Sensors Deployed in RF-Hostile Environments Using Acoustic Communications and GNU Radio (GRCON 2026)

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Abstract

Sensor networks are increasingly required in environments where conventional radio-frequency communication is unreliable, attenuated, or unavailable. Examples include dense metallic structures, liquids, enclosed industrial assets, and high-multipath environments where RF propagation is constrained. This paper presents a GNU Radio-based acoustic communication approach for connecting low-data-rate sensors in RF-hostile environments using orthogonal frequency division multiplexing (OFDM) with packet framing based on preamble and postamble detection. The proposed system targets short text and sensor-status messages rather than high-throughput data transfer, reflecting monitoring applications where reliability, repeatability, and environmental tolerance are more important than bandwidth. Implemented in GNU Radio, the acoustic modem can be developed, tested, and modified using SDR principles. OFDM improves robustness in multipath acoustic channels by distributing data across multiple subcarriers and using a cyclic prefix to reduce inter-symbol interference. A preamble supports packet acquisition and synchronisation, while a postamble assists message-boundary detection and validation. Experimental work demonstrates that acoustic signalling can provide an alternative communication path where RF links are limited or unavailable. The paper discusses system architecture, GNU Radio implementation, framing, acoustic channel challenges, and intended sensor-networking applications, contributing a practical SDR-based framework for short-message acoustic sensor communication in difficult physical environments.

Proceedings of the 16^{th} GNU Radio Conference,

1. Introduction

Wireless sensor networks (WSNs) are traditionally built on RF transmission, which is fast, well standardised, and supported by mature hardware. RF, however, is a poor carrier in several environments of practical importance. Water absorbs RF energy so strongly that useful ranges fall to a few metres even at low frequencies; metal enclosures and buried structures shield RF almost entirely; and dense granular or solid media scatter and attenuate electromagnetic waves in ways that make reliable RF links impractical without physical penetrations for cabling or antennas (Akyildiz et al., 2005; Partan et al., 2007).

Acoustic (pressure) waves behave very differently. Sound propagates efficiently through water, through solids such as metal and concrete, and through air, because these media couple mechanical energy far more readily than they couple electromagnetic energy. This property has made acoustic transmission the medium of choice for underwater sensor networks for several decades, and it is now attracting renewed interest for in-air sensor arrays and for structural and industrial monitoring where RF cannot reach.

This survey draws together the literature on acoustic transmission as a wireless medium across three application settings that are directly relevant to sensor network design:

- **Underwater acoustic sensor networks (UASNs) —** by far the most mature body of work, covering ocean and freshwater monitoring, offshore infrastructure and autonomous underwater vehicles (AUVs).
- **In-air wireless acoustic sensor networks (WASNs)** — networks of microphones and acoustic transducers used for soundscape monitoring, localisation and, increasingly, low-rate data-over-sound communication.
- **Through-solid acoustic sensor networks —** sensors embedded within or attached to solid structures (pipes, wellbores, metal vessels, buildings), where acoustic waves carry both data and, in some designs, power.

The remainder of this paper is organised as follows. Section 2 reviews the relevant literature on acoustic communication in RF-constrained environments, with particular emphasis on multipath propagation, OFDM, and software-defined radio approaches. Section 3 presents the proposed system concept and architecture, followed by the GNU Radio implementation in Section 4. Section 5 describes the OFDM waveform and packet-framing approach, including preamble and postamble detection. Section 6 outlines the experimental methodology, while Section 7 presents and discusses the experimental results. Section 8 considers potential sensor-network applications in RF-hostile environments, and the Conclusion in Section 9 summarises the paper and identifies directions for future work.

2. Literature Review and Related work

Acoustic communication has been extensively investigated for environments in which conventional radio-frequency communication is constrained by the transmission medium. The most mature body of research is underwater acoustic communication, where electromagnetic propagation is severely limited and acoustic signalling provides a practical means of transferring sensor and control data over useful distances. Early work by (Akyildiz et al., 2005) (Partan et al., 2007) identified the principal characteristics of acoustic communication channels, including limited bandwidth, long propagation delay, multipath propagation and time-varying channel conditions. These characteristics remain central to the design of practical acoustic sensor communication systems.

Multipath is particularly significant because reflected signal components arrive at the receiver with different delays and amplitudes, producing inter-symbol interference and frequency-selective fading. Similar effects occur not only underwater but also when acoustic signals propagate through solid structures and enclosed environments. (Climent et al., 2014) (Heidemann et al., 2012) describe the resulting challenges for reliable acoustic communication, while (Song et al., 2019) identify orthogonal frequency division multiplexing (OFDM) as an effective technique for dispersive acoustic channels. By dividing the available bandwidth across multiple narrowband subcarriers and incorporating a cyclic prefix, OFDM can reduce the effect of delayed signal components and improve tolerance to frequency-selective multipath.

Acoustic transmission is also relevant to structural and industrial sensing where RF propagation through metallic enclosures, pipes, vessels and structural members may be unreliable or unavailable. Wireless sensor-network research in structural health monitoring has demonstrated the value of distributed sensing for difficult-to-access infrastructure (Abdulkarem et al., 2020). Related research has investigated acoustic data and power transfer through solid materials, including batteryless and embedded sensing applications where physical penetrations through a structure are undesirable (Oppermann & Renner, 2023). These applications demonstrate that the physical structure itself can provide a propagation path for acoustic energy and information.

Software-defined radio provides a flexible platform for investigating these communication techniques without requiring a purpose-built acoustic modem. GNU Radio allows modulation, synchronisation, framing and signal-processing functions to be implemented as configurable software flowgraphs, enabling communication techniques to be evaluated across different physical media using a common experimental platform. Earlier GNU Radio experiments by (Alldritt & Braun, 2026a) demonstrated acoustic data transmission through air, water and solid steel and identified multipath as a significant limitation for conventional single-carrier modulation techniques.

Subsequent experimental work investigated OFDM specifically as a means of reducing acoustic multipath effects. (Alldritt, 2024) demonstrated that an OFDM-based GNU Radio implementation provided improved robustness in severe multipath environments, including transmission through a solid steel rail. Complementary work investigated packet synchronisation using preamble and postamble detection within GNU Radio OFDM flowgraphs (Alldritt & Braun, 2026b), while further experiments demonstrated ultrasonic BFSK and BPSK transmission through water and other difficult media (Alldritt & Braun, 2025).

Collectively, the literature demonstrates that acoustic communication can provide a viable data path in environments where RF communication is constrained, but much previous work has focused either on specialised underwater acoustic networks or on individual physical-layer experiments. The present work focuses instead on the practical integration of these techniques into a GNU Radio-based communication approach for low-data-rate sensor applications. The objective is not high-throughput acoustic networking, but reliable transmission of short sensor-status and text messages using OFDM together with explicit packet acquisition and message-boundary detection. This provides a reproducible SDR framework for investigating sensor communication across RF-hostile physical environments.

3. System Concept and Architecture

The proposed system provides a low-data-rate communication path for sensors deployed in environments where conventional RF communication is unreliable or unavailable. Rather than attempting to provide a high-throughput replacement for conventional wireless networking, the system is intended to transfer short messages such as sensor readings, equipment status, alarms and basic control information. This reflects industrial monitoring applications in which successful delivery of relatively small amounts of information is more important than high data rate.

The communication architecture is based on a software-defined implementation in GNU Radio. At the transmitting end, sensor or text data is formatted into a packet and processed by the GNU Radio transmitter flowgraph. The digital information is modulated using OFDM and converted into an acoustic waveform suitable for transmission through the physical medium. An acoustic transducer converts the electrical waveform into mechanical energy, which propagates through the selected transmission medium.

At the receiving end, a second acoustic transducer converts the received mechanical signal back into an electrical waveform. The signal is then processed by the GNU Radio receiver, where packet acquisition, synchronisation, OFDM demodulation and data recovery are performed. Preamble and postamble sequences are incorporated into the packet structure to assist with detection of the beginning and end of each transmitted message. The detailed OFDM configuration and packet-framing method are described in Section 5.

A principal feature of the architecture is that the software-defined communication chain remains substantially unchanged when the physical transmission medium changes. The acoustic transducers and associated interface hardware provide the connection between the GNU Radio implementation and the physical channel, while modulation, framing, synchronisation and data processing remain software controlled. This allows the same communication concept to be evaluated across RF-hostile environments without requiring a dedicated modem design for each application.

The resulting end-to-end communication architecture is shown in Fig. 1.
Sensor data → GNU Radio transmitter → acoustic interface → transmitting transducer → physical medium → receiving transducer → acoustic interface → GNU Radio receiver → recovered sensor data

This modular architecture separates the sensor application, digital communication processing and physical acoustic channel. It also enables individual elements of the communication chain to be modified and evaluated independently, supporting repeatable experimentation and further development of acoustic sensor communication using GNU Radio.

4. GNU Radio Implementation

The acoustic communication system was implemented using GNU Radio, allowing the transmitter and receiver to be constructed as configurable software-defined signal-processing flowgraphs. This approach separates the communication functions from the physical acoustic channel and allows modulation, packet handling, synchronisation and receiver processing to be modified without redesigning the complete hardware system.

Figure 2 summarises the principal processing stages implemented in the GNU Radio transmitter and receiver flowgraphs.

The transmitter flowgraph accepts the information to be communicated, such as a short text message or sensor-status value, and converts it into a form suitable for transmission. The data is packetised and passed through the OFDM modulation chain before being presented to the acoustic output interface. The resulting electrical waveform drives the transmitting acoustic transducer, which couples the signal into the selected physical medium.

At the receiving end, the signal captured by the receiving transducer is returned to the GNU Radio receiver through the acoustic input interface. The receiver flowgraph performs signal acquisition, packet detection, synchronisation, OFDM demodulation and reconstruction of the transmitted data. The recovered payload can then be displayed, stored, or passed to a sensor-monitoring application.

The GNU Radio implementation was developed using a modular flowgraph structure. Individual processing functions can therefore be examined or modified independently during testing. This is particularly useful when operating through difficult acoustic channels, where changes to gain, filtering, synchronisation or modulation parameters may be required as the transmission medium changes.

A further advantage of the software-defined approach is that signal behaviour can be observed at multiple points within the communication chain. Time-domain, frequency-domain and constellation displays can be incorporated into the flowgraph to examine signal quality during development and experimental testing. These diagnostic functions assist in identifying attenuation, multipath distortion, synchronisation errors and other channel effects without requiring changes to the underlying communications architecture.

The same basic GNU Radio transmitter and receiver arrangement can be retained across different acoustic transmission environments. The physical coupling between the transducers and the transmission medium may change, but the principal digital processing functions remain software controlled. This supports repeatable experimentation and

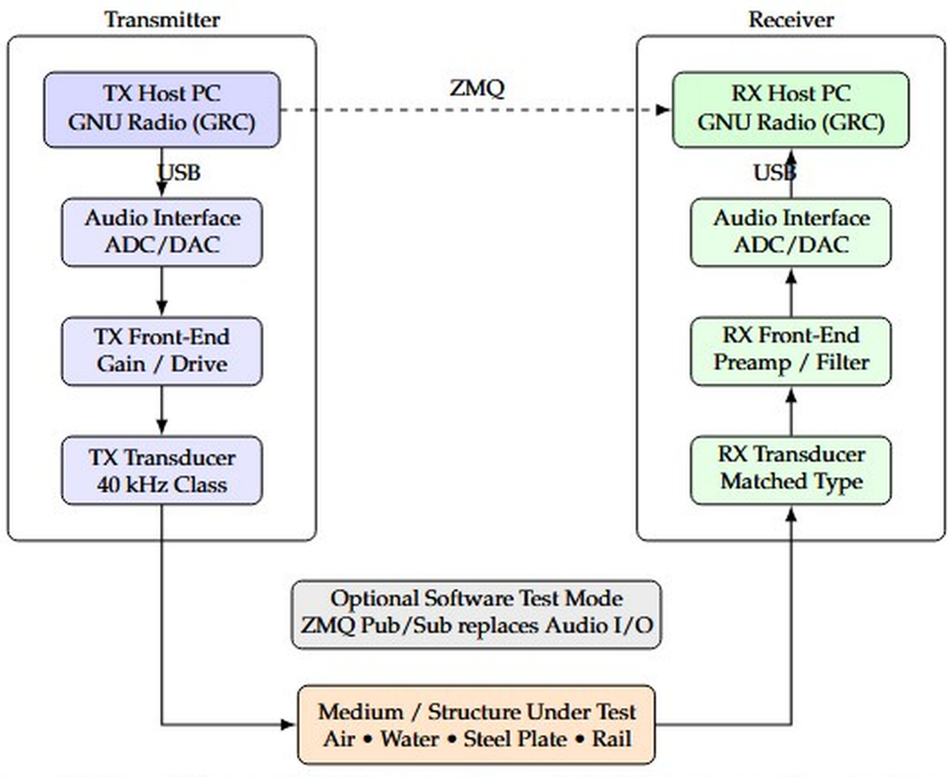

Figure 1. End-to-end architecture of the GNU Radio acoustic sensor communication system.

allows the communication system to be adapted for different RF-hostile sensor applications using a common SDR platform.

The OFDM waveform configuration, subcarrier structure, cyclic prefix and packet-framing method used within these flowgraphs are described in the following section. The GNU Radio implementation used for the acoustic communication system is illustrated in Fig. 2, showing the principal transmitter and receiver processing stages.

5. OFDM and Packet Framings

The communication system uses orthogonal frequency division multiplexing (OFDM) to improve robustness in acoustic channels affected by multipath propagation. Rather than transmitting the data as a single high-rate carrier, OFDM divides the available bandwidth across multiple orthogonal subcarriers. The resulting increase in symbol duration reduces sensitivity to delayed signal components and allows a cyclic prefix to be used to mitigate intersymbol interference produced by acoustic reflections.

The GNU Radio implementation uses a 64-point fast Fourier transform (FFT) with a cyclic prefix of 16 samples. Forty-eight subcarriers are allocated within the OFDM waveform, with pilot carriers positioned at subcarrier indices (-21), (-7), (7), and (21). BPSK modulation is used for the pilot carriers, while the payload data is transmitted using QPSK. This configuration provides a balance between spectral efficiency and robustness suitable for the relatively narrow bandwidth available from the acoustic transducers.

The cyclic prefix is formed by copying the final portion of each OFDM symbol and inserting it before the transmitted symbol. Reflected components of an acoustic signal may arrive at the receiver after the direct component and interfere with the following symbol. Provided that the dominant multipath delay remains within the cyclic-prefix interval, these delayed components can be absorbed without significantly corrupting the useful portion of the OFDM symbol. This property makes OFDM particularly suitable for the highly reflective acoustic environments considered in this work.

Reliable communication also requires the receiver to determine when a valid transmission begins. Continuous acoustic noise, reverberation and propagation delay make it impractical to assume that the receiver is already aligned with

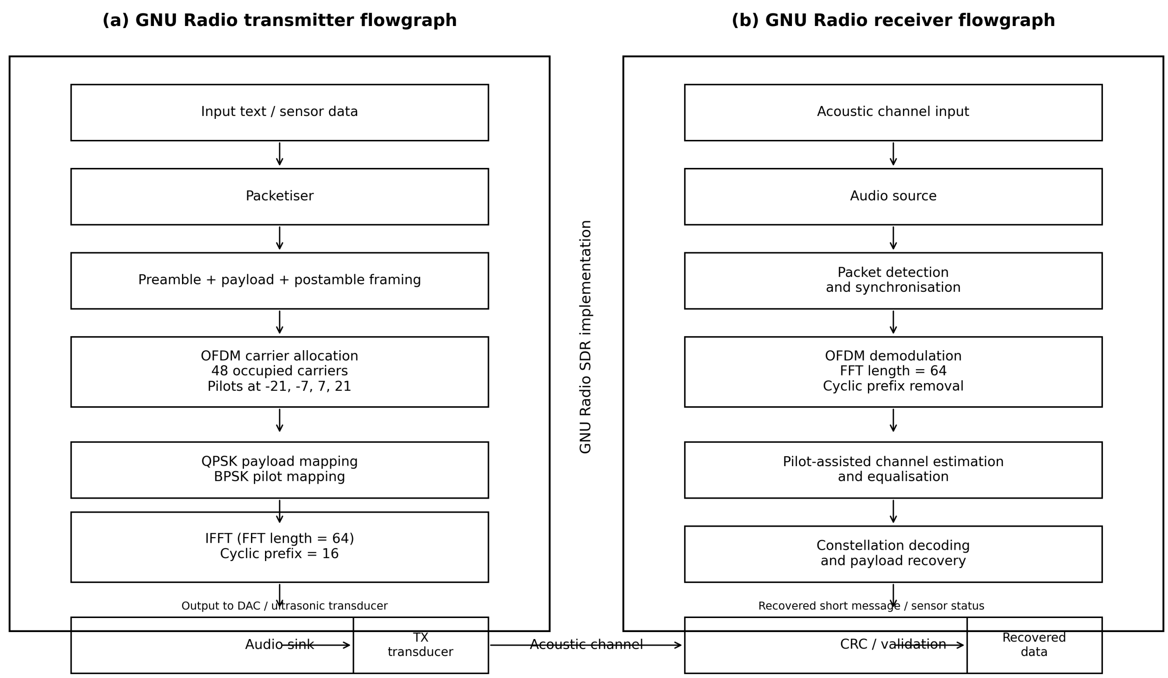

Figure 2. GNU Radio OFDM transmitter and receiver flowgraphs used for acoustic sensor communication. The transmitter packetises short text or sensor data, applies preamble/postamble framing, maps payload and pilot symbols, and generates the OFDM waveform. The receiver performs packet detection, synchronisation, OFDM demodulation, channel estimation/equalisation, and payload recovery.

the incoming data stream. A known preamble is therefore transmitted before the payload. Detection of this sequence provides packet acquisition and establishes a reference from which the receiver can perform timing and OFDM synchronisation.

A corresponding postamble is transmitted after the payload. The postamble provides an identifiable end-of-message condition and assists the receiver in distinguishing the completed packet from subsequent noise or acoustic reflections.

The resulting packet-framing structure is shown in Fig. 3.

The preamble and postamble perform different but complementary functions. The preamble identifies the beginning of a valid transmission and supports receiver synchronisation, while the postamble identifies the end of the transmitted message. This approach is particularly useful for low-data-rate sensor applications where transmissions are intermittent and the receiver cannot rely on a continuously active communication link.

The payload itself may contain short text, sensor measurements, equipment status information or alarm messages. The proposed framing arrangement is therefore intended for packet-based communication rather than continuous streaming. This allows the acoustic channel to remain inactive between transmissions and enables individual sensor messages to be acquired and processed independently.

The resulting OFDM and packet-framing structure combines multipath tolerance with explicit message-boundary detection. These characteristics are important in RF-hostile environments where acoustic propagation delay, reflections and attenuation may vary considerably between physical media. The experimental configuration used to evaluate this implementation is described in the following section.

6. Experimental Method and Test Configuration

The experimental programme was designed to evaluate the practical operation of the GNU Radio acoustic communication system in representative RF-hostile environments. The objective was to determine whether packet-based OFDM communication could maintain reliable data transfer through strongly reflective and attenuating acoustic channels rather than to perform a complete characterisation of the physical propagation channel.

The experimental signal path consisted of the GNU Radio transmitter, an audio interface providing digital-to-analogue conversion, a transmitting acoustic transducer, the physical transmission medium, a receiving transducer,

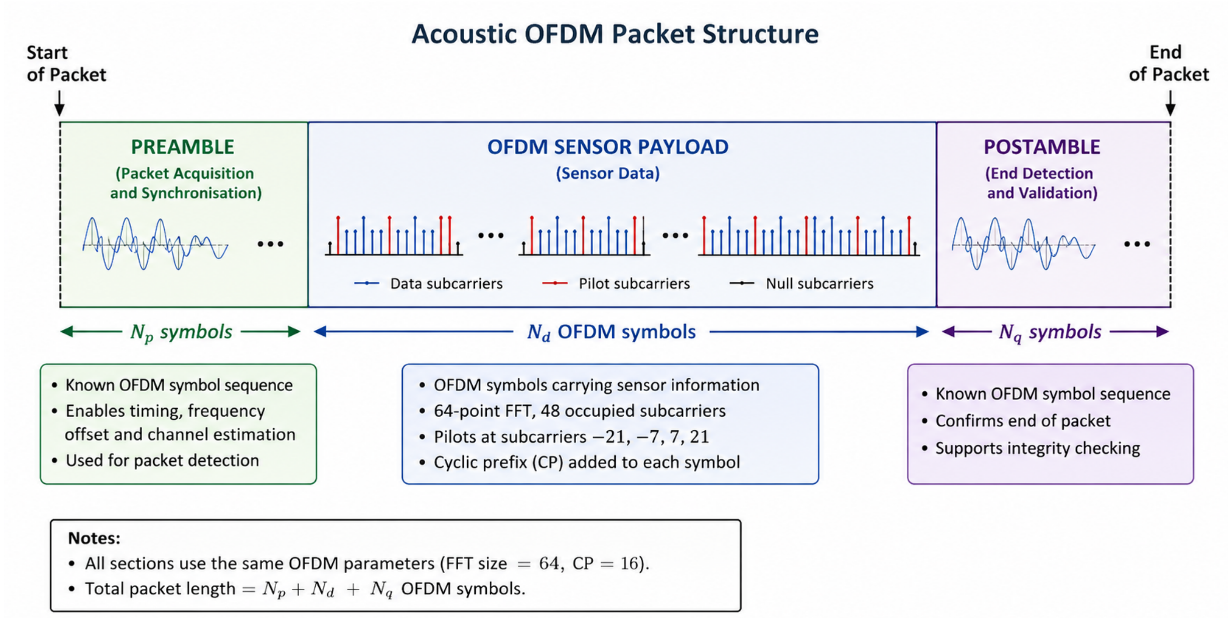

Figure 5. OFDM packet framing structure with preamble, payload and postamble.

Figure 3. OFDM packet-framing structure showing the preamble, sensor-data payload, and postamble used for packet acquisition, synchronisation, data transmission, and end-of-message detection.

the corresponding analogue-to-digital interface, and the GNU Radio receiver. The recovered data were processed by the receiver flowgraph, where cyclic redundancy checking and bit-error-rate measurement were used to assess transmission integrity.

The principal experimental arrangements used in this work are illustrated in Fig. 4.

Prior to connection of the physical acoustic hardware, the transmitter and receiver flowgraphs were tested as a complete software communication chain. ZeroMQ source and sink blocks were used during this stage to verify packet processing, modulation, synchronisation, demodulation and data reconstruction. The physical audio source and sink were then introduced for transmission through the acoustic channel.

A 192 kHz-capable audio interface was used to provide sufficient sampling bandwidth for ultrasonic operation. Transducer selection was found to be particularly important. Conventional narrowband 40 kHz ultrasonic transducers were suitable for simple modulation schemes but restricted frequencies outside a narrow region around their centre frequency. OFDM requires a wider usable spectrum; consequently, extended-bandwidth transducers centred around 40 kHz were used for the OFDM experiments. The available acoustic bandwidth was approximately 3 kHz.

Physical experiments were conducted under controlled and repeatable conditions using representative transmission paths including steel rail, liquid-filled environments and enclosed structures. These environments were selected because they introduce substantial attenuation, reflection and multipath propagation while also representing practical situations in which conventional RF communication may be constrained.

For each physical configuration, data generated by the transmitter flowgraph were modulated, converted to an acoustic waveform and transmitted through the test medium. The received acoustic signal was converted back to an electrical signal and processed by the GNU Radio receiver. Successful packet acquisition, reconstruction of the transmitted information and measured error performance were then used to evaluate the communication link.

The OFDM configuration described in Section 5 was maintained as the principal modulation scheme during these tests. Particular attention was given to operation in the presence of multipath, since reflected and delayed acoustic components represent one of the principal causes of communication failure in solid and enclosed transmission environments.

The experiments were intended as a practical validation of the communication approach rather than a complete channel-sounding study. Delay spread, channel impulse response and coherence bandwidth were therefore not in-

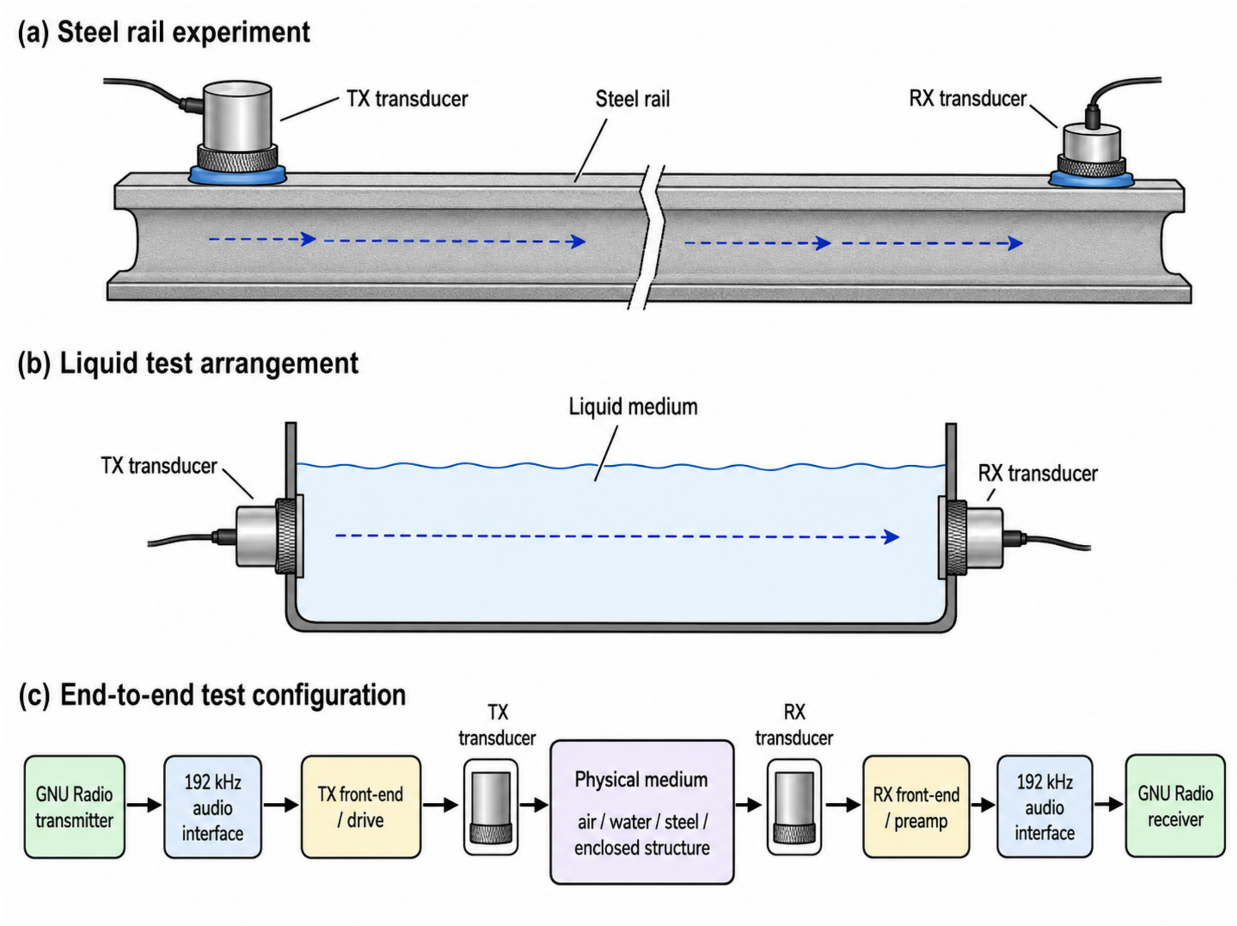

Figure 4. Representative experimental configurations used to evaluate acoustic transmission through RF-hostile media: (a) steel rail experiment, (b) liquid test arrangement, and (c) end-to-end test configuration.

dependently measured. Instead, the combined effects of attenuation and multipath were reflected in the observed signal quality and bit-error-rate performance. Dedicated channel characterisation remains an area for future investigation.

This experimental methodology provides a direct means of determining whether the proposed GNU Radio architecture can support the short, intermittent messages expected from low-data-rate sensors deployed in RF-hostile environments.

7. Results and Discussion

The experimental results demonstrate that the GNU Radio OFDM implementation can maintain reliable acoustic data communication in propagation environments affected by attenuation, reflection and multipath. Performance was evaluated initially using software loopback testing and subsequently through physical acoustic channels representative of RF-hostile sensor applications.

7.1. OFDM Baseline Performance

A software loopback configuration was used to establish the baseline performance of the OFDM transmitter and receiver before introducing the physical acoustic channel. With the transmitter and receiver correctly synchronised, the measured bit error rate (BER) was better than 10^{-5} under controlled conditions. Deliberately changing the receiver timing from the optimum alignment increased the BER to approximately 10^{-4}.

This result demonstrates the importance of packet acquisition and timing synchronisation in the OFDM communication chain. It also provides a reference against which degradation introduced by the acoustic transmission medium can be assessed.

Simulated BER-versus-SNR testing was also performed with additive white Gaussian noise. Under these conditions, OFDM provided an approximately 3 dB performance improvement relative to BFSK in the tested configuration, as shown in Fig. 5. Although simulation does not reproduce all characteristics of a physical acoustic channel, the result provides an indication of the improved tolerance of the multicarrier waveform to degraded signal conditions.

7.2. Performance in Multipath Acoustic Channels

Physical experiments confirmed that the transmission medium had a substantial effect on communication performance. Simple single-carrier schemes such as BFSK operated satisfactorily in air and relatively low-attenuation liquids, but performance deteriorated significantly in highly reflective or dense media.

One example involved BFSK transmission of a JPEG image through laundry detergent. A BER of 0.2069% was measured, resulting in severe degradation of the recovered image. This illustrates an important limitation of using raw BER alone as an indication of application performance. A relatively small number of errors can corrupt critical header or structured data and prevent successful reconstruction of the transmitted information.

OFDM demonstrated substantially greater resilience when the propagation medium introduced strong multipath. In steel-based experiments, where multiple acoustic propagation paths and reflections were present, the OFDM system maintained BER values typically around 10^{-4}. Reliable transmission was therefore possible despite the substantially more difficult propagation environment.

The improvement is consistent with the OFDM structure described in Section 5. The longer symbol duration reduces sensitivity to delayed signal components, while the cyclic prefix provides protection against inter-symbol interference. Pilot carriers and receiver equalisation further assist reconstruction of the transmitted subcarriers after propagation through the frequency-selective acoustic channel.

7.3. Packet Framing and Data Recovery

The experimental work also demonstrated the importance of packet framing for practical acoustic communication. The introduction of explicit preamble and postamble sequences improved the ability of the receiver to identify message boundaries and recover complete data packets.

This was demonstrated experimentally by transmitting encoded data through a steel rail using the modified OFDM flowgraph. Complete JPEG files were successfully reconstructed without data corruption when the framing mechanism was incorporated. While image transmission represents a substantially larger payload than the short messages targeted by the present sensor application, it provides a useful stress test of end-to-end packet integrity.

For sensor communication, the same mechanism can be applied to much smaller payloads containing measurements, status information or alarms. A short packet places considerably lower demands on the acoustic channel than an image or audio file and is therefore well suited to intermittent monitoring applications.

7.4. Comparison with Single-Carrier Modulation

The experimental results highlight a trade-off between implementation simplicity and multipath robustness. BFSK requires comparatively simple transmitter and receiver processing and remains appropriate where the acoustic channel is stable and multipath is limited. Its performance, however, deteriorates rapidly as delayed components and reflections increase.

OFDM requires greater processing complexity, including FFT operations, channel estimation, equalisation and synchronisation. The experiments indicate that this additional complexity provides a significant practical advantage in highly reflective acoustic channels. OFDM maintained reliable operation across a wider range of tested media, including air, water, dense liquids and solid steel, whereas BFSK became unreliable as multipath severity increased.

This distinction is particularly important for RF-hostile sensor deployments. The required data rate for many monitoring applications is relatively low, meaning that maximum throughput is less important than the ability to recover a short message reliably. The additional digital processing required for OFDM can therefore be justified where the physical environment prevents a simpler modulation scheme from maintaining an acceptable error rate.

7.5. Discussion

The results support the use of software-defined acoustic communication as a practical method for connecting sensors where conventional RF propagation is constrained. The principal benefit is not high data throughput, but the ability to establish a communications path through physical media that would otherwise isolate the sensor from a conventional wireless network.

The experiments also demonstrate that the physical acoustic interface is as important as the modulation technique. Narrowband 40 kHz transducers that performed well with BFSK restricted the spectrum required for OFDM. Reliable OFDM operation therefore required transducers with sufficient bandwidth to accommodate the multicarrier waveform. This confirms that modulation, transducer bandwidth and the physical transmission medium must be considered as a complete communication system rather than as independent elements.

The measured results should be interpreted within the scope of the experimental programme. The work demonstrates communication feasibility and comparative robust-

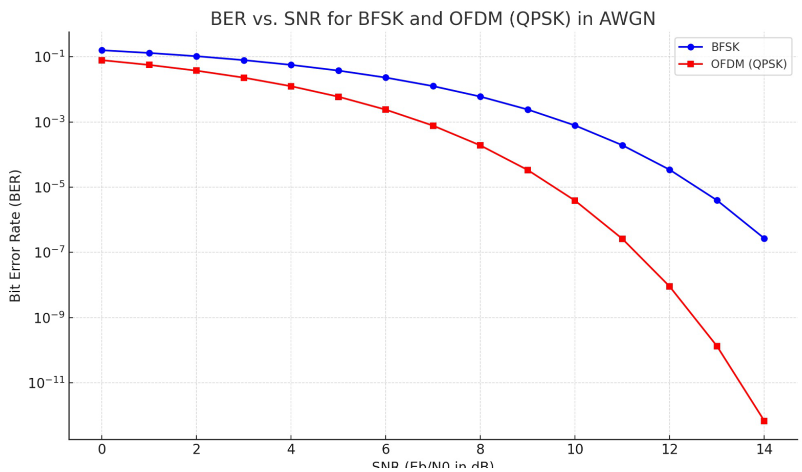

Figure 5. BER versus SNR comparison of OFDM and BFSK under simulated AWGN channel conditions.

ness under controlled physical conditions; it does not provide a complete acoustic channel characterisation. Delay spread, impulse response and coherence bandwidth were not measured independently. These measurements would provide a useful basis for future optimisation of cyclic-prefix length, subcarrier spacing and adaptive modulation parameters.

Overall, the results demonstrate that the GNU Radio OFDM architecture can provide reliable packet-based acoustic communication in environments where severe multipath limits simpler modulation schemes. For the short and intermittent messages expected from sensor networks, the combination of OFDM, explicit packet framing and software-defined signal processing provides a practical basis for communication in RF-hostile environments.

8. Sensor-Network Applications

The acoustic communication architecture developed in this work is intended primarily for low-data-rate sensing applications in environments where conventional RF communication is unreliable, strongly attenuated or unavailable. In these applications, the communication requirement may consist only of a sensor measurement, equipment-state message, alarm condition or periodic health report. The relatively small payload allows communication reliability and environmental tolerance to be prioritised over high data throughput.

One potential application is railway infrastructure. Steel rail provides a continuous structural path through which acoustic energy can propagate, including in tunnels, cuttings and other locations where conventional radio coverage may be limited. Sensors monitoring rail temperature, vibration, track condition or infrastructure status could use the rail itself as part of the communication path to transfer short messages between otherwise isolated locations. Previous experiments demonstrated that OFDM could maintain low BER when transmitting through steel rail despite the strong multipath characteristics of the structure.

A second application is sensing within sealed metallic enclosures. Shipping containers, tanks, vessels and similar structures can significantly attenuate RF signals and may require physical penetrations for conventional wired or antenna-based communications. An acoustic sensor link provides the possibility of transferring information through the structure without introducing an additional cable or antenna penetration. This may be particularly useful where maintaining environmental sealing or structural integrity is important.

Liquid-filled and submerged environments provide another relevant application. Industrial tanks, pipelines and submerged equipment may contain sensors for temperature, pressure, fluid condition, contamination or equipment status. Acoustic signalling can propagate through liquids where RF communication is severely constrained, allowing sensor information to be transferred to a receiver outside or elsewhere within the monitored environment. The experimental programme demonstrated acoustic data transmission through water and other liquids using the same software-defined communication approach.

Structural and industrial monitoring represent a broader application class. Sensors attached to or embedded within metallic structures, pipes and other assets may be located in positions where conventional wireless access is difficult. Acoustic transmission provides a means of using the physical structure itself as the propagation medium. This could support condition-monitoring applications in which individual sensors transmit small amounts of information periodically or when a defined threshold is exceeded.

The proposed approach should therefore be considered complementary to, rather than a replacement for, conventional RF sensor networking. An acoustic link may be used only across the portion of the system where RF propagation is impractical, with the recovered data subsequently transferred through a conventional wired or wireless network. In this arrangement, the acoustic modem acts as a bridge between an otherwise isolated sensor and the wider monitoring system.

The use of GNU Radio further allows the communication parameters to be modified for different sensor applications without redesigning the complete modem. Packet size, transmission interval, modulation parameters and receiver processing can be adapted in software according to the requirements of the physical environment and the sensor being monitored.

These applications share a common requirement: relatively small quantities of information must be transferred reliably through a physical environment that restricts conventional electromagnetic communication. The experimental results presented in this work indicate that OFDM-based acoustic communication, combined with explicit packet framing and software-defined processing, provides a practical platform for investigating such sensor-network deployments.

9. Conclusion

This paper has presented a GNU Radio-based acoustic communication approach for low-data-rate sensor applications in environments where conventional RF communication is unreliable, strongly attenuated or unavailable. The system combines software-defined signal processing, OFDM modulation and explicit preamble/postamble packet framing to provide a configurable communication path for short sensor measurements, equipment-status information and alarm messages.

Experimental testing demonstrated that OFDM provides substantial resilience to the multipath propagation encountered in difficult acoustic channels. The combination of increased symbol duration, cyclic-prefix protection, pilot-assisted channel estimation and receiver equalisation allowed reliable data recovery in media where simpler single-carrier modulation schemes became increasingly vulnerable to reflection and inter-symbol interference. In steel-based experiments, OFDM maintained bit error rates of approximately 10^{-4} under challenging propagation conditions, demonstrating that useful data communication can be maintained through highly reflective solid structures.

The results also demonstrated the importance of treating the software waveform, packet-framing method, acoustic transducers and physical propagation medium as a complete communication system. Transducer bandwidth was particularly important for OFDM operation, while the use of preamble and postamble sequences improved packet acquisition and message-boundary detection. These characteristics make the approach well suited to intermittent sensor communication, where relatively small quantities of information must be transferred reliably rather than continuously at high data rates.

The proposed acoustic link is intended to complement rather than replace conventional RF networking. It can provide a communication bridge across the portion of a sensor network where electromagnetic propagation is impractical, after which the recovered information may be transferred through conventional wired or wireless infrastructure. Potential applications include railway infrastructure, sealed metallic enclosures, industrial tanks and pipelines, submerged equipment and structural monitoring.

The present work demonstrates communication feasibility rather than providing a complete characterisation of the acoustic channel. Future work will therefore include dedicated channel sounding to quantify delay spread, coherence bandwidth and channel impulse response, together with further optimisation of OFDM parameters and packet-framing techniques. Development toward compact sensor nodes and field deployment would provide the next step in evaluating the approach as a practical communication system for sensors operating in RF-hostile environments.

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