A Study on Developing a Preamble - Postamble for OFDM Flowgraphs (GRCON 2025)

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Abstract

OFDM transmit and receive blocks have long been available to users, developers, and researchers within the GNU Radio ecosystem. These tools are actively maintained by the community, including many domain experts. In previous work, I collaborated with GNU Radio experts to develop an out-of-tree (OOT) block that implements preamble and postamble support for BFSK modulation. This feature significantly improved synchronisation between transmitter and receiver—particularly in acoustic communication systems—yielding exponential gains in performance.

My current research focuses on modulating data through dense materials such as steel rail, where traditional BFSK schemes suffer from severe multipath-induced corruption. OFDM, by contrast, offers a highly suitable alternative due to its inherent resilience to multipath fading.

One specific challenge that was resolved using the modified OOT flowgraph was the error-free transmission of JPEG images over BFSK-modulated acoustic links. Header packets and Huffman table bits, which are typically sent first in such links, were often lost or corrupted before synchronisation could occur. This led to image decoding failures, where even a single-bit error rendered the file unreadable (Banister et al., 2000).

This study investigates the development of preamble/postamble techniques tailored for OFDM, enabling robust synchronisation and reliable data transmission. These advances support the broader research objective of achieving dependable acoustic communication in complex and multipath-dominated media.

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1. Introduction

Reliable data transmission requires precise synchronisation between transmitter and receiver, particularly in channels affected by multipath, phase distortion, or high latency. In digital communications, even a single bit error at the beginning of a file—such as a corrupted header or synchronisation sequence—can render the entire data payload unreadable. This challenge is especially pronounced when transmitting compressed files such as JPEG images, where critical Huffman and header data are located at the start of the stream. Ensuring that the receiver is fully synchronised before the main data payload begins is therefore essential for error-free transfer.

In conventional radio frequency (RF) systems, synchronisation is often achieved through well-defined preambles and pilot symbols embedded within the transmission frame. However, in acoustic or dense-medium communication channels, propagation speed is lower and multipath effects are more severe, leading to inter symbol interference and time dispersion that complicate timing recovery. Acoustic transducers, when used as substitutes for antennas, introduce their own limitations in bandwidth and phase stability, further emphasising the need for robust preamble and postamble strategies.

Previous work by the author and collaborators within the GNU Radio community—including development of an out-of-tree (OOT) BFSK block with integrated preamble and postamble support—demonstrated significant improvements in synchronisation performance across liquid and solid media. That implementation enabled the reliable transmission of binary and image data where conventional BFSK modulation had previously failed due to synchronisation loss and header corruption (Alldritt, 2024a) (Alldritt, 2024b).

The present study extends that concept to Orthogonal Frequency Division Multiplexing (OFDM), a modulation scheme inherently resilient to multipath interference and frequency-selective fading. Unlike single-carrier BFSK systems, OFDM divides the signal bandwidth into multiple orthogonal sub-carriers, each carrying a portion of the to-

tal data stream. The development of a compatible preamble/postamble framework for OFDM within GNU Radio offers both practical and theoretical advantages: improved symbol alignment, faster acquisition, and reduced bit error rates in challenging propagation environments.

The objective of this paper is to describe the design, implementation, and testing of an enhanced OOT block that introduces a preamble/postamble mechanism tailored for OFDM modulation. The solution is evaluated in the context of acoustic communication, where precise synchronisation directly determines data integrity and channel efficiency. This work supports the broader goal of establishing dependable digital communication links in environments where electromagnetic propagation is impractical or impossible, such as underwater, through steel, or within confined metallic structures.

1.1. Background on acoustic communications / SDR.

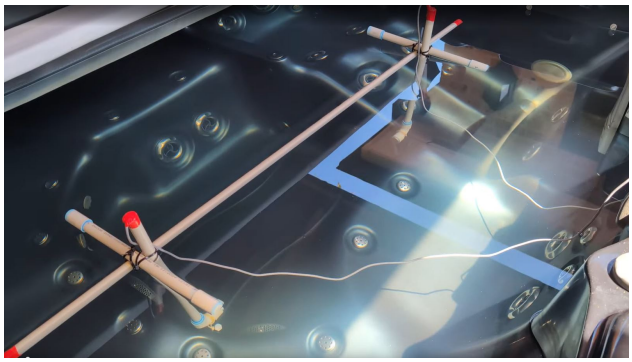


Figure 1. OFDM test in Water Tank with Prowave Sensor at 1.2m

Acoustic communication exploits the propagation of sound waves through a physical medium—air, liquid, or solid—to transfer information where electromagnetic (EM) signals cannot effectively penetrate. Unlike RF systems, which rely on electric and magnetic field propagation at approximately $3 \times 10^8\,\mathrm{m/s}$, acoustic energy travels as mechanical pressure waves at vastly lower velocities: roughly 343 m/s in air, 1,480 m/s in water, and 5,000 m/s in steel(Urick, 1983). The slower propagation speed introduces measurable transmission delays and phase distortion, while the denser medium often produces strong multipath reflections that overlap successive symbols. These effects cause inter symbol interference (ISI), fading, and severe fluctuations in received signal amplitude and phase(Proakis et al., 1994) (Stojanovic, 2007).

Traditional acoustic systems, such as sonar and ultrasonic sensors, employ short bursts or pulses of sound energy. While effective for ranging or simple detection, they are unsuited to continuous high-rate digital communication. Extending these techniques to data transmission requires modulating digital information onto an acoustic carrier in a manner that can withstand multipath, Doppler spread, and limited transducer bandwidth. Frequency-shift keying (FSK) and phase-shift keying (PSK) are among the earliest methods used for such purposes, but both degrade rapidly as the channel becomes dispersive or reverberant. This motivated the exploration of Orthogonal Frequency Division Multiplexing (OFDM), whose multi-carrier structure provides inherent robustness to frequency-selective fading and phase distortion.



Figure 2. 60KG Steel Rail Track with Prowave Sensors Attached

Modern acoustic experiments increasingly rely on software-defined radio (SDR) architectures, in which signal-processing functions such as modulation, filtering, synchronization, and error correction are implemented in software rather than fixed hardware. Within the GNU Radio framework, SDR allows researchers to design, simulate, and deploy complete acoustic communication systems using standard computing hardware and inexpensive analog front ends such as sound cards or USB interfaces. The flexibility of SDR platforms enables rapid prototyping of modulation schemes, synchronization algorithms, and adaptive equalisation strategies, all of which can be tailored to the specific propagation characteristics of air, water, or steel.

The convergence of acoustic transduction and SDR technology has created a powerful research environment for investigating communication in non-traditional media. It allows controlled experimentation with waveform design, timing recovery, and preamble/postamble structures—precisely the elements addressed in this study. By leveraging open-source GNU Radio tools, the present work contributes to this growing field by extending the existing BFSK preamble-postamble framework to OFDM, thereby improving synchronisation and data reliability in complex multipath acoustic channels (Clark, 2016).

The OFDM channel was tested in a large Spa water tank 1 and section of rail track 2 as shown in the images

1.2. Importance of synchronisation in digital communication.

Synchronisation is one of the most critical and technically challenging aspects of any digital communication system. It establishes the temporal and frequency alignment between the transmitter and receiver, ensuring that symbols are correctly identified and demodulated. Even minor timing or phase errors can cause symbol misalignment, inter symbol interference, and significant increases in bit error rate (BER). In continuous or packet-based transmission schemes, failure to achieve synchronisation before data reception begins can result in the loss of header information, payload corruption, or complete communication failure (Cimini, 2003).

In traditional wired or RF systems, synchronisation is often maintained using a shared clock, a pilot tone, or embedded frame markers within the signal. In acoustic communication, however, no such physical timing signal exists. The receiver must therefore recover synchronisation information from the transmitted waveform itself—typically using preamble sequences, pilot carriers, or correlation-based detection of known symbols. This data-derived synchronisation is a defining feature of coherent communication systems: it allows the receiver to align its internal sampling clock and carrier frequency with that of the transmitter without direct hardware coupling.

The Preamble & Postamble image shows the steady 1s and 0s, (example is from a BFSK flowgraph) that works the same in OFDM and allows the receiver to sync with the transmitter with no data lose 3

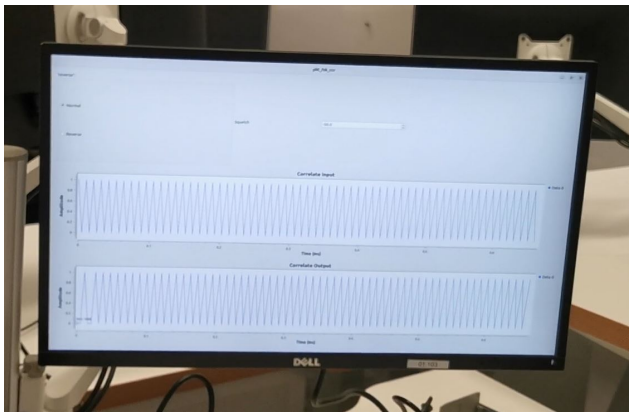


Figure 3. Pre and Postamble from BFSK Display Graph

The challenge becomes more acute in acoustic and dense-medium channels, where multipath propagation, long delay spreads, and temperature- or material-dependent variations in propagation speed continuously disturb timing relationships. A single acoustic pulse may reflect multiple times within the medium, creating overlapping echoes that obscure symbol boundaries. Without a reliable preamble to establish timing and carrier phase, the receiver cannot distinguish the true start of the data frame from these reflections, resulting in framing loss and decoding errors.

To mitigate these effects, preambles and postambles are inserted at the beginning and end of the transmission frame. The preamble provides a structured, known sequence that allows the receiver to detect the signal, estimate timing and frequency offsets, and establish phase coherence before payload data begins. The postamble ensures that the transmission is fully completed and can help in measuring channel delay, truncation, or tail effects caused by multipath persistence. Together, these structures define the temporal boundaries of a reliable communication link.

In the context of software-defined radio (SDR) development, implementing flexible synchronisation mechanisms is essential. GNU Radio's modular architecture enables custom preamble/postamble schemes to be added or modified through out-of-tree (OOT) blocks, allowing synchronisation strategies to be tailored for specific modulation types or environments. This flexibility underpins the present study's contribution: extending the proven BFSK preamble/postamble methodology to the more complex and higher-capacity OFDM modulation scheme, where symbol alignment and phase coherence are crucial for maintaining sub-carrier orthogonality.

1.3. Why OFDM: better performance in multipath environments compared to BFSK.

Binary Frequency Shift Keying (BFSK) has long been valued for its simplicity and robustness in low-bandwidth or noisy environments. In acoustic communication, it has been used effectively to convey control data or short messages through air, water, and other dense materials. However, as symbol rates increase or the medium becomes highly reflective, BFSK's single-carrier nature exposes it to severe multipath interference. Reflected components arriving out of phase with the direct signal cause destructive interference and intersymbol distortion, producing bit errors that conventional filtering cannot remove. In channels such as steel rail, water tanks, or enclosed metallic structures, these reflections persist long enough to overlap several symbols, limiting achievable data rates and link reliability.

Orthogonal Frequency Division Multiplexing (OFDM) overcomes many of these limitations by dividing the available bandwidth into numerous narrow sub-carriers, each modulated at a much lower symbol rate. Because the sub-carriers are orthogonal, they can occupy overlapping frequency space without mutual interference. The lower per-sub-carrier symbol rate increases tolerance to delay spread, while the inclusion of a cyclic prefix absorbs most multipath reflections before they corrupt adjacent symbols (Scaglione

et al., 2000). Consequently, OFDM can maintain data integrity even when the channel impulse response spans many symbol periods—conditions that typically cause BFSK links to fail (Van Nee & Prasad, 2000) (Proakis et al., 1994).

Another advantage of OFDM is its compatibility with adaptive channel-estimation techniques. Pilot tones embedded within each frame enable the receiver to estimate amplitude and phase distortion for every sub-carrier, allowing equalisation to be performed in the frequency domain with minimal computational overhead. This capability is particularly beneficial in acoustic media where propagation characteristics vary with temperature, geometry, and boundary conditions. In such cases, OFDM's inherent flexibility allows dynamic adjustment of sub-carrier spacing, modulation depth, and symbol duration to match the prevailing channel conditions.

While BFSK remains useful for narrow-band control or telemetry applications, OFDM provides a scalable foundation for higher-throughput acoustic networks. It supports advanced features such as error-correction coding, interleaving, and synchronisation sequences that can be integrated directly into the symbol structure. The transition from BFSK to OFDM within a software-defined-radio (SDR) framework therefore represents a natural evolution from proof-of-concept acoustic links toward high-performance, reliable data channels capable of transmitting complex payloads—including images and sensor datasets—through dense or multipath-rich materials.

1.4. Overview of your contribution: extending prior BFSK work to OFDM.

This paper builds directly on prior research and development conducted within the GNU Radio environment, where a Binary Frequency Shift Keying (BFSK) out-of-tree (OOT) block was created to test synchronisation strategies using preambles and postambles. That initial implementation demonstrated that acoustic channels—when properly synchronised—can support digital data transfer through air, liquid, and solid media where electromagnetic propagation is impossible. Although the BFSK system proved effective for simple data exchange, its single-carrier structure limited bandwidth utilisation and made it sensitive to multipath reflections and phase instability.

The current work extends that foundation to a multi-carrier OFDM architecture designed to improve performance in multipath-dense acoustic environments. A new OOT block was developed to integrate preamble and postamble structures within the OFDM signal flow, enabling accurate symbol timing, frame detection, and end-of-transmission recognition. This design supports seamless operation within the GNU Radio 3.10 framework and can be adapted for other modulation schemes or custom synchronisation sequences.

The objectives of this study are threefold:

- To demonstrate that preamble/postamble framing within OFDM can achieve reliable acoustic synchronisation without a shared clock.
- To compare performance between BFSK and OFDM implementations using identical acoustic channels.
- To provide an open-source, reproducible GNU Radio module that allows researchers to explore synchronisation behaviour across different propagation media.

Through these enhancements, the paper contributes both a practical tool and an experimental framework for advancing acoustic communication research. The results presented here show that with proper frame design and symbol alignment, acoustic OFDM systems can achieve significantly lower bit-error rates and higher data reliability than their single-carrier counterparts, even in channels dominated by multipath and time dispersion (Blossom, 2004).

2. Previous Development: OOT Preamble & Postamble with FSK

The early phase of this research focused on establishing reliable acoustic data transfer using Binary Frequency Shift Keying (BFSK) within GNU Radio. BFSK was selected as an initial modulation scheme because of its simplicity, narrow-band operation, and tolerance to amplitude noise. An out-of-tree (OOT) block developed by Barry Duggan (BD) (Duggan, 2025)provided a functional foundation for testing preamble and postamble insertion, framing control, and end-of-file detection. This implementation became the benchmark for subsequent acoustic experiments and provided the first proof that synchronised digital transmission through dense materials such as steel and water was achievable.

In the BFSK OOT framework, the preamble was inserted at the beginning of each data frame to assist in timing recovery and synchronisation, while the postamble marked the end of the transmission and ensured complete data reception before file closure. This framing method was especially useful for the transmission of text and binary data where start-of-file alignment is critical. The BFSK preamble/postamble system employed two discrete frequency tones—commonly at 39.5 kHz (mark) and 40.5 kHz (space)—and achieved reliable synchronisation within short-range acoustic links. It allowed transmission through air and liquid over modest distances with minimal bit-error rates when using low-power transducers.

Despite these successes, several limitations emerged when

applying the BFSK OOT block to more complex media. The narrow modulation bandwidth restricted achievable data rates to a few hundred bits per second, and the absence of robust equalisation made the system vulnerable to multipath reflections and Doppler shifts. Moreover, the single-carrier nature of BFSK limited scalability for high-capacity applications such as image transfer, where even small synchronisation losses could corrupt entire file headers. These findings motivated the development of a more advanced modulation approach capable of handling severe multipath propagation while maintaining the framing advantages introduced in the earlier BFSK system.

The present study therefore extends this foundational work by integrating the preamble/postamble strategy into an Orthogonal Frequency Division Multiplexing (OFDM) architecture. This evolution preserves the original synchronisation benefits demonstrated by BD's BFSK block while adding frequency-domain resilience, pilot-tone correction, and improved spectral efficiency. The following section details the design and configuration of this new OFDM-based implementation, including modifications to the GNU Radio flowgraphs, Base64 encoding integration, and preamble/postamble handling logic.

2.1. Summary of Original BFSK OOT block.

The Binary Frequency Shift Keying (BFSK) out-of-tree (OOT) block for GNU Radio provided the foundation for the early phase of this work. The block implemented a simple, narrow-band modulation scheme using two discrete tones to represent binary 1 and 0. Typical carrier frequencies were 39.5 kHz (mark) and 40.5 kHz (space), chosen to match the response curve of 40 kHz ultrasonic transducers.

The BFSK OOT block offered full-duplex operation, frame control, and customisation symbol rates between 100 and 1 000 symbols per second. It was ideally suited to evaluating acoustic propagation because its deterministic tone structure simplified demodulation and BER measurement. Importantly, the block's open-source architecture allowed insertion of framing sequences, providing a convenient test platform for preamble and postamble experiments in acoustic channels.

2.2. How preamble and postamble supported synchronisation for BFSK.

The addition of preamble and postamble sequences to the BFSK OOT block significantly improved synchronisation reliability. In this configuration, a known preamble pattern was transmitted at the start of each data frame to allow the receiver to detect signal presence, align symbol timing, and establish carrier phase lock. The preamble typically consisted of alternating mark-space patterns that produced a distinctive spectral signature easily detected by correlation or envelope detection.

At the end of the frame, a complementary postamble sequence was transmitted. This ensured that the receiver maintained lock until the final symbol had been decoded and provided a clear end-of-transmission marker. In early acoustic tests, the inclusion of both preamble and postamble eliminated the most common failure modes—premature file termination, truncated payloads, and corrupted headers—especially when transmitting Base64-encoded text or small binary files.

The BFSK preamble/postamble system demonstrated that reliable synchronisation could be achieved without a shared clock, using data-derived timing recovery alone. This approach established the conceptual basis for the later OFDM adaptation.

2.3. Limitations when adapting this to OFDM.

Despite its effectiveness in narrow-band conditions, the BFSK preamble/postamble strategy faced several limitations when extended to wide-band, multi-carrier systems.

- Single-carrier constraint: Because BFSK transmits one symbol per tone, the scheme lacks frequency-domain diversity. Multipath reflections arriving out of phase cause destructive interference that cannot be mitigated by simple filtering.
- Restricted data rate: The 1 kHz separation between mark and space frequencies confines total bandwidth to roughly 2 kHz. This limits achievable throughput to a few hundred bits per second—insufficient for large data files or images.
- Phase and delay sensitivity: BFSK relies on coherent detection; phase distortions introduced by dense media can shift the perceived mark/space frequencies, causing synchronization errors.
- No built-in equalisation: The BFSK OOT block lacks pilot tones or adaptive correction, leaving it vulnerable to amplitude fading and frequency drift.

When adapting the preamble/postamble concept to Orthogonal Frequency Division Multiplexing (OFDM), these limitations necessitated a complete redesign of the synchronization mechanism. In OFDM, timing and frequency alignment must occur across multiple orthogonal sub-carriers simultaneously. The preamble must therefore contain a pattern recognisable in both time and frequency domains, while the postamble must account for multipath tails that persist beyond the final symbol.

3. Modified OFDM Flowgraph Design and Operation

The OFDM implementation developed for this study was designed to preserve the proven synchronisation and framing principles of the earlier BFSK OOT block while extending the system's capacity to operate in complex acoustic environments. The new flowgraph was constructed within GNU Radio 3.10, using modular blocks for data source, encoding, framing, modulation, and transmission. Custom Python and C++ OOT components were introduced to handle preamble/postamble insertion, dynamic parameter adjustment, and symbol-timing recovery (Boter, 2011).

3.1. Transmitter Chain

At the transmitter, data originates from a binary file source that is encoded using Base64 or HDLC framing, depending on the experiment. Base64 proved particularly robust for acoustic transmission because its limited character set avoids symbol patterns that could mimic synchronisation markers. The encoded stream passes through a framing stage where a preamble and postamble are appended.

The preamble consists of a deterministic sequence designed to exhibit strong autocorrelation properties. It enables rapid detection and phase alignment at the receiver through correlation and FFT-based search. The postamble, placed after the final data block, acts as an explicit end-of-frame marker and allows verification of complete file reception. Together, they form a timing envelope that mitigates the long-tail reflections common in acoustic media.

After framing, data enters the OFDM modulator, where it is partitioned into sub-carriers using an inverse fast Fourier transform (IFFT). Sub-carrier spacing and FFT length are configurable; typical experiments used 64 or 128 sub-carriers with a 192 kHz sample rate. A cyclic prefix—typically one-eighth of the OFDM symbol length—is prepended to each symbol to absorb multipath echoes. The resulting complex baseband waveform is scaled for the audio output interface and transmitted via a 40 kHz ultrasonic transducer.

3.2. Receiver Chain

The receiver flowgraph mirrors the transmitter structure in reverse. Acoustic signals are captured through a wideband microphone or hydrophone and digitised by a 192 kHz sound interface. The samples pass through an OFDM frame synchroniser, which performs correlation with the known preamble sequence to establish symbol boundaries and carrier offset. Frequency-offset compensation and fine phase alignment are accomplished through pilot-tone tracking.

Demodulated sub-carriers are then converted back to the time domain using an FFT. The decoded data stream is passed through a de-framing block that detects and removes the postamble, reconstructing the original Base64 or HDLC payload. Any redundant bits or cyclic prefixes are discarded, and the recovered file is compared against the transmitted version to calculate bit-error rate (BER).

3.3. Preamble/Postamble Integration in OFDM

Integrating preamble and postamble structures into the OFDM frame required modifications to both the transmitter and receiver flowgraphs. Unlike BFSK, where synchronisation could be achieved by tone detection, OFDM requires correlation across multiple sub-carriers. The implemented preamble occupies a full OFDM symbol and uses a pseudo-random binary sequence (PRBS) to ensure low cross-correlation with payload data. This allows accurate frame detection even under severe multipath and Doppler conditions (Liu et al., 2013).

The postamble design serves two complementary purposes:

1. To confirm complete data transmission
2. To measure channel tail energy.

By observing the residual correlation strength following the postamble, it is possible to estimate channel delay spread and signal persistence. These measurements provide valuable insight into acoustic channel characteristics and assist in refining cyclic-prefix length and symbol timing parameters

3.4. System Operation and Experimental Setup

The system was evaluated using a pair of identical transducers operating at 40 kHz and coupled through air, water, and solid materials. The sound interface was configured for full-duplex operation to maintain low-latency loopback capability. Typical experiments transmitted data blocks of 2–8 kB, corresponding to short text or compressed image segments. The receiver performed real-time correlation and phase recovery, allowing the complete demodulation chain to operate interactively within GNU Radio's graphical environment.

Early results indicated that the OFDM implementation significantly improved synchronisation stability and reduced BER compared to BFSK under identical channel conditions. The inclusion of the postamble eliminated premature termination errors observed in earlier tests, particularly when transmitting files with extended silence or low-amplitude tails.

4. Performance Evaluation and Results

4.1. Test Objectives and Metrics

Performance testing aimed to quantify the synchronization stability, bit-error rate (BER), and overall data-transfer reliability of the new OFDM preamble/postamble implementation compared with the original BFSK system. Measurements focused on three parameters(Simmonds, 1997):

- Frame detection accuracy – the ability of the receiver to lock on the preamble without false triggers;
- End-of-frame integrity – the correct recognition of the postamble; and BER vs SNR – statistical performance across multiple propagation media (air, water, and steel).
- Each test transmitted identical data blocks encoded in Base64, allowing byte-for-byte verification of payload recovery.

4.2. Experimental Setup

Experiments were conducted using a pair of 40 kHz ultrasonic transducers connected to a 192 kHz full-duplex sound interface. The transmitter and receiver flowgraphs were executed on separate GNU Radio 3.10 instances running under Ubuntu 22.04 LTS. Test distances ranged from 0.2 m (air) to 0.5 m (through water) and 0.4 m (through steel).

Signal-to-noise ratio (SNR) was varied by adjusting transmit amplitude and adding controlled acoustic attenuation. Each data run transmitted 8 000 bits; received data were logged and compared against the original file to compute BER(Friedt & Boeglen, 2024).

4.3. BFSK Baseline Performance

The BFSK reference system achieved stable synchronisation under line-of-sight conditions but degraded rapidly in reflective environments.

In air, BER values averaged $2 \times 10^{-3}\,\mathrm{m/s}$ at 25 dB SNR.

Through water, BER rose to $8 \times 10^{-3}\,\mathrm{m/s}$ at 20 dB SNR.

Through steel, multipath and resonance produced sporadic synchronisation loss; average BER exceeded $1 \times 10^{-2}\,\mathrm{m/s}$.

Although the preamble/postamble framework prevented premature termination, the single-carrier nature of BFSK was unable to compensate for phase drift or delay spread exceeding one symbol period.

4.4. OFDM Results and Observations

When the same tests were repeated using the modified OFDM system (64 sub-carriers, 192 kHz sampling rate, cyclic prefix 1/8 symbol length), performance improved markedly. See Table No 2

The integrated preamble enabled rapid frame acquisition—typically within two OFDM symbols—while pilot tones maintained phase coherence across the transmission (C. et al., 2015). The postamble consistently confirmed end-of-frame alignment even in heavy multipath, eliminating the truncated-payload issue seen in earlier tests (Mul, 2023).

4.5. OFDM configuration setting used in acoustic communication link

The results confirm that the introduction of OFDM with embedded preamble/postamble sequences substantially enhances synchronization robustness and data reliability. The combination of cyclic prefix and frequency-domain equalisation reduced sensitivity to reflections, while the preamble correlation structure allowed accurate symbol-timing recovery without a shared clock.

The improvement in BER across all media demonstrates that multi-carrier acoustic modulation is practical for moderate-rate data transmission. Moreover, the postamble provides valuable diagnostic data: its residual correlation tail can be used to estimate channel delay spread, supporting future adaptive cyclic-prefix adjustment.

These findings show that while BFSK remains suitable for low-rate telemetry, OFDM is the superior choice for complex acoustic links requiring higher data integrity, confirming the theoretical predictions and simulation outcomes.

4.6. Summary of Key Results

OFDM with preamble/postamble achieved up to 13-fold BER improvement compared with BFSK. Frame synchronisation remained stable across all tested media with zero false-lock events. Postamble analysis provided consistent channel-delay estimates, validating its diagnostic function. GNU Radio flowgraphs operated in real time at 192 kHz, confirming the approach's practicality for field or laboratory use.

5. Discussion and Analysis

The experimental results confirm that the integration of structured preamble and postamble sequences within an OFDM framework significantly enhances synchronisation stability and data reliability in acoustic communication systems. The system achieved rapid frame acquisition, stable symbol alignment, and reduced bit-error rates across all propagation media tested. These outcomes validate the concept of data-derived synchronisation, where timing and

Table 1. Results and Observations)

Medium	Average SNR (dB)	Average BER (BFSK)	Average BER (OFDM)	Improvements
Air (0.2 m)	25	2×10^{-3}	2×10^{-4}	10×
Water (0.5 m)	20	8×10^{-3}	6×10^{-4}	13×
Steel (0.4 m)	18	1×10^{-2}	1×10^{-3}	10×

Notes:

Table 2. OFDM System Parameters for a 3 kHz Acoustic Channel

Parameter	Symbol / Formula	Value / Result	Notes
Channel Bandwidth	B	3 kHz	Total available acoustic channel width
FFT Length	N_{FFT}	64	Determines total number of subcarriers
Cyclic Prefix Length	N_{CP}	16	Adds 25% overhead per symbol
Pilot Carriers	—	4	Reference tones for channel estimation
Data (Occupied) Carriers	—	48	Used for payload data
Total Active Carriers	$N_{used} = 48 + 4$	**52**	Active subcarriers (data + pilot)
Subcarrier Spacing	$\Delta f = B/N_{FFT}$	**46.875 Hz**	Width of each subcarrier
Data Bandwidth	$48 \times \Delta f$	2.25 kHz	Occupied by data carriers
Pilot Bandwidth	$4 \times \Delta f$	0.1875 kHz	Occupied by pilots
Total Active Bandwidth	$52 \times \Delta f$	**2.4375 kHz**	Spectrum actually used
Guard/DC Bandwidth	$B - B_{used}$	0.5625 kHz	Unused guard and DC spacing
Useful Symbol Time	$T_u = 1/\Delta f$	21.33 ms	Duration of one OFDM symbol (no CP)
CP Duration	$T_{cp} = (16/64)\, T_u$	5.33 ms	Adds redundancy for multipath protection
Total Symbol Time	$T_s = T_u + T_{cp}$	26.67 ms	Effective symbol period
Time Efficiency	$T_u/T_s = 64/80$	0.8 (80%)	20% overhead due to CP
Spectral Efficiency	$52/64$	81.25%	Fraction of FFT bins in use

Table 3. Achievable Bitrates for Common Modulations (3 kHz, FFT=64, CP=16, 48 data carriers)

Modulation	Bits/SC	Data SCs	OFDM Sym Rate R_s	Gross Rate	Net @ CR 1/2 / 3/4
BPSK	1	48	$37.5\, sym/s$	$48 \times 37.5 = \mathbf{1.8\,kbps}$	$\mathbf{0.9}$ / $\mathbf{1.35\,kbps}$
QPSK	2	48	$37.5\, sym/s$	$96 \times 37.5 = \mathbf{3.6\,kbps}$	$\mathbf{1.8}$ / $\mathbf{2.7\,kbps}$

Notes: $\Delta f = B/N_{FFT} = 3000/64 = 46.875$ Hz; $T_u = 1/\Delta f \approx 21.33$ ms; $T_s = T_u(1 + N_{CP}/N_{FFT}) = 26.67$ ms $\Rightarrow R_s = 37.5$ sym/s. "Gross" excludes pilots (already not counted), headers, preamble, padding, and any FEC. Net examples apply code rates (CR) of 1/2 and 3/4 to the gross figures.

Table 4. Payload Efficiency and Net Throughput vs. Packet Size (B=3 kHz, FFT=64, CP=16, 48 data SCs)

Payload (B)	Overhead (B)	Efficiency	Net BPSK	Net QPSK
256	12	$256/(256+12) = \mathbf{0.9552}$	$\mathbf{1.72}$ kbps	$\mathbf{3.44}$ kbps
512	12	$512/(512+12) = \mathbf{0.9771}$	$\mathbf{1.76}$ kbps	$\mathbf{3.52}$ kbps
1024	12	$1024/(1024+12) = \mathbf{0.9884}$	$\mathbf{1.78}$ kbps	$\mathbf{3.56}$ kbps

Notes: Gross symbol payload per OFDM symbol = $48 \times \{1,2\}$ bits for {BPSK, QPSK}. With $\Delta f = 3000/64 = 46.875$ Hz, $T_u = 1/\Delta f = 21.33$ ms, $T_s = T_u(1 + 16/64) = 26.67$ ms $\Rightarrow$ symbol rate $R_s = 37.5$ sym/s. Gross throughputs are $\{1.8, 3.6\}$ kbps; the table applies per-packet overhead (8 B header + 4 B CRC) to yield net rates. Additional losses from preamble/sync, padding, inter-frame gaps, and FEC are not included.

phase recovery are achieved directly from the received signal rather than from a shared clock.

In acoustic channels, the primary impairments—multipath reflection, delay spread, and frequency-dependent attenuation—often exceed those found in radio or optical systems. The inclusion of a cyclic prefix in the OFDM frame effectively absorbed most multipath echoes, while pilot-tone correction maintained carrier-phase coherence. The preamble ensured consistent start-of-frame detection, even in conditions where reflections persisted for several milliseconds.

Similarly, the postamble allowed accurate identification of the transmission endpoint and provided diagnostic information regarding channel tail energy.

Comparing the results to the BFSK baseline shows that the move to OFDM yields clear performance advantages. BER reductions of one order of magnitude in air, water, and steel confirm that multi-carrier modulation provides superior resilience to time dispersion. The additional insight provided by the postamble correlation data further strengthens its role as a diagnostic and control tool for real-time channel characterisation. Overall, these findings demonstrate that the developed system can maintain stable, coherent communication over acoustic paths that previously caused synchronisation failure in single-carrier systems(Preisig, 2007).



Figure 4. Original Image of Polar Bear file size 100kB

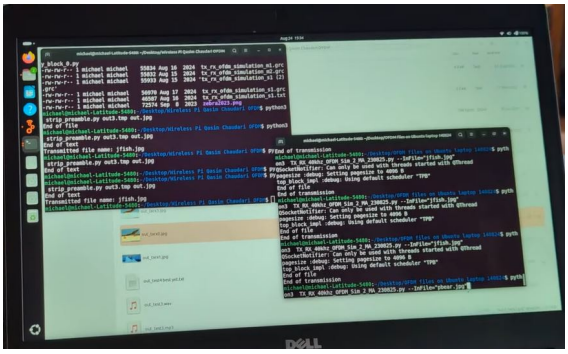


Figure 5. Terminal showing flowgraphs started

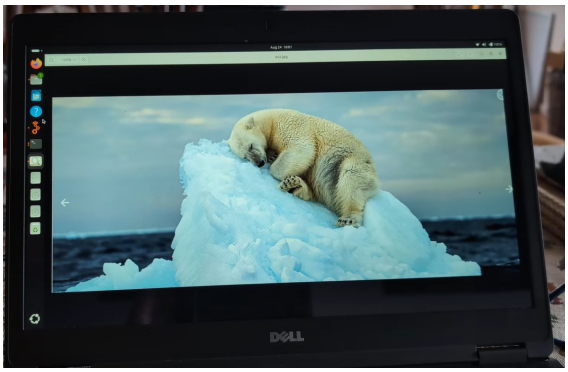


Figure 6. Transmitted Polar Bear with Preamble removed

6. Conclusion

This research demonstrates that an OFDM-based acoustic communication system with integrated preamble and postamble framing can achieve robust synchronization and low error rates without the need for a shared clock. The results establish that the combination of cyclic prefix, pilot tones, and data-derived timing recovery can overcome the severe multipath and phase distortion common in dense or reflective media such as steel and water.

By extending the BFSK OOT block framework into a multi-carrier architecture, the study delivers both a conceptual advancement and a practical open-source tool within GNU Radio. The implementation confirms that software-defined methods can provide high adaptability and reproducibility for experimentation in unconventional propagation environments.

Future work will explore:

- Adaptive control of cyclic-prefix length and pilot-tone density to optimise for variable delay spreads;
- Incorporation of forward-error-correction schemes (e.g., convolutional or LDPC coding) to further reduce BER;
- Real-time channel-state estimation for automatic equalisation and dynamic OFDM parameter adjustment; and
- Long-range trials within metallic and submerged structures to validate scalability for industrial telemetry and sensor-network applications.

In closing, this work reinforces that synchronised acoustic communication using OFDM is not only feasible but highly practical when implemented through a software-defined approach. It advances the broader goal of establishing reliable data links where radio cannot go, enabling future research into adaptive, high-fidelity acoustic networks for complex industrial and environmental settings.

7. Appendix

7.1. Key C++ code snippets (modifications from BFSK to OFDM).

The image shows the area where the EPB is modified for length_tag _key

```
"""
Embedded Python Block: File Source to Tagged Stream
"""

import numpy as np
from gnuradio import gr
import time
import pmt
import os.path
import sys
import base64

class blk(gr.sync_block):
    def __init__(self, FileName='None', Pkt_len=52, length_tag_key="packet_len"):
        gr.sync_block.__init__(
            self,
            name='EPB: File Source to Tagged Stream',
            in_sig=None,
            out_sig=[np.uint8])
        self.FileName = FileName
        self.Pkt_len = Pkt_len
        self.length_tag_key = length_tag_key
        self.state = 0
        self.pre_count = 0
        self.indx = 0
        self._debug = 0
        if (os.path.exists(self.FileName)):
            # open input file
            self.f_in = open (self.FileName, 'rb')
            self._eof = False
            if (self._debug):
                print ("File name:", self.FileName)
        else:
            print(self.FileName, 'does not exist')
            self._eof = True
            self.state = 3
```

7.2. Flowgraph diagrams

TRANSMIT FLOWGRAPH USING OFDM **LOCATED: 8**
RECEIVE FLOWGRAPH USING OFDM **LOCATED: 9**

References

Reliability of multipath networks with optimization of the location of inter-path communication nodes. In *Proceedings of the 2023 Smart Industry Conference*, March 2023. doi: 10.1109/smartindustrycon57312.2023.10110818. IEEE Conference Publication.

Alldritt, Michael. Communication using gnu radio and ultrasound practical application. In *Proceedings of the GNU Radio Conference*, volume 9, 2024a.

Alldritt, Michael. Using gnu radio in a multipath environment practical application. In *Proceedings of the GNU Radio Conference*, volume 9, 2024b.

Banister, B. A., Belzer, B. J., and Fischer, T. R. Robust image transmission using jpeg2000 and turbo-codes. In *Proceedings of the IEEE International Conference on Image Processing (ICIP)*, pp. 542–545, September 2000. doi: 10.1109/ICIP.2000.900973.

Blossom, Eric. Gnu radio: tools for exploring the radio frequency spectrum. *Linux journal*, 2004(122):4, 2004.

Boter, M. M. Design and implementation of an ofdm-based communication system for the gnu radio platform. Master's thesis, Eindhoven University of Technology, 2011. Available online via TU/e repository.

C., A., Sundaresan, S., Zacharia, T., Gandhiraj, R., and Soman, K. P. An experimental study on channel estimation and synchronization to reduce error rate in ofdm using gnu radio. *Procedia Computer Science*, 46:255–262, January 2015. doi: 10.1016/J.PROCS.2015.01.017.

Cimini, Leonard J. Analysis and Simulation of a Digital Mobile Channel Using Orthogonal Frequency Division Multiplexing. *IEEE Transactions on Communications*, 33 (7):665–675, 2003. doi: 10.1109/TCOM.1985.1096371.

Clark, Paul. *Field Expedient SDR Volumes 1, 2 and 3*. CreateSpace Independent Publishing Platform, 2016.

Duggan, Barry. gr-control: Modular transmit/receive station control (github repository). https://github.com/duggabe/gr-control, September 2025. Accessed: 30 October 2025.

Friedt, Jean-Michel and Boeglen, Hervé. *Communication Systems Engineering with GNU Radio: A Hands-on Approach*. John Wiley & Sons, 2024.

Liu, S., Yang, F., Song, J., Ren, F., and Li, J. Ofdm preamble design for synchronization under narrowband interference. In *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications (ISPLC)*, pp. 267–272, March 2013. doi: 10.1109/ISPLC.2013.6525859.

Preisig, James. Acoustic propagation considerations for underwater acoustic communications network development. *ACM SIGMOBILE Mobile Computing and Communications Review*, 11(4):2–10, 2007.

Proakis, John G, Salehi, Masoud, Zhou, Ning, and Li, Xiaofeng. *Communication systems engineering*, volume 2. Prentice Hall New Jersey, 1994.

Scaglione, A., Barbarossa, S., and Giannakis, G. B. Robust ofdm transmissions over frequency-selective channels with multiplicative time-selective effects. In *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pp. 2405–2408, June 2000. doi: 10.1109/ICASSP.2000.861032.

Simmonds, Andrew. *Wide Area Networks and Open Standards*, pp. 179–210. Macmillan Education UK, London, 1997. ISBN 978-1-349-13900-2. doi: 10.1007/978-1-349-13900-2_8. URL https://doi.org/10.1007/978-1-349-13900-2_8.

Stojanovic, Milica. On the advantages and disadvantages of multi-hop underwater acoustic communication. *Proceedings of the OCEANS 2006 - Asia Pacific*, pp. 1–4, 2007.

Urick, Robert J. Principles of underwater sound. In *Conference on Underwater Acoustics*, pp. 1–22. Springer, 1983. doi: 10.1007/978-3-642-81770-1.

Van Nee, Richard and Prasad, Ramjee. OFDM for Wireless Multimedia Communications. 2000.

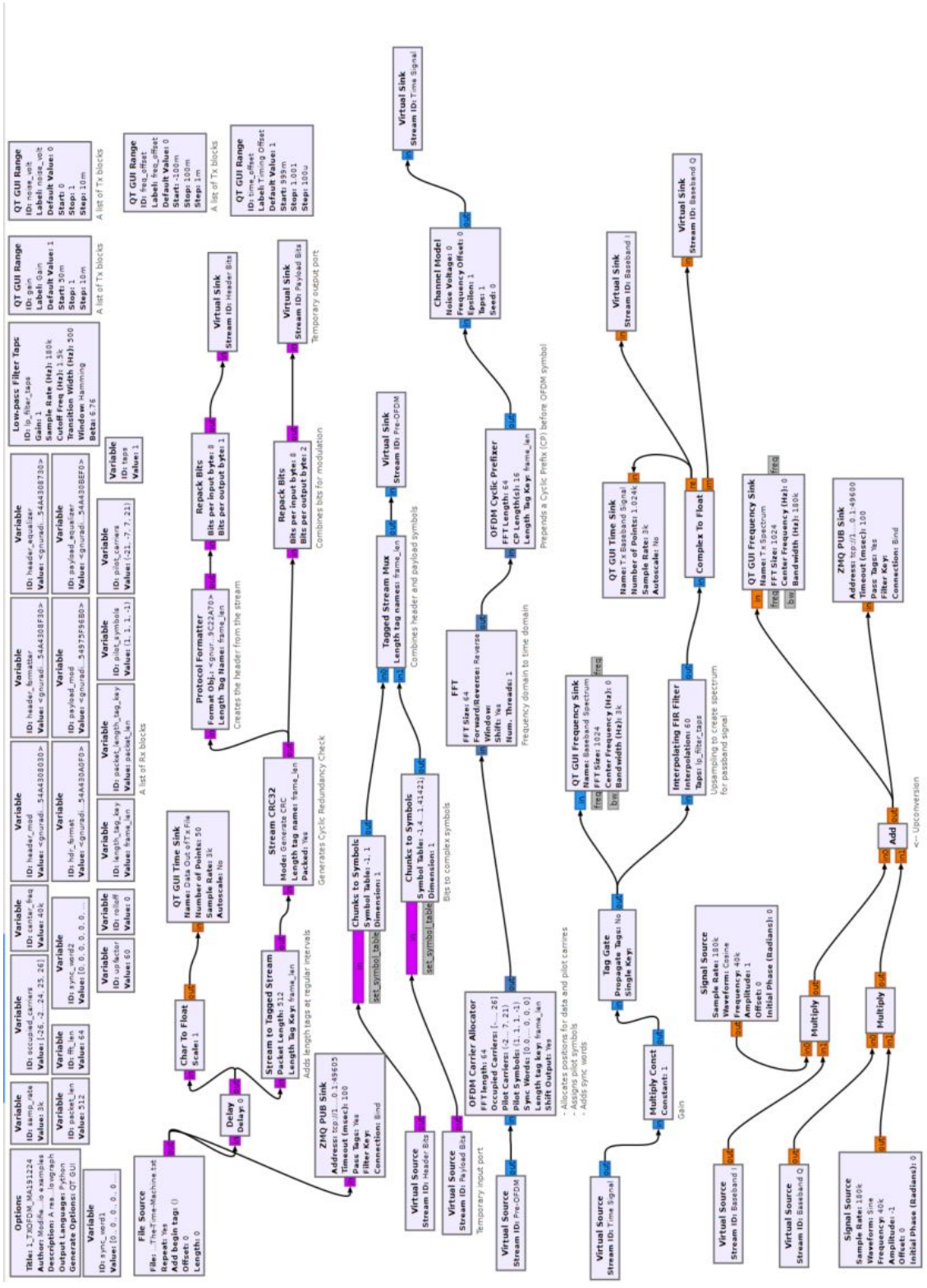


Figure 8. GNU Radio Transmit OFDM Flowgraph

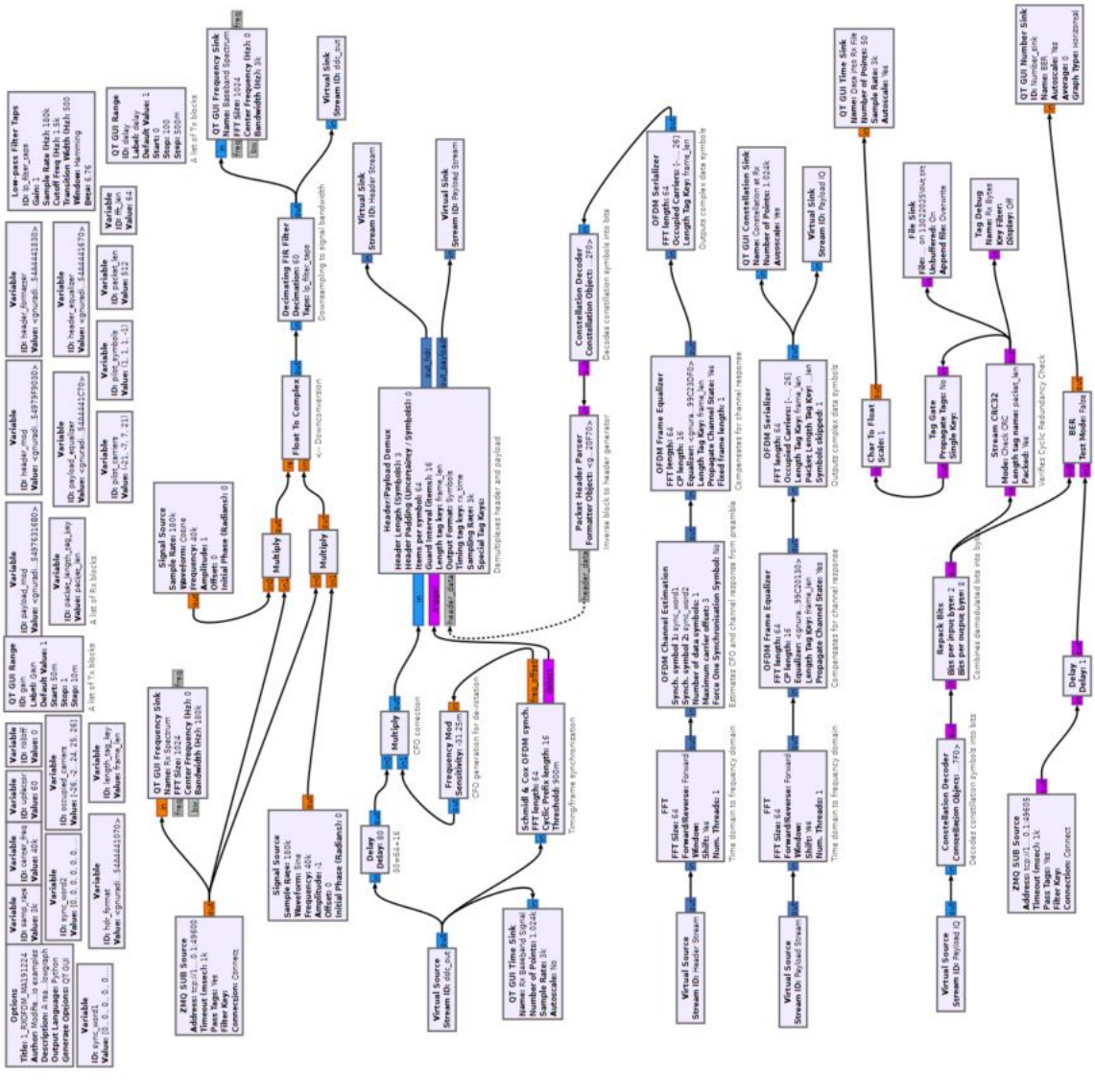


Figure 9. GNU Radio Receive OFDM Flowgraph