, digital standards – DMR and TETRA – deliver built-in security, group addressing, acknowledgments, and structured data services suitable for command-and-control; DMR uses 12.5 kHz with two TDMA slots (~9.6 kb/s gross), whereas TETRA uses 25 kHz with four slots (up to ~28.8 kb/s). Both have extensive public-safety and industrial pedigrees and enable reliable two-way signalling with low latency for small messages, including broadcast-group activation and per-device confirmations.

- LPWAN (LoRa and Related)
- LoRa in 868 MHz bands enables long-range, low-power links and low-cost private deployments, but throughput is extremely limited (roughly 0.3–50 kb/s depending on SF and bandwidth), downlink capacity is constrained, and synchronized, near-simultaneous group actuation across many endpoints is challenging in standard LoRaWAN classes. While siren controllers could operate as Class C nodes for continuous reception, duty-cycle limits and contention significantly complicate mass-command delivery, making LoRa better as a tertiary fallback for sparse, critical signalling rather than a primary backup for many endpoints. Security is available (AES-128 in LoRaWAN), but AES-256 would require application-layer additions, and interoperability with voice radios is not available.
- Broadband and Mesh (WiFi, MANET) and Private Cellular

- Long-range 802.11 point-to-point links and tactical MANET radios can provide IP broadband over tens of kilometres but demand precise RF engineering, greater power budgets, and substantially higher costs and complexity than required for low-rate siren control. Private LTE/5G can replicate carrier-grade IP, SIM-based security, and high throughput, yet spectrum access, EPC/eNodeB infrastructure, and cost render it disproportionate for a backup path with minimal data needs. Such broadband options may be justified only if the mission expands to include rich-media sensing (e.g., video), which lies outside the present functional scope.
- Recommendation Focus: DMR and TETRA
- Both DMR and TETRA meet the core requirements of two-way, secure, narrowband communications with group addressing and device acknowledgments, and both have proven records in public warning systems. TETRA provides more slots per carrier and richer trunking features, whereas DMR generally achieves wider area coverage per site and materially lower capital and operating costs for small-to-medium systems. Given the modest data volumes, the need for national coverage with limited sites, and budgetary realism, a DMR Tier II conventional architecture is the most proportionate primary backup, with TETRA as an alternative where integration with existing national TETRA infrastructure is feasible and administratively supported.

A proportionate national design employs a central DMR base/repeater connected to the control server over Ethernet/IP, plus a set of regionally sited repeaters on elevated masts or rooftops to ensure over-

lapping coverage across urban and rural areas. Siren controllers integrate a UHF DMR terminal with RS232 for application protocol exchange and an SMA-fed external antenna; devices operate in receive-ready standby, with unique IDs and shared/group AES keys provisioned centrally. Routine “heartbeat” tests verify readiness, and upon LTE loss, the server automatically switches to the UHF path, broadcasting encrypted activation commands to groups and collecting acknowledgments and status reports for logging and operator action.

- Planning and spectrum: coverage modelling, site selection, and application for UHF 12.5 kHz channels; choice of vendor platform and dispatcher/telemetry software.
- Procurement: DMR repeaters, antennas/feeder and surge protection, power systems, siren-end mobile radios/modules, server-side adapters and software licenses.
- Deployment: site works, antenna installation and grounding, RF/power integration, device programming (IDs, frequencies, groups, keys), and dispatcher integration via APIs or telemetry adapters.
- Testing and acceptance: over-the-air coverage verification, simulated LTE outage failover drills, end-to-end activation/acknowledgment timing, interference checks, and logging validation.
- Operations: personnel training, periodic drills, preventive maintenance, and monthly test activations on the backup channel during off-hours with full event retention for audit.

All traffic is end-to-end encrypted, devices are authenticated, and events are logged centrally with alerts on anomalous IDs or missing acknowledgments to detect spoofing or interference attempts. Equip-

ment selection adheres to IP65+ enclosures, extended temperature and humidity limits, EMC protections per EN 6100042/4/5, and 24 VDC with UPS to maintain service through power disruptions.

The control system under development is intended for operation in emergency conditions where the radio environment can be unpredictable. Therefore, a key requirement is stable operation of the communications channel even under elevated levels of interference. It should be noted that the frequency bands initially allocated for DMR (400–470 MHz) may become congested in real-world conditions due to intensive use by other services or even deliberate blocking. In such scenarios, the system must be able to quickly switch to alternative frequency ranges without loss of functionality.

The following backup and experimental bands are considered for establishing the communications channel:

- 150 MHz (VHF) – Offers greater range and resistance to attenuation, but requires larger, harder-to-pack antennas that are more vulnerable to mechanical damage.
- 430–450 MHz (UHF) – The standard band for DMR systems; a compromise between range and compactness.
- 868 MHz (ISM) – Convenient as a backup band because it is compatible with mass-produced modules and antennas, but subject to regulatory power limitations.

- 1.2 GHz (L-band) – Allows for relatively compact antennas and a good balance of range and throughput.
- 2.4 GHz (ISM) – The most readily available band with a wide choice of equipment and antennas, but primarily intended for broadband systems and heavily subject to interference from Wi-Fi, Bluetooth, and other technologies.

Thus, multi-band support in the control system will improve its resilience and survivability, enabling adaptation to the specific radio environment and ensuring transmission of critical telemetry even under adverse RF conditions.

It is also worth noting that when a band is flooded with broadband interference, a narrowband DMR signal may still succeed in getting through because its energy is concentrated in a narrow frequency slot. This gives it higher inherent resistance to broadband interference compared with wideband systems. Conversely, if an attempt is made to block a DMR channel using narrowband interference, the system must have a mechanism for rapid switching to an adjacent channel within the same band. If that channel is also blocked, transition to a different band is envisaged, which significantly increases the system's survivability and adaptability under electronic countermeasures.

In summary, a multi-band, frequency-reconfigurable architecture will allow the control system to remain operational even under intentional electronic suppression.

2. EXPERIMENTAL SETUP AND METHODOLOGY

A point-to-point architecture was selected to establish a ~6 km experimental radio link. The prototype of the multi-band DMR-based communication system was

implemented on an SDR transceiver combining a Xilinx Zynq-7020 SoC with an AD9363 RF front-end, covering all required frequency bands (Fig. 1).

System control and application logic were executed on a Raspberry Pi 4 running Ubuntu 22.04 LTS with GNU Radio. For remote access to one endpoint, an LTE modem was integrated, providing both backhaul connectivity and network aggregation.

As the DMR protocol requires strict time and frequency synchronization, a GPS-disciplined oscillator (GPSDO) was employed, supplying a 10 MHz reference and a 1 PPS timing signal to align TDMA slots.

The RF section was configured in a multi-band arrangement comprising five independent channels at 150 MHz, 430 MHz, 868 MHz, 1.2 GHz, and 2.4 GHz. Each channel was equipped with a dedicated antenna and matching chain, including:

- a T/R switch for separating transmit and receive paths;
- band-pass filters (BPF) optimised for each band;
- a matching attenuator in the transmit chain;
- a power amplifier (PA) with ~ 20 dB gain, providing up to +21 dBm output (~ 100 mW);
- a low-pass filter (LPF) for harmonic suppression and spectral compliance.

This configuration enables direct comparison of transmission performance across frequency bands under identical hardware conditions, ensuring reproducibility and consistent channel quality.

In addition to free-space path loss, every RF chain exhibits insertion losses introduced by filters, switches, cables, and other components. These losses increase with frequency due to higher conductor resistance (skin effect) and dielectric losses in RF materials. Since all frequency bands in our setup were implemented using an iden-

tical architecture, the differences in overall losses were primarily frequency-dependent. Approximate estimates of total attenuation from the PA output to the antenna (TX path) and from the antenna to the SDR input (RX path) are as follows:

- 150 MHz: RF components at this frequency introduce minimal losses. A wideband band-pass or low-pass filter contributes ~ 0.5 dB, while the SPDT switch and connectors add ~ 0.2 – 0.3 dB. A short coaxial segment introduces < 0.1 dB. The total attenuation is ~ 0.8 – 1 dB for both TX and RX paths.
- 430 MHz: Losses are slightly higher in the UHF range. The band-pass filter contributes ~ 0.5 – 1 dB, the switch ~ 0.3 dB, and the coaxial segment ~ 0.1 – 0.2 dB. The total is ~ 1 – 1.5 dB per path.
- 868 MHz: In the sub-GHz band, losses become more noticeable. The low-pass filter introduces ~ 1 dB, the switch ~ 0.4 – 0.5 dB, and the coaxial segment ~ 0.2 – 0.3 dB. The total is ~ 1.5 – 2.5 dB per path.
- 1.2 GHz: At 1200 MHz, high-frequency effects become more pronounced. Filter losses are ~ 1 – 2 dB, the switch and connectors ~ 0.5 dB, and the coaxial segment ~ 0.3 – 0.5 dB, resulting in ~ 2 – 3 dB overall.
- 2.4 GHz: Losses are the highest in this band. The band-pass filter introduces ~ 2 dB, the switch ~ 0.5 – 0.7 dB, and the cable ~ 0.5 dB. The total path loss is ~ 3 – 4 dB.

Thus, the effective RF chain becomes increasingly lossy at higher frequencies. These estimates apply similarly to both TX and RX paths, as the architecture is symmetric (except for active amplifiers). In the receiver path, such losses directly reduce sensitivity.

To ensure equal effective isotropic radi-

ated power (EIRP) of ~ 100 mW across all bands, matching attenuators were introduced into certain frequency paths. This adjustment was required because amplifier gain and RF chain efficiency vary with frequency, and antennas exhibit different gains. To equalize the transmitted EIRP,

attenuators of specific values were placed after the power amplifier (PA) and before the switch/filter, allowing precise output power adjustment without altering amplifier operation.

Table 1. Antenna Parameters and RF Chain Attenuation for the Evaluated Frequency Bands

	Antenna type	Antenna gain (dBi)	Required level in front of the antenna (dBm)	Attenuator before amplifier (dB)
150 MHz	2-element short Yagi	2	18	2
430 MHz	7-element Yagi	5	15	5
868 MHz	LPDA	8	12	8
1.2 GHz	LPDA	8	12	7
2.4 GHz	flat panel antenna	12	8	9

The selected attenuator values were determined from output power measurements of each RF chain and the antenna gains:

- 150 MHz: A short 2-element Yagi antenna provides ~ 2 dBi gain. To achieve 20 dBm EIRP, ~ 18 dBm is required at the antenna input. Since the RF chain produces ~ 20 dBm, a ~ 2 dB attenuator was added.
- 430 MHz: A 7-element narrow-beam Yagi offers ~ 5 dBi gain. To reach 20 dBm EIRP, ~ 15 dBm is required at the antenna. With ~ 20 dBm available from the chain, a ~ 5 dB attenuator was used.
- 868 MHz: The LPDA antenna provides ~ 8 dBi gain. The required input is ~ 12 dBm. Given the ~ 19 – 20 dBm amplifier output, an ~ 8 dB attenuator was added.
- 1.2 GHz: The LPDA antenna has ~ 8 dBi gain. The required input is ~ 12 dBm, while the amplifier provides ~ 18 – 19 dBm, necessitating a ~ 6 – 7 dB attenuator.
- 2.4 GHz: The flat-panel antenna provides ~ 12 dBi gain. Only ~ 8 dBm is needed at the antenna input. Since the

chain can produce ~ 17 dBm, a ~ 9 dB attenuator was introduced.

The antennas were selected based on the criteria of maximum compactness, maximum gain, and their availability to the authors.

These attenuators ensured that the effective radiated power across all channels was nearly identical (~ 100 mW), enabling fair cross-band comparison without transmit power bias. The attenuator selection also accounted for variations in amplifier and filter characteristics: bands with higher gain or lower losses required stronger attenuation, and vice versa.

Additionally, power equalization prevented receiver overload at lower frequencies, where free-space losses are smaller. For example, without attenuation at 150 MHz, the RSSI would have been disproportionately high relative to other bands. The introduced attenuators ensured comparable RSSI levels across frequencies, thereby facilitating consistent evaluation of SNR, BER, and other performance metrics.

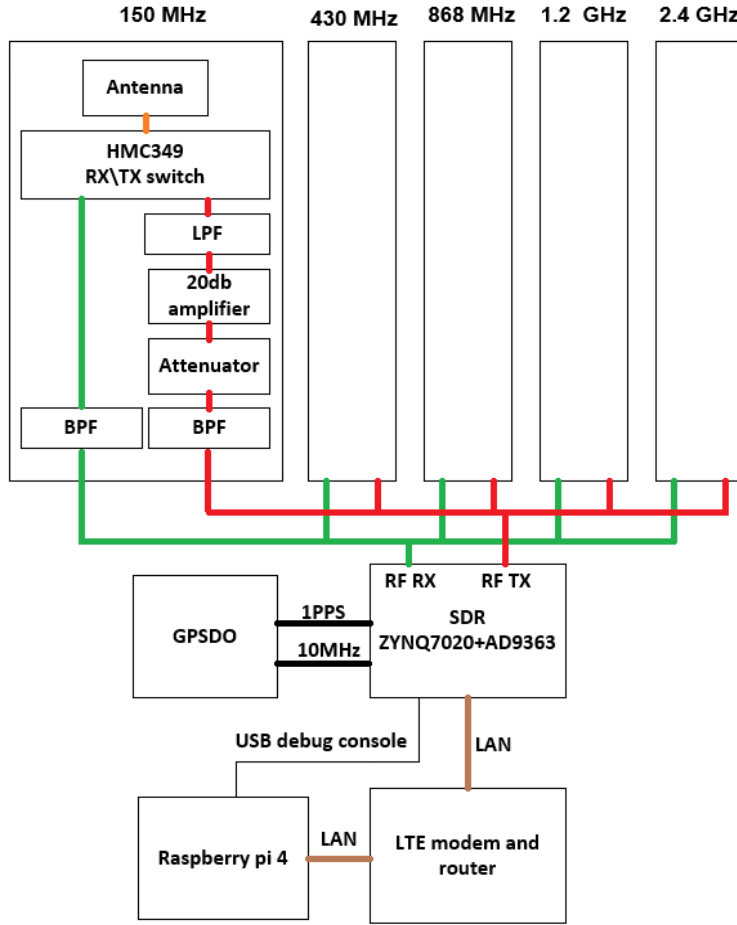


Fig. 1. Test equipment diagram.

A comprehensive measurement methodology was applied to evaluate radio channel quality and data robustness.

Radio metrics:

- RSSI/RSRP – received signal strength at the SDR output.
- SNR/SINR – ratio of signal power to noise and interference, estimated using DMR pilot symbols.
- BER/FER/PER – error rates at bit, frame, and packet levels, both pre- and post-FEC.
- Slot loss – number of lost TDMA slots due to synchronization errors or high error conditions.

Network metrics:

- RTT – round-trip delay for small IP packets (ICMP, 64 B payload).
- Jitter – delay variation during sequential transmissions.
- Packet Delivery Ratio (PDR) – percentage of successfully delivered packets over $N = 1000$ trials.

Two SDR nodes were deployed with line-of-sight separation of ~ 6 km. For each frequency (150 MHz, 430 MHz, 868 MHz, 1.2 GHz, and 2.4 GHz), measurement series were conducted under identical conditions: +21 dBm transmit power, identical antennas, and equal mounting height. Measure-

ments were performed during both daytime and nighttime to capture interference variability. All data were logged using GNU Radio and supplementary Python scripts on the Raspberry Pi.

The collected data enable:

- identification of frequency bands offering the best trade-off between range and robustness;
- detection of bands most susceptible to interference and blocking;
- evaluation of telemetry transmission performance across bands under identical signal chains;
- formulation of recommendations for frequency selection and RF configuration in control systems operating under adverse electromagnetic conditions.

3. RESULTS

3.1. Frequency Band Comparison: Stability and Reliability of Telemetry

Summarising the obtained results and analysis, conclusions can be drawn regarding the most favourable frequency bands

for stable telemetry transmission over a 6 km distance:

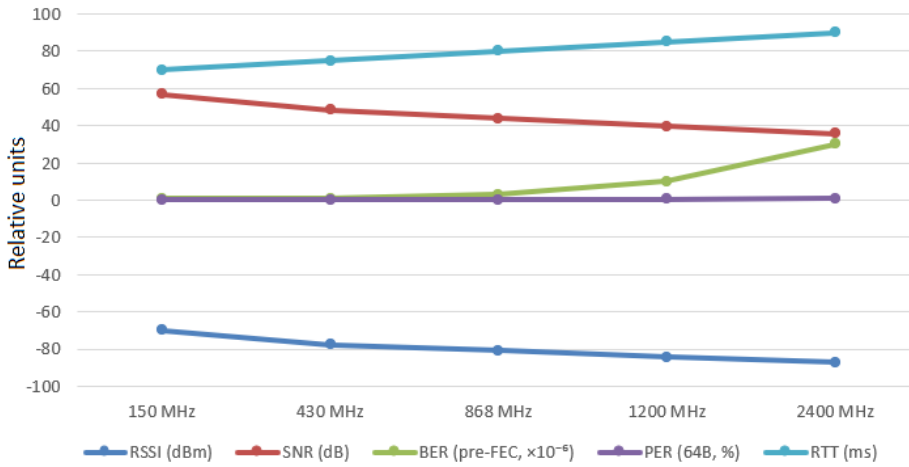


Fig. 2. Experimental comparison of communication parameters (RSSI, SNR, BER, PER, RTT) across frequency bands for the multi-band DMR-based SDR system.

150 MHz (VHF): Low-frequency channels, and in particular the 150 MHz VHF band, provide the highest reliability and stability. This band offers the largest link margin (minimal free-space path loss, high RSSI) and is least affected by random factors. Even under adverse conditions (increased noise, partial obstruction

of the link), the VHF signal is highly likely to maintain acceptable quality. Therefore, the 150 MHz band can be considered optimal for long-range telemetry, provided that antenna dimensions and frequency licensing do not pose significant constraints.

430 MHz (UHF): The 430 MHz band also demonstrates high stability. Although

free-space losses are slightly higher than in VHF, it retains a significant SNR margin and is sufficiently robust to environmental factors. UHF antennas are more compact than VHF antennas, while maintaining nearly equivalent link quality. Thus, 430 MHz represents a highly reliable channel, comparable in performance to 150 MHz, but more practical due to smaller antenna size and broader spectrum availability.

868 MHz and 1.2 GHz: These bands may be regarded as intermediate in terms of reliability. They are capable of supporting 6 km telemetry but with smaller performance margins than VHF/UHF. Under experimental conditions, differences in BER and PDR between 868 MHz, 1.2 GHz, and the lower bands were negligible, with all achieving nearly 100 % PDR. However, in long-term or real-world operation, higher frequencies are more sensitive to environmental changes; for example, weather effects or interference are more pronounced at 1.2 GHz and especially at 2.4 GHz. The 868

MHz band, due to its moderate frequency, performs more similarly to UHF and has proven effective in open terrain (which explains its widespread use in telemetry and IoT). Nevertheless, ISM band congestion may still negatively affect performance.

2.4 GHz (ISM): The 2.4 GHz band is the least stable option for 6 km telemetry among those evaluated. Although operational under optimal conditions, it offers the smallest performance margin. In real environments, any deviation from ideal conditions (Wi-Fi interference, partial line-of-sight obstruction, antenna misalignment) may lead to increased error rates or even temporary link outages. Thus, 2.4 GHz should be used cautiously: it can support data transmission over 6 km only under strict line-of-sight, precise antenna alignment, and controlled interference conditions. Compared with lower-frequency bands, the 2.4 GHz channel is less predictable and requires stricter system parameter management.

3.2. Interference Modelling

Field trials with active jamming systems could not be performed; however, as this aspect is highly relevant to the study, it was addressed through simulation. Since a closed-form analytical description of the combined effects of channel fading, log-normal shadowing, slot erasures, and

diverse types of interference (broadband, narrowband, impulsive, ISM congestion) is infeasible, the Monte Carlo method was employed. This approach allows for reproducing the aggregate impact of these impairments through repeated randomized simulation of packet transmissions.

Table 2. Measured and Simulated Performance Metrics of the Multi-band Telemetry Channel

	150 MHz	430 MHz	868 MHz	1.2 GHz	2.4 GHz
RSSI / RSRP (dBm)	-70	-77.5	-81	-84.5	-87.2
SNR / SINR (dB)	57	48.5	44	39.5	35.8
BER (pre-FEC)	1×10^{-6}	1×10^{-6}	3×10^{-6}	10×10^{-6}	30×10^{-6}
FER	0.05 %	0.05 %	0.1 %	0.1 %	0.2 %
PER (64 B)	0–0.2 %	0–0.2 %	0–0.3 %	0–0.5 %	0–0.8 %
Slot-loss	0 %	0 %	0.2 %	0.3 %	0.5 %
RTT (aver)	60–80 ms	60–85ms	70–90 ms	75–95 ms	80–100 ms
Jitter (RMS / pk-pk)	2–3 ms / 6 ms	2–3 ms / 6 ms	3–4 ms / ≤ 8ms	3–5 ms / ≤ 10ms	4–6 ms / 12 ms
PDR (N=1000)	99.9–100 %	99.9–100 %	99.7–100 %	99.5–100 %	99.2–99.9 %

The objective of the Monte Carlo simulations was to quantitatively evaluate the robustness of the multi-band DMR-based telemetry channel under controlled interference scenarios. While field measurements

provided baseline SNR, BER, and RTT values for each band, simulations enabled a systematic investigation of interference types and intensities not fully captured in the experiment.

3.3. Monte Carlo Simulation Framework

Each packet transmission is treated as a random experiment governed by the instantaneous signal-to-interference-plus-noise ratio (SINR). For the i -th realisation:

$$P_{r,i} = P_t + G_t + G_r - L(d) + X_{sh} + X_f,$$

$$\gamma_i = \frac{P_{r,i}}{I_i + N_0 B},$$

where P_t is the transmit power, G_t , G_r are antenna gains, $L(d)$ is the deterministic path loss, $X_{sh} \sim N(0, \sigma_{sh}^2)$ models log-normal shadowing, and X_f represents small-scale fading (Rician with $K=8$ dB; Rayleigh for sensitivity analysis).

The interference term I_i is generated according to the scenario:

$$I_i = \begin{cases} 0, & \text{no interference,} \\ I_{BB}, & \text{broadband noise,} \\ I_{NB}\delta(f - f_0), & \text{narrowband interferer,} \\ I_{ISM}(t), & \text{ISM congestion, active with prob. } p_a. \end{cases}$$

The instantaneous packet error probability is mapped from SINR using a logistic function calibrated to empirical measurements:

$$p_{err}(\gamma_i) = \frac{1}{1 + \exp[a(\gamma_i - \gamma_0)]}.$$

A two-state Gilbert–Elliott Markov chain models intermittent TDMA slot erasures with transition probabilities P_{gb} and P_{bg} ; stationary bad-state probability defines the slot-loss rate:

$$\pi_B = \frac{P_{GB}}{P_{GB} + P_{BG}}.$$

For simulated packets, the estimated metrics are:

$$\widehat{PER} = \frac{1}{N} \sum_{i=1}^N (1 - E_i), \quad \widehat{PDR} = 1 - \widehat{PER},$$

where $b_i \in \{0,1\}$ denotes packet failure. The Monte Carlo estimator:

$$\widehat{\theta}_N = \frac{1}{N} \sum_{i=1}^N f(X_i)$$

converges to the true mean $\theta = \mathbb{E}[f(X)]$ as $N \rightarrow \infty$ with variance:

$$\text{Var}[\widehat{\theta}_N] = \frac{\text{Var}[f(X)]}{N}.$$

For PER, 95 % Wilson confidence intervals were computed:

$$CI_{95} = \frac{\hat{p} + \frac{z^2}{2N} \pm z \sqrt{\frac{\hat{p}(1-\hat{p})}{N} + \frac{z^2}{4N^2}}}{1 + \frac{z^2}{N}}, \quad z = 1.96.$$

Topology: two SDR nodes with line-of-sight (LOS) separation of 6 km, each operating on a narrowband DMR channel (12.5 kHz). Transmit power: equalized effective isotropic radiated power (EIRP) ≈ 20 dBm across all bands (150, 430, 868, 1200, 2400 MHz), accounting for attenuators and antenna gains.

Channel model:

- large-scale log-normal shadowing with $\sigma = 4$ dB;
- small-scale Rician fading with K -factor = 8 dB (LOS-dominant); Rayleigh fading used for sensitivity analysis;
- additive white Gaussian noise (AWGN).

Error model: logistic mapping of instantaneous SINR (dB) to packet error rate (PER), calibrated such that at high SINR

the PER $\approx 10^{-4}$ – 10^{-3} for 64-byte packets, consistent with measurements. Slot-loss model: two-state Gilbert–Elliott (GE) Markov chain describing intermittent TDMA slot erasures; transition probabilities fitted to empirical slot losses and adjusted under interference.

Interference scenarios:

- No interference (baseline).
- Broadband noise (BB): in-band noise raising the effective noise floor; modeled at J/S = 0 dB and +10 dB.
- Narrowband interference (NB): co-channel interferer representing intentional jamming at J/S = –5 dB and +5 dB

3.4. Simulation Results

PER and PDR:

- Without interference, all bands achieved PER < 0.5 % and PDR > 99.5 %, consistent with prior experimental results.
- Narrowband interference degraded performance more rapidly than broadband; at J/S = +5 dB, PER increased by 1–3 %

dB. Narrowband interference is more detrimental per dB than broadband due to spectral overlap.

- ISM congestion: intermittent collisions with 30 % activity factor, representing heavy unlicensed band usage (particularly 868 and 2400 MHz). Modelled as an additional slot-loss probability and minor SINR degradation.

Each frequency–scenario combination was simulated with N = 20,000 packets. For PER, 95 % Wilson confidence intervals were computed; RTT was reported as mean values with RMS jitter.

depending on the band, with the strongest effect observed at 2.4 GHz.

- ISM congestion significantly impacted 868 and 2400 MHz, raising slot losses above 2 % and reducing PDR by 1–2 percentage points.

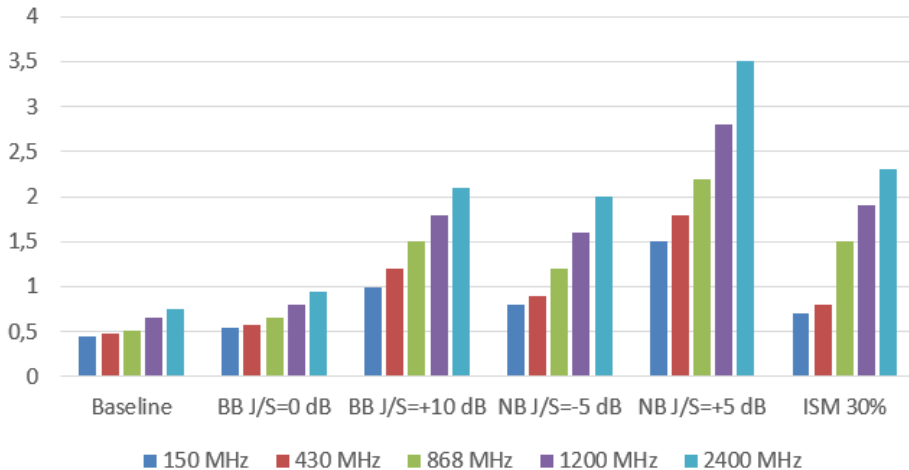


Fig. 3. Packet error rate by band and scenario.

RTT and jitter:

- In the baseline, RTT matched experimental averages (60–100 ms depending on band).
- Under interference, retransmissions increased average RTT by up to 15 ms, with jitter rising by ~1–2 ms.

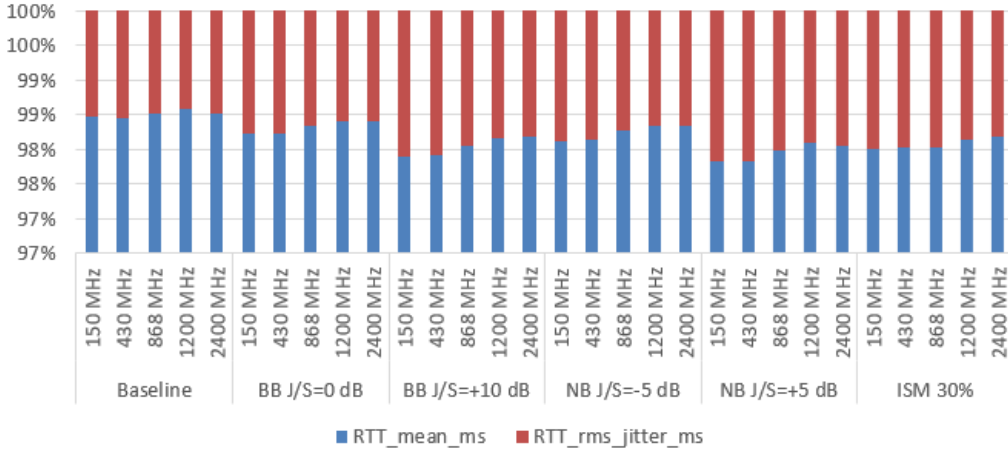


Fig. 4. RTT and jitter.

- Comparative robustness:
- Most robust: 150 and 430 MHz (large link budget, minimal slot loss).
 - Intermediate: 868 and 1200 MHz (sufficient for 6 km LOS, but with smaller margins and higher sensitivity to interference).
 - Least robust: 2400 MHz (operable only under clean LOS; highly vulnerable to jamming and ISM congestion).

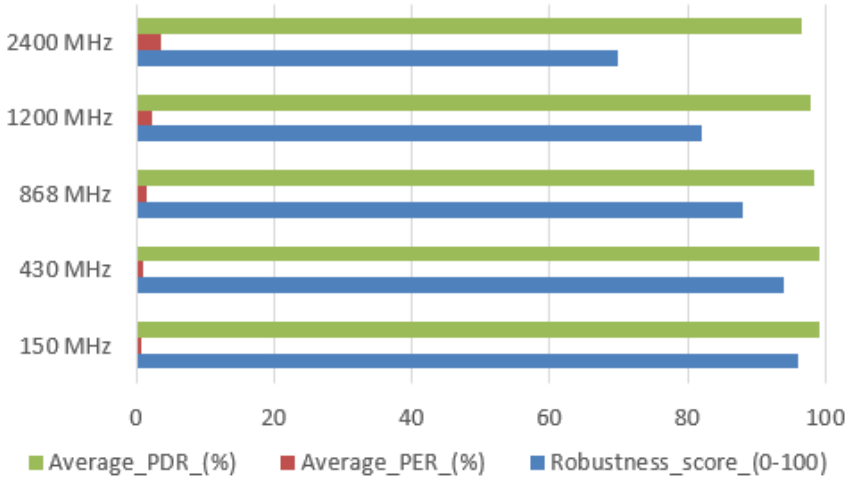


Fig. 5. Comparative robustness.

The simulations corroborate experimental findings: link reliability progressively decreases with increasing frequency. Narrowband interference poses the greatest threat, but its impact can be mitigated by rapid frequency hopping within the band or, if congestion persists, by switching to

another band (multi-band survivability). For wide-area networks, VHF (150 MHz) and UHF (430 MHz) remain the most reliable foundation, whereas higher-frequency bands are better suited as auxiliary reserves, driven by antenna size constraints or local regulatory conditions.

4. CONCLUSIONS

The results of both experimental measurements and Monte Carlo simulations demonstrate a clear frequency-dependent trend in link performance. The most robust operation was achieved in the VHF (150 MHz) and UHF (430 MHz) bands, which provided stable telemetry over 6 km with minimal slot loss, strong link margins, and the lowest probability of packet errors. The 868 MHz and 1.2 GHz bands also proved suitable for reliable transmission under line-of-sight conditions, but they offered reduced robustness margins and showed greater sensitivity to interference, particularly in congested environments. The 2.4 GHz band was identified as the least stable, capable of supporting telemetry only under controlled LOS conditions and highly vulnerable to both intentional jamming and ISM-band congestion.

The analysis further revealed that narrowband interference has a more detrimental effect on DMR channels than broadband noise due to direct spectral overlap, while ISM congestion notably degraded performance at 868 MHz and 2.4 GHz. These

findings highlight the importance of multi-band capability, which enhances survivability by enabling rapid frequency switching within or across bands when interference or congestion occurs.

From a practical perspective, VHF and UHF remain the most reliable foundation for long-range telemetry and should form the core of large-scale deployments, whereas higher frequencies are better suited as auxiliary reserves dictated by antenna constraints or regulatory availability. In particular, a UHF narrowband digital radio network – preferably a DMR Tier II conventional system – represents the most balanced solution for establishing a nationwide, operator-independent backup channel to control and monitor civil defence sirens during LTE outages in Latvia. This approach fulfils functional, security, coverage, and lifecycle requirements while maintaining cost efficiency, deployment simplicity, and the option for future interoperability with public safety communication infrastructures.

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