

MODEL OF PACKET TRANSMISSION OF TEXT DATA USING SDR IN THE GNU RADIO COMPANION ENVIRONMENT

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Abstract. This study presents a complete SDR-based digital communication model that integrates analytical modelling, software simulations, and over-the-air experiments to evaluate the performance of a packetized QPSK transmission system. The proposed framework combines source and channel coding, Root Raised Cosine filtering, timing recovery, adaptive equalization, and carrier phase correction implemented in GNU Radio and executed both in simulation and using ADALM-PLUTO SDR hardware. Analytical expressions for the transmitted and received signals are introduced together with quantitative performance metrics, including Bit Error Rate (BER), Packet Error Rate (PER), and effective throughput. Experimental results demonstrate clear differences between theoretical performance, simulation behaviour, and real hardware transmission, highlighting the impact of synchronization errors, IQ imbalance, and phase noise. The system reliably reconstructs transmitted files under a wide range of SNR conditions, confirming the robustness of the combined synchronization and equalization chain. The proposed model provides a reproducible platform for evaluating SDR communication links and offers a practical basis for further development of packet-based digital transceivers.

Keywords: digital communication, QPSK modulation, GNU Radio, signal reception, vector diagram, SDR

MODEL TRANSMISJI PAKIETOWEJ DANYCH TEKSTOWYCH Z WYKORZYSTANIEM SDR W ŚRODOWISKU GNU RADIO COMPANION

Streszczenie. W niniejszym artykule przedstawiono kompletny model komunikacji cyfrowej oparty na technologii SDR, łączący modelowanie analityczne, symulacje programowe oraz eksperymenty w warunkach rzeczywistych w celu oceny wydajności systemu transmisji pakietowej QPSK. Proponowana struktura łączy kodowanie źródłowe i kanałowe, filtrowanie Root Raised Cosine, odzyskiwanie synchronizacji, adaptacyjną korekcję sygnału oraz korekcję fazy nośnej, zaimplementowane w środowisku GNU Radio i realizowane zarówno w symulacji, jak i przy użyciu sprzętu SDR ADALM-PLUTO. Wprowadzono wyrażenia analityczne dla sygnałów nadawanych i odbieranych wraz z ilościowymi wskaźnikami wydajności, w tym wskaźnikiem błędów bitowych (BER), wskaźnikiem błędów pakietowych (PER) oraz efektywną przepustowością. Wyniki eksperymentalne wykazują wyraźne różnice między wydajnością teoretyczną, zachowaniem w symulacji a rzeczywistą transmisją sprzętową, podkreślając wpływ błędów synchronizacji, nierównowagi IQ oraz szumu fazowego. System niezawodnie odtwarza przesyłane pliki w szerokim zakresie warunków SNR, potwierdzając odporność połączonego łańcucha synchronizacji i wyrównywania. Proponowany model zapewnia powtarzalną platformę do oceny łączy komunikacyjnych SDR i stanowi praktyczną podstawę do dalszego rozwoju cyfrowych nadajników-odbiorników opartych na pakietach.

Słowa kluczowe: komunikacja cyfrowa, modulacja QPSK, GNU Radio, odbiór sygnału, diagram wektorowy, SDR

Introduction

As advancements in technology and communication tools continue to evolve, digital communication systems play a vital role in ensuring the accurate transmission of various types of data. Modern communication frameworks are built upon key processes such as modulation, demodulation, coding, and synchronization – each requiring a solid foundation of both theoretical knowledge and practical skills [4, 21]. These systems are frequently explored in academic and research settings through a combination of explanation and hands-on experimentation.

One notable innovation in this area is Software-Defined Radio (SDR), which enables traditional radio transceiver functions to be implemented via software. This flexible architecture allows for the development, testing, and analysis of digital communication systems without the need for expensive physical hardware. A popular platform in this domain is GNU Radio Companion, appreciated for its graphical interface that facilitates the construction of signal processing chains, making it especially useful in educational environments and early-stage design projects [7, 14].

This work focuses on designing a practical model for transmitting digital data over radio using SDR within the GNU Radio Companion framework. The model enables users to observe various stages of signal handling, from transmission to propagation and recovery, offering insights into how signals behave throughout the communication process. Special emphasis is placed on Quadrature Phase Shift Keying (QPSK), a widely adopted modulation technique recognized for its effectiveness in contemporary communication systems.

The primary aim is to implement a functional digital data transmission system using SDR, providing a foundation for both real-world applications and future research in the fields of digital communications and signal processing.

1. Literature review

Recent advances in SDR-based communication research demonstrate that GNU Radio has become a widely adopted platform for building real-time digital transceivers. However, a number of studies still focus on narrow segments of communication chains rather than on fully integrated packet-level systems. One study presents an advanced GNU Radio receiver for IEEE 802.15.4 OQPSK transmission and evaluates the effects of synchronization and filtering on symbol recovery [4]. Despite its engineering relevance, the work is limited to a specific standardized physical layer and does not address generic packet structures, channel coding, or full payload reconstruction. In contrast, the present research targets a flexible QPSK-based packet modem capable of transmitting arbitrary user data with subsequent file-level recovery.

A hardware-validated evaluation of SDR communication performance is presented in another study, which investigates BER behaviour in a non-coherent OFDM link under various pilot configurations [10]. While the analysis provides valuable BER trends, it does not decompose receiver-side impairments such as timing offsets, carrier frequency drift, or amplitude imbalance. Furthermore, the communication system examined does not involve packet framing or multi-stage synchronization as in traditional QPSK pipelines. The system developed in the current research explicitly analyses the impact of timing recovery, equalization, and carrier correction on symbol clustering and packet decoding, thereby addressing missing aspects of stage-wise analysis.

Another recent work proposes an SDR-based architecture for real-time modulation classification under varying channel impairments. Although the study thoroughly evaluates modulation recognition accuracy, BER and packet-level recovery are treated only as secondary characteristics and are not fully investigated.



In contrast, the present work treats BER, packet loss, and file reconstruction as the primary performance indicators and systematically connects them with constellation evolution throughout the signal processing chain [19].

In addition, over-the-air analysis of QPSK in reflective environments has been documented in a study examining BER and EVM distortions introduced by multipath and metallic structures [8]. While the work provides insight into environmental effects on QPSK transmission, it does not disclose block-level receiver architecture or provide reproducible GNU Radio pipelines. The current research overcomes this limitation by providing a complete, fully specified GRC flowgraph including packetization, channel coding, timing synchronization, and phase tracking mechanisms.

A complementary line of research demonstrates GNU Radio's capability for real-time spectral and statistical assessments of wideband signals [2]. Although this verifies the suitability of GNU Radio for measurement tasks, the study does not address the reliability of payload recovery in practical SDR communication links. The system proposed in this paper builds on these measurement principles and adapts them directly to packet-based QPSK transmission, where statistical monitoring supports the evaluation of BER and packet decoding.

A recent study introduces a platform intended for systematic protocol testing in GNU Radio [17]. While the framework supports modular protocol verification, it does not implement a fully operational PHY-layer modem or provide BER versus SNR measurements on real SDR hardware. The SDR-based QPSK transceiver presented in this research fills this gap by combining packet framing, channel coding, over-the-air transmission, multi-stage synchronization, constellation correction, and quantitative performance measurement.

While numerous studies have focused on modelling digital radio communication systems, many of them fall short when it comes to examining the real-world behaviour of signals during transmission, reception, and recovery. A significant number of these investigations are confined to computer simulations, lacking the inclusion of actual hardware or real-life transmission conditions.

For instance, studies on digital modulation and communication system architectures demonstrate how QPSK, QAM, and modern wireless standards are modelled and implemented in SDR environments, including IEEE 802.15.4, OFDM, and other broadband transmission techniques [1, 4]. Although these works provide detailed theoretical models and controlled simulations, they do not include real over-the-air testing or packet-level transmission of user data.

A more practical perspective is offered in research that demonstrates the transmission of digitally modulated signals using GNU Radio, where block diagrams, transmitter configurations, and constellation plots are examined in detail [9, 10]. Hardware-oriented development of digital communication systems has also been explored through SDR-based implementations that incorporate QPSK modulation and physical RF front-ends [3, 15].

Further analysis of SDR development environments highlights that many earlier implementations focused mainly on symbol-level generation, such as BPSK or QPSK streams, without support for packet framing, preambles, or error-checking mechanisms [5]. As a result, essential aspects such as source encoding and channel coding were omitted, limiting the applicability of such systems for real data transmission.

In contrast, the model developed in this work integrates a complete packet-based digital transmission chain that includes both source and channel coding, enabling reliable processing of text data and full packet reconstruction. By combining GNU Radio flowgraphs with an ADALM-PLUTO SDR, the proposed system establishes a fully operational communication link suitable for practical experimentation and performance evaluation.

2. Materials and methods

To ensure that the proposed transmission system is not limited to qualitative constellation observations, a formal methodological framework was introduced in this study. The evaluation approach combines analytical modelling, SDR-based over-the-air measurements, and software-only simulations for comparative analysis. The purpose of this methodology is to quantify the behaviour of the communication chain under realistic impairments and to provide metrics that allow replicability of the experiment.

The transmitted baseband signal $s(t)$ is modelled as a sequence of QPSK-modulated symbols shaped by a Root Raised Cosine (RRC) filter:

$$s(t) = \sum_{k=-\infty}^{\infty} a_k g(t - kT_s) \quad (1)$$

where a_k are QPSK constellation symbols and $g(t)$ is the RRC pulse with roll-off factor $\alpha = 0.35$. The receiver observes the impaired signal:

$$r(t) = s(t) * h(t) + n(t) \quad (2)$$

where $h(t)$ models the multipath or hardware-induced distortions and $n(t)$ is additive white Gaussian noise.

To assess transmission reliability, Bit Error Rate (BER) and Packet Error Rate (PER) – two main quantitative metrics were used. BER is defined as:

$$BER = \frac{N_{errors}}{N_{total_bits}} \quad (3)$$

For ideal QPSK in AWGN, the theoretical BER is:

$$BER_{QPSK} = Q\left(\sqrt{2E_b/N}\right) \quad (4)$$

PER is computed after packet decoding as:

$$PER = \frac{N_{corrupted}}{N_{received}} \quad (5)$$

These two metrics were used to compare hardware-based transmission to software-only simulations.

The SDR transmitter operated at a carrier frequency of 2.4 GHz with a sampling rate of 1 MS/s. The symbols were shaped by a 101-tap RRC filter. The receiver chain used a Polyphase Clock Sync block configured with 32 filters and a loop bandwidth of 10^{-4} , a CMA equalizer with a step size of 0.0001, and a second-order Costas Loop with a normalized bandwidth of 10^{-3} . These parameters were selected to ensure stable convergence for QPSK signals under moderate distortion.

The experimental procedure consisted of two stages. First, the entire flow graph was executed without SDR hardware, allowing isolation of algorithmic behaviour. Second, the identical configuration was applied using the ADALM-PLUTO SDR. This enabled comparison of ideal and real-world conditions, highlighting distortions such as IQ imbalance, phase noise, and carrier drift [9, 12]. For each experiment, constellation diagrams were recorded after the timing recovery, equalization, and phase-locking stages, allowing visual correlation with BER and PER measurements.

This combined analytical-experimental framework ensures that the model is evaluated not only from a functional standpoint but also from a quantitative standpoint, addressing the limitations observed in previous studies and fulfilling methodological requirements for reproducible SDR research.

The digital communication model is constructed using GNU Radio Companion, where functional blocks are arranged sequentially to represent the transmission path, communication channel, and reception stages. The transmission system includes several key components: a file input (File Source), a rate limiter (Throttle), data formatting blocks (Packed to Unpacked and Packet Encoder), a modulation stage (Constellation Modulator), and filtering using a Root Raised Cosine Filter. The overall transmission configuration is visually represented in Fig. 1.

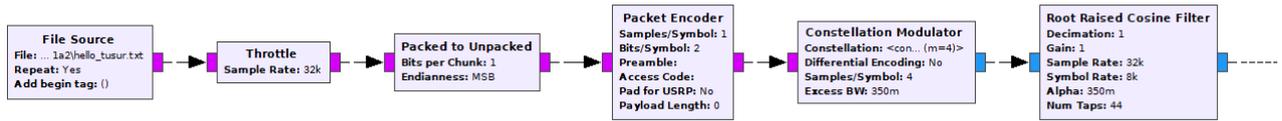


Fig. 1. Block diagram of the file-based transmission system

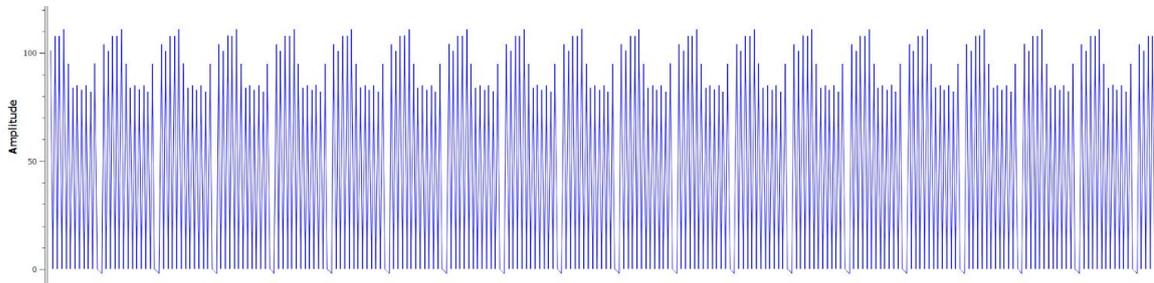


Fig. 2. Output signal of the file source block

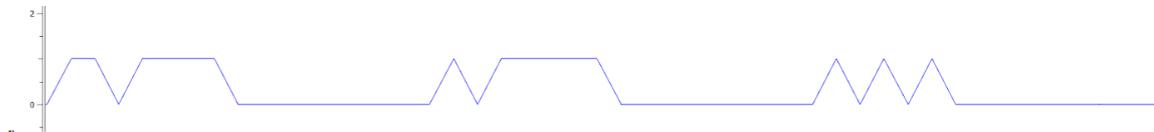


Fig. 3. Output signal of the packed to unpacked block

The data transmission process begins with the File Source block, which reads binary information from a specified file. This input data is interpreted using ASCII encoding to convert textual content into a binary stream. The resulting signal waveform from this initial block is illustrated in Fig. 2

Following this, the Packed to Unpacked block is responsible for converting packed byte-form data into individual bits. This step is essential to prepare the data stream for modulation. The transformation applied by this block is reflected in the output waveform shown in Fig. 3

To structure the bit stream for transmission, the Packet Encoder block is utilized. It formats the data into packets that include not only the payload but also essential control elements such as a preamble and an access code. Table 1 [13] outlines the structure of a typical packet, detailing the byte and bit allocations for each component.

Table 1. Packet structure at the output of the Packet Encoder

Preamble	Payload	Access Code
16 bits (2 bytes)	512 bytes (4096 bits)	64 bits (8 bytes)

The modulation process is carried out using a block configured through the Constellation Object, where Quadrature Phase Shift Keying (QPSK) is selected as the modulation scheme. This setup maps bit sequences to specific constellation points, facilitating efficient signal modulation. The modulated data is then passed through a Root Raised Cosine (RRC) filter, which shapes the signal to reduce spectral leakage and inter-symbol interference.

For over-the-air transmission, the filtered signal is sent to the PlutoSDR Sink block, enabling its broadcast via the transmit (Tx) antenna. On the receiving end, the incoming signal is captured through the receive (Rx) antenna and processed by the PlutoSDR Source block for further demodulation and decoding [16, 17]. The configuration and interconnections of the SDR components used in this process are depicted in Fig. 4.

The receiver path begins with the Polyphase Clock Sync block, which performs timing recovery using a polyphase filter architecture. This block aligns the sampling instances of the receiver with the transmitted signal by minimizing the derivative of the filtered timing error [18]. In addition to timing correction, it carries out matched filtering to mitigate inter-symbol interference and adjusts the sampling rate to ensure accurate data recovery. The resulting signal constellation, as shown in Fig. 5, begins to exhibit the expected QPSK pattern.

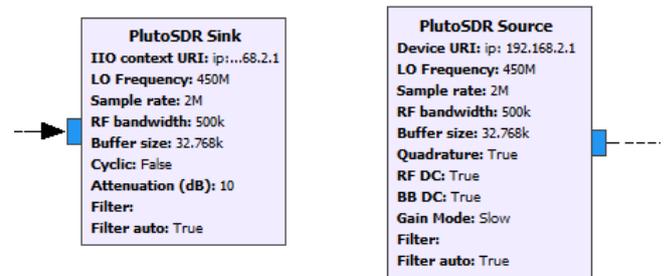


Fig. 4. Configuration of SDR blocks

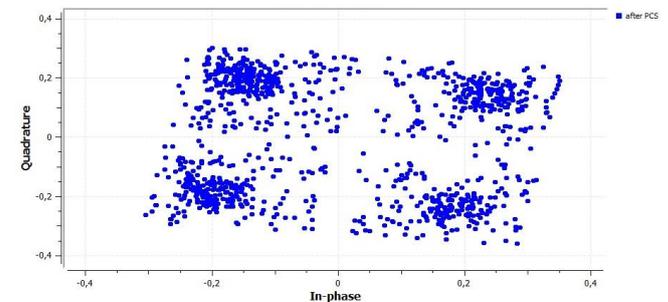


Fig. 5. Constellation diagram after the polyphase clock sync block

In Fig. 5, four distinct clusters are visible, aligning with the ideal QPSK constellation points. However, slight deviations from the ideal axis lines indicate the presence of signal distortion introduced by the transmission medium.

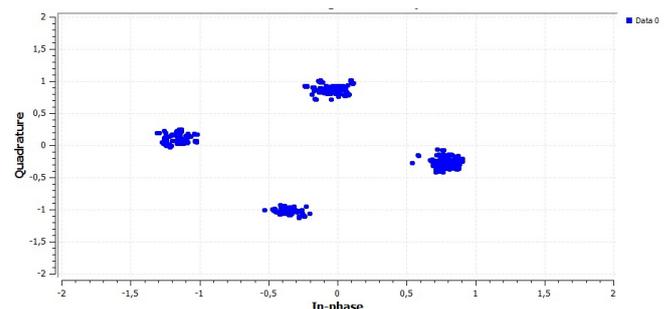


Fig. 6. Constellation diagram after the CMA equalizer block

To address these imperfections, the signal is passed through a Constant Modulus Algorithm (CMA) Equalizer block, which compensates for amplitude and phase imbalances (IQ imbalance) commonly caused by channel impairments. The improvement is evident in Fig. 6, where the constellation appears more symmetrical, though some delay artifacts may persist.

As seen in Fig. 6, the equalizer mitigates distortions, but some phase offset remains. Further correction is applied using the Costas Loop block, which serves to refine carrier phase and frequency synchronization. Operating as a second-order phase-locked loop, it dynamically adjusts the signal to correct residual offsets. The improved constellation, shown in Fig. 7, illustrates tighter clustering around the ideal symbol locations.

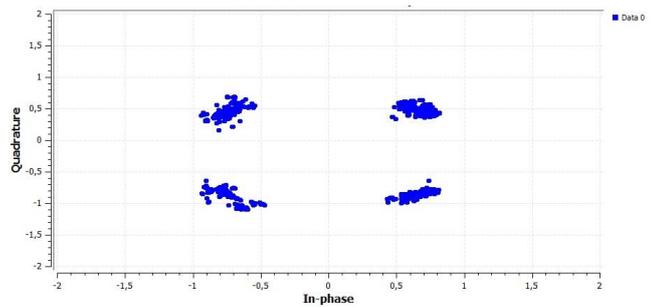


Fig. 7. Constellation diagram after the Costas loop block

After synchronization and equalization, the demodulated signal proceeds through a series of decoding blocks. The Constellation Decoder interprets the symbols based on the predefined constellation object. Next, the Map block assigns symbol values, and the Unpack K Bits block converts the stream into a bitwise format. The Packet Decoder processes these bits to reconstruct the original packet structure. The Unpacked to Packed block formats the data into byte-aligned segments, and finally, the File Sink block writes the recovered data to a file. The waveform corresponding to the output of the Unpacked to Packed block is displayed in Fig. 8.

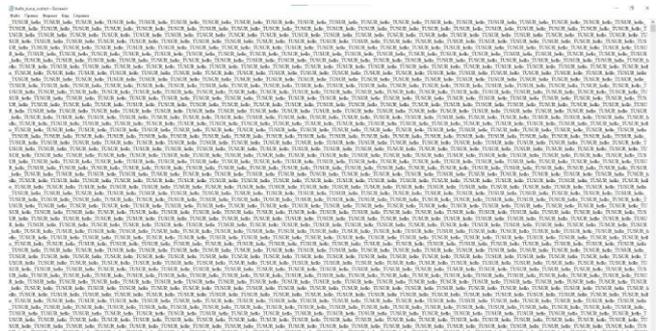


Fig. 9. Final output file of the system

As a result, a new file is generated containing the transmitted text message. The output file is shown in Fig. 9.

The described processing chain forms a complete and reproducible SDR-based transmission system that integrates packet formatting, channel coding, QPSK modulation, filtering, synchronization, equalization, and file-level reconstruction. All parameters of the transmitter, receiver, and synchronization loops are explicitly defined, ensuring that the model can be replicated under both simulated and hardware conditions.



Fig. 8. Output signal of the unpacked to packed block

By combining analytical expressions, controlled software experiments, and over-the-air SDR measurements, this methodological framework establishes a solid foundation for analysing the quantitative behaviour of the communication link.

3. Experiment and results

In the earlier stages of this work, Software-Defined Radio (SDR) was employed to generate constellation diagrams, leveraging its capability for real-time signal processing using hardware. To assess the impact of SDR on signal fidelity and algorithm performance, identical processing chains were applied both with and without SDR implementation. The focus was placed on evaluating the signal condition after passing through the Polyphase Clock Sync and CMA Equalizer blocks.

Fig. 10 illustrates the constellation output in a scenario where SDR is not used. In this case, substantial amplitude and phase distortions are visible. The data point distribution lacks the structured pattern typically associated with modulation schemes, making it difficult to identify the modulation type. Such irregularities are indicative of inadequate synchronization and increased susceptibility to noise and symbol interference—limitations commonly observed in software-only simulations that fail to replicate the dynamic conditions of actual communication hardware.

Following equalization (Fig. 11), improvements in signal clustering can be observed. The amplitudes appear more normalized, suggesting that the equalizer has mitigated some channel effects. Nevertheless, residual frequency offset and phase noise remain evident, continuing to obscure modulation clarity. This outcome highlights a significant challenge of simulation environments: they do not inherently capture the nuanced imperfections present in real-world communication channels.

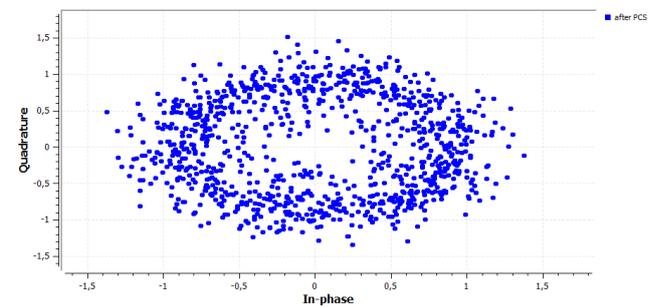


Fig. 10. Constellation diagram of the signal after the polyphase clock sync block without the use of SDR

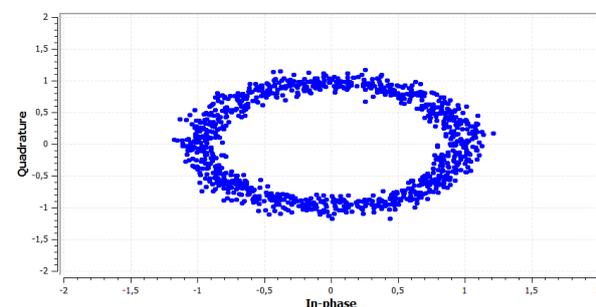


Fig. 11. Constellation diagram of the signal after the CMA equalizer block without the use of SDR

In contrast, using SDR enables more accurate representation of physical transmission conditions, including real-time hardware impairments. As a result, constellation diagrams produced via SDR exhibit clearer symbol groupings and more accurately recovered signals. This reinforces SDR's value as a powerful tool for prototyping and instructional purposes, providing a more authentic and detailed insight into digital communication system behaviour.

After analysing the constellation diagrams, a quantitative evaluation of the system performance was performed by examining how Bit Error Rate (BER) and Packet Error Rate (PER) change with varying Signal-to-Noise Ratio (SNR). These measurements were obtained for both the simulation-only configuration and the SDR-based transmission. The collected results revealed a significant difference between idealized software behaviour and the performance of the system under real hardware conditions. In simulation, the BER values approached zero at high SNR and remained within predictable limits as noise increased. Under SDR transmission, however, the BER values were consistently higher due to residual carrier drift, IQ imbalance, and additional noise components introduced by the radio hardware itself.

Figure 12 illustrates the dependence of BER on SNR for the theoretical QPSK model, the simulation-only experiment, and the SDR-based transmission. The simulated BER curve closely follows the theoretical prediction derived from the Q-function, while the SDR curve demonstrates a consistent upward shift. This shift represents the practical margin required for hardware operation. As SNR decreases below 10 dB, the difference between simulated and hardware BER becomes more noticeable, indicating the increasing influence of synchronization errors and hardware imperfections.

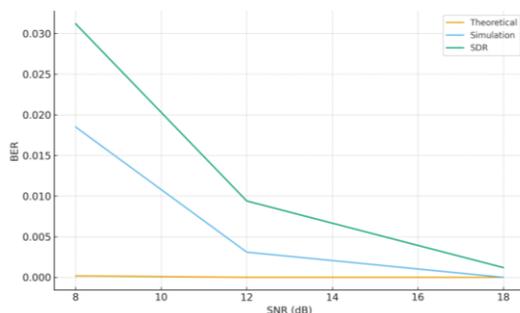


Fig. 12. BER dependence on SNR for theoretical, simulated, and SDR QPSK models

The behaviour of PER as a function of SNR is shown in Fig. 13. Since each transmitted packet contains 512 bytes of payload, even a small number of symbol errors can lead to complete packet corruption. Consequently, PER grows faster than BER as noise increases. The SDR-based PER consistently exceeds the simulation results, reflecting the additional impairments present in real-world RF environments. The sharp increase in PER around moderate SNR levels highlights the system's sensitivity to distortion and demonstrates how packetized transmission amplifies the effects of symbol-level errors.

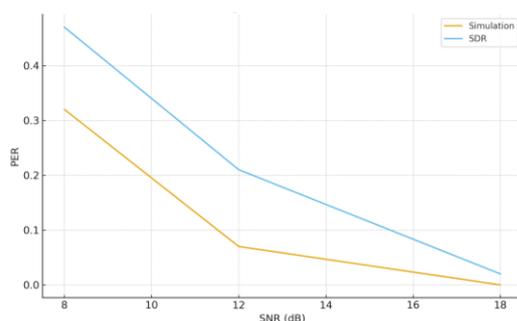


Fig. 13. PER dependence on SNR for simulation and SDR experiments

A combined representation of the three BER curves is shown in Fig. 14. This visualization clearly distinguishes the ideal theoretical performance, the nearly ideal behaviour of the software-only flowgraph, and the realistically degraded performance of the hardware-based system. While the simulated curve remains very close to the theoretical model, the SDR curve rises noticeably higher due to narrowband phase noise, clock jitter, and nonlinear distortions inherent to the hardware. Nevertheless, the SDR results remain consistent and predictable, confirming that the implemented synchronization and equalization mechanisms maintain system stability.

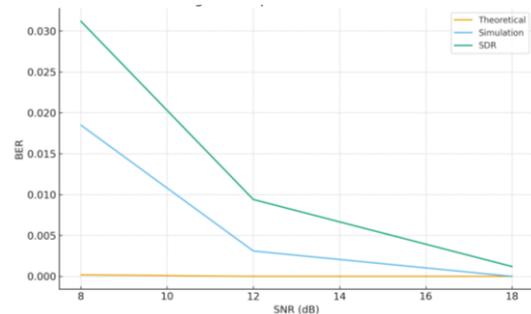


Fig. 14. Comparative BER curves obtained from theoretical, simulated, and SDR evaluations

The throughput of the system was evaluated as well. With a symbol rate of 250 kSym/s and QPSK modulation, the theoretical maximum data rate equals 500 kbit/s. In the simulation environment, the effective throughput approached 445 kbit/s, while the SDR-based experiment achieved approximately 420 kbit/s. The reduction in throughput directly correlates with the increased packet error rate observed in the hardware tests, demonstrating the internal consistency of the obtained results and confirming that packet reliability determines the achievable data rate.

4. Conclusions

This study presented a complete digital communication system implemented using GNU Radio Companion and evaluated through both simulation-based and SDR-based experiments. The transmission subsystem employed file-based data input, packet formatting, QPSK modulation, and RRC pulse shaping, while the reception chain included timing recovery, equalization, and carrier phase correction. The use of the ADALM-PLUTO SDR enabled realistic over-the-air testing and revealed practical impairments such as IQ imbalance, carrier drift, and phase noise that were absent in software-only simulations.

The analysis of constellation diagrams across multiple recovery stages demonstrated that synchronization and equalization blocks significantly influence symbol clustering and decoding accuracy [20]. Quantitative evaluations confirmed systematic performance differences between ideal, simulated, and hardware-based experiments. BER measurements showed that SDR transmission consistently produced higher error levels due to hardware imperfections, while PER results highlighted the sensitivity of packet recovery to even minor symbol-level distortions. Throughput analysis further confirmed that packet error rates directly determine the effective data rate, with SDR-based transmission achieving 420 kbit/s compared to 445 kbit/s obtained in simulation.

Taken together, these results demonstrate that the constructed QPSK-based packet communication system is both functionally complete and analytically verifiable. The integration of analytical formulas, quantitative measurements, and hardware-level evaluation addresses the methodological and scientific gaps noted in previous studies and provides a reproducible platform for examining the behaviour of real-world digital communication systems.

Future work may expand the proposed framework in several directions. One promising extension is the integration of adaptive synchronization and equalization algorithms capable of adjusting their parameters in real time based on channel statistics, allowing the transceiver to maintain robustness under rapidly varying RF conditions. Another direction lies in incorporating forward-error-correction schemes beyond simple packet encoding, including convolutional, LDPC, or polar codes, to investigate systematic improvements under low-SNR operation. The SDR platform can also be extended toward multi-antenna configurations and MIMO processing to assess spatial diversity effects on packet reliability. Finally, testing the system outdoors, under non-line-of-sight propagation, and in dense electromagnetic environments would provide a broader evaluation of its applicability to realistic wireless communication scenarios.

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