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Original Article

Development of GNSS Transmitter and Receiver Using GNU Radio: A Software-Defined Approach

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Abstract - *Numerous novel systems and technologies have surfaced in the domain of satellite navigation since the seminal advancement of the Global Positioning System (GPS). The entities comprise autonomous Global Navigation Satellite Systems (GNSSs), including but not limited to the IRNSS of India, GLONASS of Russia, GALILEO of Europe, and BEIDOU-2 of China. Amidst this ever-changing environment, there has been a growing need for dependable and adaptable receivers in a vast array of applications, including military, commercial, research, and commercial sectors. Flexibility in this context entails the ability to adapt to future enhancements as well as reconfigure in real-time to accommodate various signal formats. One potential strategy for achieving these design goals is to implement the Software-Defined Radio (SDR) paradigm. Recent progress in processor technology has facilitated the creation of (completely) software-defined receivers that exhibit performance levels comparable to or surpassing those of conventional hardware devices. Moreover, these receivers provide the benefits of adaptability and complete configurability. However, there are obstacles to upgrading existing hardware devices, particularly regarding support for and compatibility with legacy protocols. The implementation of reconfigurable hardware architecture offers a feasible resolution to these challenges by facilitating the modification of hardware to accommodate advancements in technology. However, the financial investment necessary to acquire the necessary hardware and software for configuring this module remains substantial. In this paper, a GNSS transmitter and receiver are implemented using GNU Radio. This demonstrates the capability of software-defined radio technology to tackle the changing requirements of satellite navigation systems effectively.*

Keywords - *GNU Radio, Software Defined Radio, GNSS, IRNSS, Global Positioning System.*

1. Introduction

The advent of Global Navigation Satellite Systems (GNSS) has brought about significant transformations in all facets of contemporary society through the provision of precise location, navigation, and timing services on a worldwide level [1]. Initially designed for military uses [2], GNSS has undergone significant advancements and now enjoys extensive utilization in civilian domains such as transportation [3], agriculture [4], telecommunications [5], crisis management [6], and scientific research [7].

This overview examines the foundational principles of GNSS, its constituent systems, and their significant implications for modern society. The fundamental component of GNSS consists of a network of satellites that revolve around the Earth, delivering uninterrupted signals that encompass accurate timing and location data. GNSS receivers can accurately establish their exact location and time on any part of the Earth by simultaneously receiving signals from several satellites. The Global Positioning System (GPS), which is developed and managed by the United States government, is widely recognized as the most prominent GNSS [8]. Nevertheless, there are other additional GNSS constellations, such as GLONASS in Russia, Galileo in the European Union, BeiDou in China [9], and NavIC in India [10]. Each of these constellations provides worldwide coverage and distinct benefits. The importance of GNSS in contemporary applications arises from its capacity to deliver precise location and timing data instantaneously.

The synchronization of cellular networks, satellite communication systems, and internet infrastructure in the field of telecommunications is significantly dependent on the GNSS. The utilization of GNSS-derived time guarantees precise synchronization of network nodes, facilitating uninterrupted connectivity and transmission of data [11]. The GNSS plays a crucial role in emergency response and disaster management by offering essential location data for search and rescue operations, disaster mapping, and the coordination of relief activities [12]. In addition, GNSS contribute to the improvement of weather forecasting, seismic monitoring, and scientific research through their ability to facilitate accurate geospatial reference and data synchronization [13]. GNSS has been utilized not only on Earth but also in space exploration and satellite navigation. GNSS receivers play a crucial role in spacecraft navigation systems by facilitating accurate trajectory control, orbit determination, and rendezvous mechanics. In addition, GNSS signals play a crucial role as a reference for Satellite-Based Augmentation Systems (SBAS), hence improving the precision and reliability of location data for users in the aviation, maritime, and land aviation sectors [14].

Software Defined Radio (SDR) technology is a revolutionary method for creating and deploying communication systems, providing the advantages of adaptability, recallability, and scalability [15]. In the realm of GNSS receivers, SDR offers a multitude of notable benefits in comparison to conventional hardware-based alternatives. This introduction presents a concise summary of SDR technology, including its fundamental concepts and the distinct advantages it offers for the design and operation of GNSS receivers [16]. SDR technology entails the substitution of conventional hardware elements in a radio system, such as mixers, filters, and amplifiers, with software algorithms that operate on a versatile computing platform. The platform, commonly referred to as a Digital Signal Processor (DSP), Field-Programmable Gate Array (FPGA), or General-Purpose Processor (GPP), is responsible for executing signal processing operations that were previously carried out by specialized hardware.

SDR allows for increased flexibility and adaptability in radio system design by separating the signal processing functions from specialized hardware. The versatility of SDR arises from its capacity to adapt and alter signal processing algorithms within the software, thereby facilitating swift development, experimentation, and customization. The adaptability of GNSS receivers is especially beneficial considering the dynamic characteristics of GNSS signals, protocols, and standards. SDR-based GNSS receivers provide the capability to adjust to alterations in signal characteristics effectively, accommodate novel satellite constellations, and seamlessly integrate sophisticated signal processing algorithms.

Implementing baseband processing algorithms for GNSS-SDR applications poses several significant challenges, reflecting the complex nature of GNSS signals and the computational requirements of signal processing. Baseband processing techniques utilized in GNSS receivers encompass computationally demanding operations, including signal acquisition, tracking, demodulation, and estimation of navigation solutions [17]. Efficient implementation strategies are typically necessary to meet performance requirements when executing these algorithms in real-time on resource-constrained platforms. Increasing the number of tracked satellites, signal modulation methods, and climatic circumstances leads to a higher computing complexity for these algorithms. This presents a substantial difficulty in attaining real-time operation while retaining accuracy. GNSS signals are vulnerable to a range of deterioration and interference factors, including multipath effects, delays in the ionospheric and tropospheric regions, jamming, and spoofing. For providing precise and dependable positioning and timing solutions, baseband processing algorithms must offset these effects effectively.

Nevertheless, the incorporation of robust signal processing techniques that may effectively reduce interference while maintaining signal integrity introduces intricacy to the execution of the algorithm, hence intensifying the computational load. The computational resources of GNSS-SDR platforms, such as FPGAs and embedded CPUs, are generally constrained, encompassing processing cores, memory, and input/output interfaces [18]. The successful implementation of intricate baseband processing algorithms under these limitations necessitates meticulous resource allocation and management, optimal algorithmic efficiency, and the careful consideration of trade-offs between performance and resource utilization.

FPGAs are essential for tackling the difficulties related to designing baseband processing algorithms for GNSS-SDR applications. FPGAs possess distinct features that render them highly suitable for the rigorous computing demands, real-time limitations, and resource constraints that are inherent in the processing of GNSS signals [19]. FPGAs demonstrate exceptional proficiency in parallel processing, enabling the concurrent execution of numerous operations across a substantial quantity of customizable Logic Elements (LEs) and processing units. The utilization of parallelism facilitates the effective execution of intricate baseband processing algorithms, like correlation, filtering, and tracking, which intrinsically possess tasks that can be parallelized. FPGAs may achieve high throughput and low-latency execution by distributing processing jobs throughout the FPGA fabric [20], hence addressing the real-time restrictions of GNSS-SDR applications.

FPGAs provide hardware platforms that can be reconfigured and reprogrammed in real-time to accommodate evolving algorithmic demands, signal circumstances, and application situations. Developers can repeatedly improve and optimize baseband processing algorithms, experiment with various implementations, and include algorithmic advances without the need for hardware redesign, thanks to this flexibility. In addition, FPGAs can do partial reconfiguration, which allows for the targeted alteration of hardware modules while the system remains functional.

This feature facilitates the ability to react to changing signal environments in real-time. High-speed interfaces are necessary for GNSS receivers to establish connections with RF front ends, receive unprocessed satellite signals, and facilitate data interchange with external components. FPGAs provide a diverse array of high-speed Input/Output (I/O) interfaces, including Serializers/Reserializes (SERDES), DDR memory interfaces, and high-speed parallel buses.

These interfaces enable effortless integration with analogue front-end components and external peripherals. These interfaces facilitate the effective processing and transfer of data between various processing stages and external memory/storage devices in FPGAs, hence ensuring seamless data flow and minimal latency.

In this study, the main goal is to investigate the design and implementation of baseband processing algorithms for GNSS-SDR applications in detail. The focus will be on utilizing FPGAs as the fundamental hardware platform. The study seeks to explore the complexities of creating GNSS receivers that are both efficient and high-performing, capable of achieving the demanding requirements of real-time operation, low power consumption, and resource utilization. Initially, the paper provides a comprehensive examination of the essential elements of GNSS-SDR systems and the fundamental concepts that govern their functioning. One of the objectives of this research is to examine the data obtained from FPGAs in the context of GNSS-SDR applications.

The study specifically concentrates on the GPS and IRNSS constellations. The point of this study is to investigate how FPGA-based processing can be used to handle data from the GPS and IRNSS satellite systems, which are important parts of GNSS navigation systems. The study aims to evaluate the effectiveness, efficiency, and suitability of FPGA-based solutions for processing signals from GNSS-SDR satellite constellations by analysing FPGA data.

2. GNU Radio for GNSS-SDR

This section is dedicated to the construction and execution of a GNU radio-based utility designed for the purpose of facilitating GNSS-SDR transmitters and receivers. The provided utility facilitates the development and implementation of software-defined radio systems for GNSS applications. It empowers users to design, simulate, and deploy transmitter and receiver modules within the GNU Radio framework.

The programme supports the quick prototyping and experimentation of GNSS-SDR systems by utilizing the flexibility and extensibility of GNU Radio. It provides a diverse platform for research, development, and testing in the field of satellite navigation.

The notion of a wireless communication system utilizing SDR technology was introduced by the authors in reference [21]. This methodology entails the utilization of SDR, which utilizes architectures for real-time signal processing. More precisely, this system utilizes Universal Software Radio Peripheral (USRP) hardware in combination with GNU Radio software for signal processing. The reference provides a detailed description of a system that has been specifically developed for an FM transmitter. This transmitter can operate within the frequency range of 88-MHz to 108-MHz. The fundamental goals of this system are to optimize signal transmission efficiency while ensuring the production of high-quality audio output. SDR is a technology that offers numerous advantages, such as cost-effectiveness, extensive administration, and adaptable infrastructure. The system under consideration employs SDR in a dynamic fashion, wherein its parameters are modified in response to interactions with the surrounding environment. This methodology enables the development of communication systems that are adaptable and flexible, customized to suit circumstances and needs [22].

In the study cited as [23,24], the researchers performed an evaluation of the standard of GNSS observables acquired using SDR technology, in contrast to those obtained using a particular u-blox low-cost receiver. The objective of their study was to assess the level of performance that may be attained in single-point locating by utilizing an ultra-low-cost SDR and to compare it with the performance of a low-cost GNSS receiver. The present evaluation encompassed an examination of the precision, dependability, and uniformity of the GNSS observables acquired from both the SDR-based system and the u-blox receiver. Through the comparison, the authors were able to evaluate the appropriateness of the SDR technology for GNSS applications and ascertain its performance in comparison to existing low-cost receiver systems.

The paper [25] provides an overview of the notion of reconfigurability in relation to the data format, variability of signal and receiver parameters, and internal functionality of the receiver. The capacity to reconfigure enables a high degree of flexibility in accommodating various signal circumstances and meeting the specific needs of users. The significance of a configuration file in governing the functioning of the SDR system is emphasized. Through the process of updating the configuration file, it is possible to customize the SDR to exhibit distinct responses to target signal circumstances. The configuration file functions as a fundamental plan, providing guidance for the behavior of the SDR and establishing its operational attributes in accordance with the intended application or signal conditions.

This survey offers significant contributions to the understanding of the utilization of SDR technology in wireless communication systems and GNSS receivers. The studies cited showcase the adaptability and benefits of SDR, specifically when integrated with GNU radio. The initial study presents an SDR-based FM transmitter system, showcasing its capacity to function effectively across a broad spectrum of frequencies while upholding superior audio output. Furthermore, the survey examines the assessment of GNSS observables received by SDR technology in comparison to those obtained from inexpensive GNSS receivers.

The present analysis provides insights into the efficacy and appropriateness of SDR in the context of GNSS applications, demonstrating its promise as a financially viable and versatile solution. In addition, the examination of reconfigurability highlights the significance of adaptability in SDR systems, emphasizing the utilization of configuration files to customize system functionality according to signal conditions or user specifications. In summary, this literature review highlights the importance of SDR technology in tackling several obstacles in wireless communication and GNSS applications, providing flexibility, cost-efficiency, and performance benefits.

3. GNSS Transmitter and Receiver Implementation

The utilization of GNU Radio for the deployment of GNSS transmitter and receiver systems represents a notable progression within the domain of SDR technology. GNU Radio offers a comprehensive and robust framework for the development, simulation, and implementation of SDR-based communication systems. It encompasses a diverse array of signal-processing functionalities and ensures interoperability with various hardware components.

Within the GNU Radio framework, we explore the complexities associated with the implementation of GNSS transmitter and receiver functionality. GNSS, such as GPS, GLONASS, Galileo, BeiDou, and NavIC, have become essential tools for accurate positioning, navigation, and timing across diverse businesses and sectors. By utilizing GNU Radio, researchers, engineers, and hobbyists can now investigate and test GNSS signal processing methodologies, receiver architectures, and system designs, hence expanding the range of possibilities for GNSS feature implementation.

3.1. Transmitting Signal

The initial phase of the procedure is the transmission of the GNSS signal, as shown in Figure 1. This approach starts by generating a stream of bits, representing the digital information to transfer, and then modulates it onto a complex constellation of points in the signal space. To implement this modulation, we make use of the GNU Radio framework's Constellation Modulator block. This block allows us to customize numerous characteristics, such as constellation type and settings, to manipulate the broadcast signal efficiently.

When monitoring the number of samples per symbol, it is imperative to minimize this value while maintaining it above a specified threshold, which is generally set at a minimum of 2. This limitation is in place to ensure that the bit rate being transmitted is synchronized with the sampling rate of the hardware device employed for the process. While this approach utilizes simulation rather than real-time transmission, it guarantees coherence across the flowgraph by preserving the samples per symbol parameter. The implementation detailed herein employs a value of 4 samples per symbol, surpassing the minimum requirement while offering further granularity to facilitate the visualization of the signal across various domains. Although this value may exceed what is strictly required, it provides advantages in terms of signal visualization and analysis, facilitating the comprehension and assessment of the properties of the transmitted Signal.

In this transmitting model, several key parameters have been chosen to configure the GNSS signal transmission process effectively. The selected parameters include:

- Sample Rate: 1M (1 Mega-sample per second)
- Arity: 4
- Samples per Symbol (SPS): 4
- Excess Bandwidth (BW): 350m (350 milli-Hertz)
- Frequency: 1.176 GHz (Gigahertz)
- Gain: 30
- Number of Points: 4.096k (4,096 points)

Each of these parameters greatly affects GNSS signal behaviour and characteristics. Signal digital sampling and processing speed depend on the step rate of 1M. Increased sample rates provide a more exact and detailed digital reproduction of the analogue signal, retaining signal integrity and decreasing distortion. The arity of 4 indicates the modulation scheme's signal states or symbols. In this case, a higher arity means more symbols, which may improve data throughput and spectral efficiency. Samples per Symbol (SPS) controls how many samples are used to display each modulation scheme symbol. As the SPS value increases, the signal is depicted more compactly in the time domain, making symbol timing and phase manipulation more exact.

The excess Bandwidth (BW) parameter adds spectral capacity to the minimum signal transmission bandwidth. A greater surplus bandwidth helps the transmitted signal withstand channel distortions and noise, making it more resilient to poor propagation conditions. GNSS signals use 1.176 GHz carrier frequency. Because it operates in the L-band spectrum, which GNSS systems use, this frequency is compatible with existing receiver apparatus and standards. The gain parameter of 30 controls the broadcast signal's strength and ensures an optimal Signal-to-Noise Ratio (SNR) at the receiver. The parameter "number of points." represents the total number of data points used to portray the sent Signal. The signal representation's resolution and granularity affect computational complexity and signal fidelity.

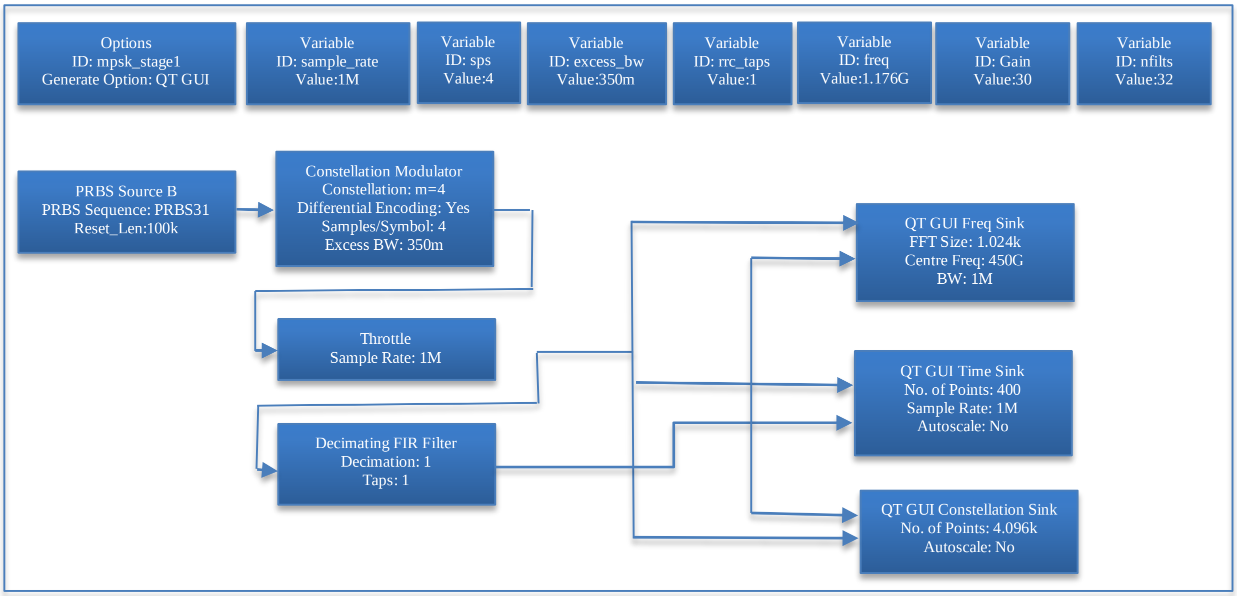

Fig. 1 Transmitter block diagram

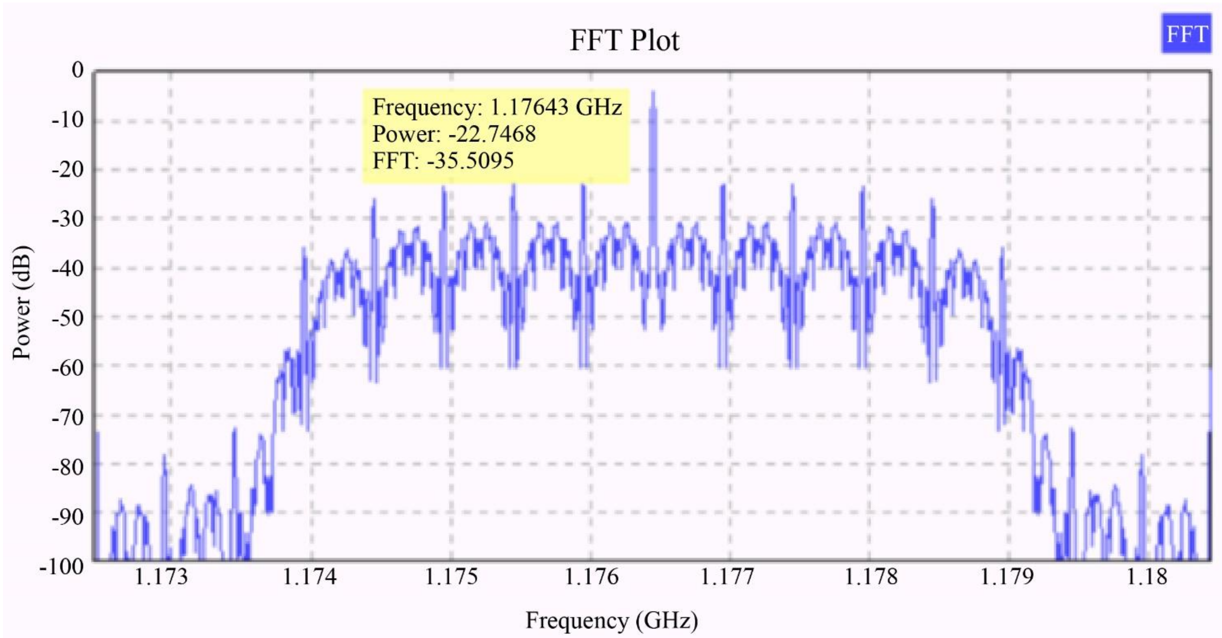

Fig. 2 Generated GNSS signal

Figure 2 depicts the generation of a GNSS signal at 1.1746 GHz, specifically targeting the L5 band of the Indian Regional Navigation Satellite System (IRNSS) [26]. In this context, the transmission of an L5 band signal is used as an example of GNSS signal generation within the specified framework. The IRNSS constellation uses the L5 band as a frequency range for satellite navigation. By emitting an L5 band signal, the illustration demonstrates the process for generating GNSS signals using the specified methodology.

It is vital to note that the transmission frequency of 1.1746 GHz corresponds to the IRNSS system's particular frequency allocation for the L5 band. This frequency selection is consistent with the properties of the IRNSS constellation and navigation signals, making it an appropriate and meaningful example for demonstration purposes. The transmission of an L5 band signal demonstrates the flexibility and applicability of the suggested methodology across other GNSS constellations and frequency bands. While the example concentrates on the IRNSS L5 band, the concept may be used to create signals for other GNSS constellations, such as GPS, GLONASS, Galileo, and BeiDou, which operate in various frequency bands.

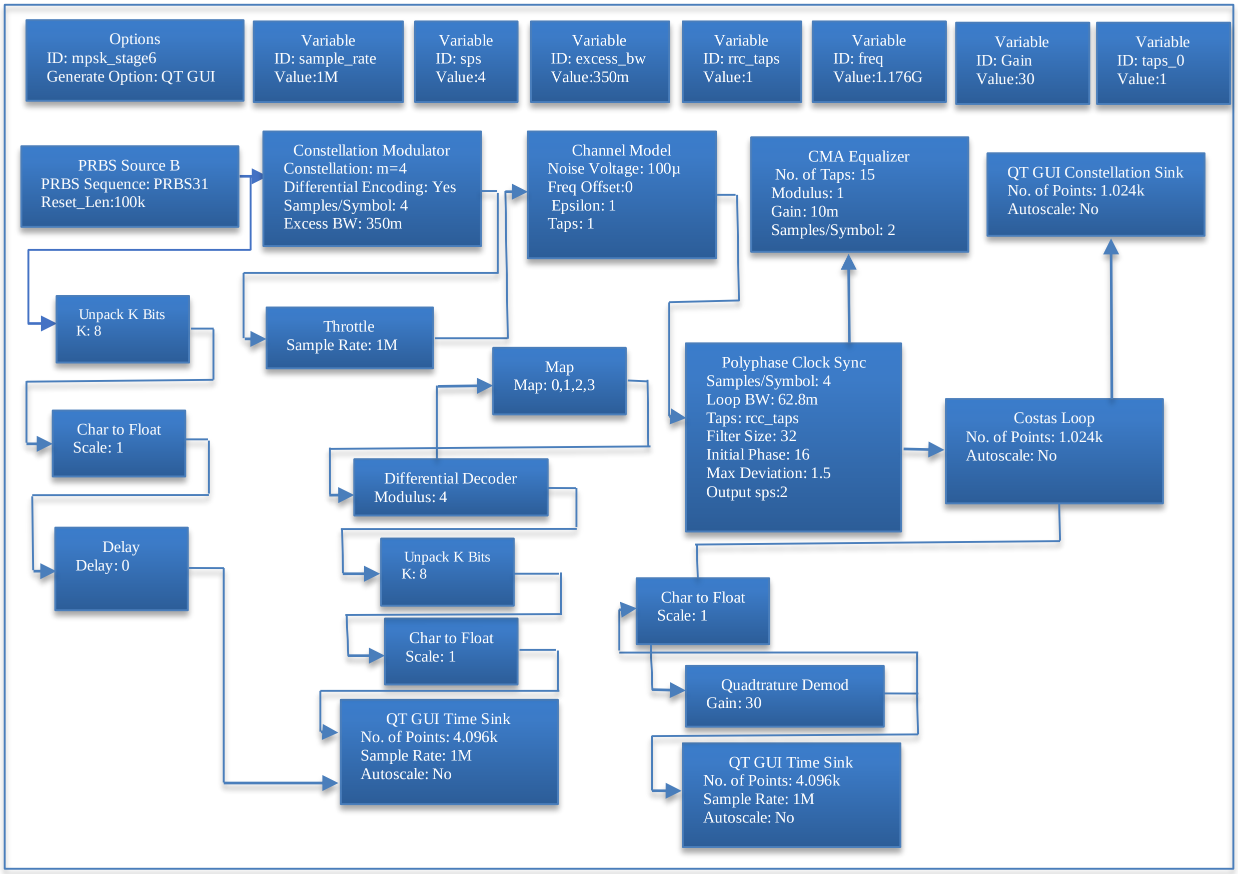

Fig. 3 Receiver architecture

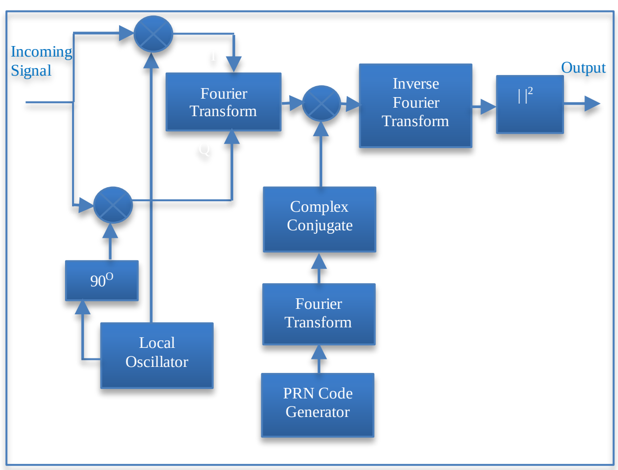

Fig. 4 PCPS Algorithm architecture

3.2. Receiver Design

Figure 3 illustrates the receiver architecture, which uses the differential decoder block to decode differentially coded signals back to their original symbols while considering phase transitions rather than absolute phase. Most people consider this component of demodulation to be the most challenging. While synchronization processes are based on fundamental physics and mathematics, symbols must be interpreted using external information at this point. Ultimately, knowing this mapping is critical. Fortunately, we have this knowledge, which allows us to use the map block to transform symbols from the differential decoder back into their original forms. The unpack bits block then unpacks the original symbols, ranging from 0 to 3, into bits, enabling the recovery of the original bit stream of data.

Software-defined receivers use the Parallel Code Phase Search (PCPS) (Figure 4.) The acquisition algorithm is a key component in acquiring and tracking GNSS signals, including GPS and IRNSS. This technique is critical to recognizing and locking onto the precise code phase of satellite signals in real-time, allowing for accurate positioning and navigation solutions. The PCPS acquisition algorithm was created in response to the necessity for an efficient and speedy way of searching for and synchronizing with the code phases of satellite signals. Unlike traditional hardware-based receivers, software-defined receivers use computer algorithms to fulfil this function, providing greater flexibility and adaptability to changing signal conditions and requirements. The PCPS acquisition algorithm works by exploring numerous code phases in parallel, hence the name. This simultaneous search approach enables faster acquisition of satellite signals, lowering the time necessary to lock onto a signal and begin tracking. The technique improves receiver sensitivity and robustness by effectively examining a variety of alternative code phases, especially in adverse signal environments or when signal collection from many satellites is taking place at the same time.

4. Results and Discussion

Figure 5 shows how the channel affects the broadcast signal and the distortion detected by the receiver. Initially, the most basic channel model block of GNU Radio is used to simulate key challenges in communication systems. Noise, as the principal concern, is modelled as Additive White Gaussian Noise (AWGN) in our receiver design to account for thermal noise. The noise power is modified by changing the noise voltage parameter in the channel model. Voltage is supplied rather than power because correct power calculation requires knowledge of the signal bandwidth. One significant feature of GNU Radio is the modularity of its blocks, which keeps the channel model oblivious to the incoming signal. The noise voltage can be computed from an ideal power level using a variety of simulation parameters. This simulation approach allows users to manipulate the effects of additive noise, frequency offset, and temporal offset. Initially, these effects are turned off in the simulation; however, sliders are available to change the parameters. The resulting signal can be viewed after introducing a small amount of noise (0.2), a frequency offset (0.025), and a temporal offset (1.0005).

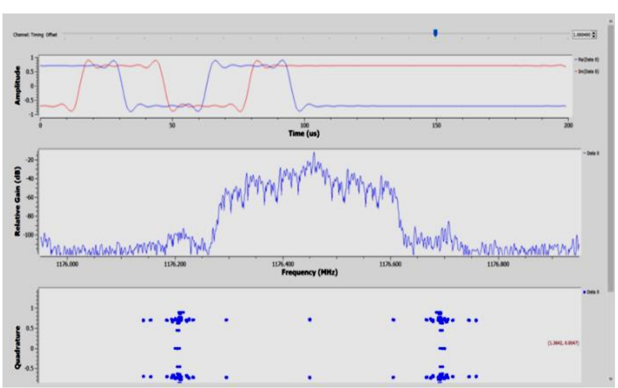

Fig. 5 Illustration of transmission channel noise

A combination of educated guesses chooses the number of taps accepted by the CMA algorithm in the equalizer, established best practices, and possibly some knowledge of the channel characteristics. Maintaining a minimal number of taps is critical for minimizing algorithm overhead while ensuring adequate degrees of freedom to adjust for channel distortions efficiently. The LMS DD equalizer works well with signals that do not meet the CMA algorithm's constant modulus criterion, allowing it to handle modulation schemes such as QAM-type modulations successfully. The decoding process involves the incorporation of a quadrature demodulator after the Costas loop. In this phase, we acquire symbols in the range of 0 to 3, which corresponds to the alphabet size in a QPSK scheme. For conveying the distinction among symbols of the constellation, the differential setting in the constellation modulator block was adjusted to true.

Figure 6 presents the results of the GNSS receiver, showcasing the processed signals and extracted navigation information acquired throughout the receiver's functioning. The presented visualization offers a thorough depiction of the receiver's performance, encompassing a range of metrics, including signal strength, satellite constellation geometry, location accuracy, and temporal synchronization. Figure 6 also shows pictures of the received satellite signals, tracking loops, and navigation solution outputs. These pictures tell us a lot about how well the receiver can receive, track, and decode GNSS signals. Through the examination of the data depicted in Figure 6, researchers and practitioners can evaluate the receiver's effectiveness, detect possible difficulties or irregularities, and make well-informed decisions on system enhancement or more analysis.

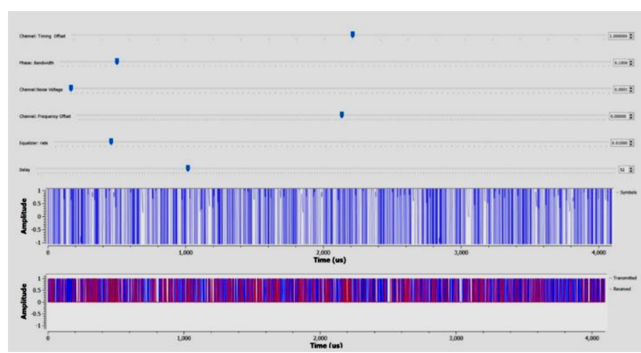

Fig. 6 Results of the GNSS receiver

The graphical representation in Figure 7 illustrates the quadrature and in-phase components of the received GNSS signal. The presented visualization offers significant insights into the received Signal's characteristics, facilitating a more profound comprehension of its modulation and phase features. The quadrature component of the signal is indicative of the imaginary component, whereas the in-phase component is associated with the real component. Researchers can analyse the modulation scheme used in the transmitted Signal, as well as any phase shifts or distortions caused during transmission or reception, by evaluating these components individually.

Furthermore, the utilization of Figure 7 facilitates the evaluation of signal quality, enabling the identification of any deviations in amplitude or phase that could potentially affect the operation of the receiver. The visualization presented herein functions as a valuable instrument for the investigation and assessment of signals within GNSS receiver systems.

The acquisition results achieved using the standard approach are illustrated in Figure 8, which presents a histogram depiction. The PRN number of the satellite is represented on the horizontal axis of the figure, while the peak metric of the satellite is represented on the vertical axis. The experiment considers a visibility threshold of 2. The relationship between this threshold value and the signal content in the received data is straightforward. Upon careful examination of Figure 8, it becomes evident that none of the satellites display a peak metric that is above the predetermined threshold. The observed phenomenon can be attributed to the divergence of the carrier frequency of the incoming signal from its initial carrier frequency, which arises due to inadequate sample sizes for signal processing. As a result, the Signal experiences data loss because of this event.

According to Table 1, the proposed method demonstrates lower data loss compared to the existing method. The proposed method was tested in various weather conditions, including rainy, cloudy, and open-sky environments. In each scenario, enough satellites were detected for position calculation using the proposed method.

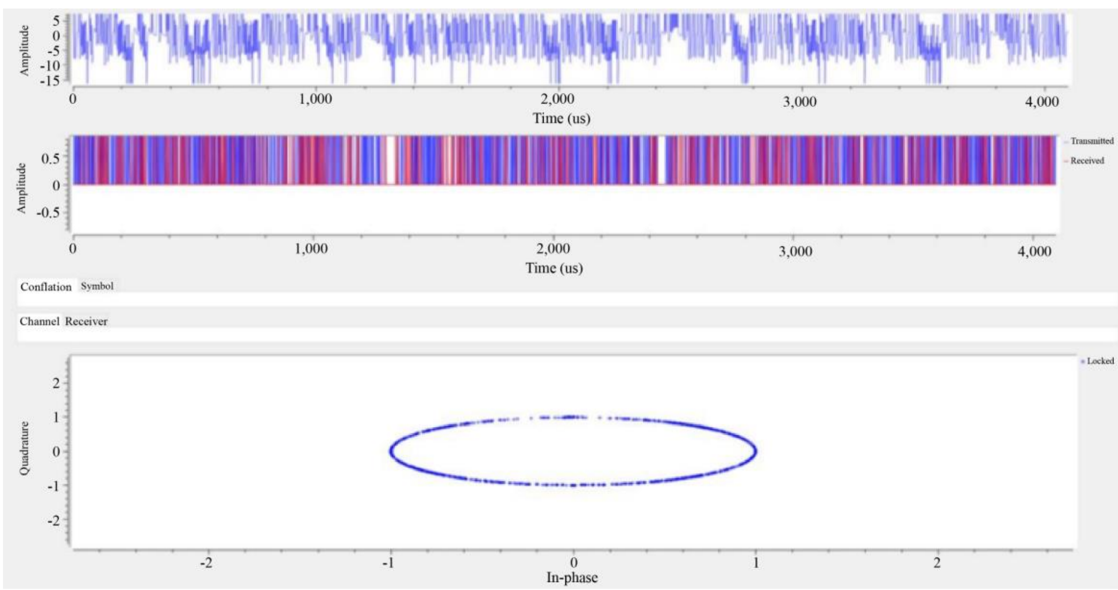

Fig. 7 Quadrature and in-phase components of the received GNSS signal

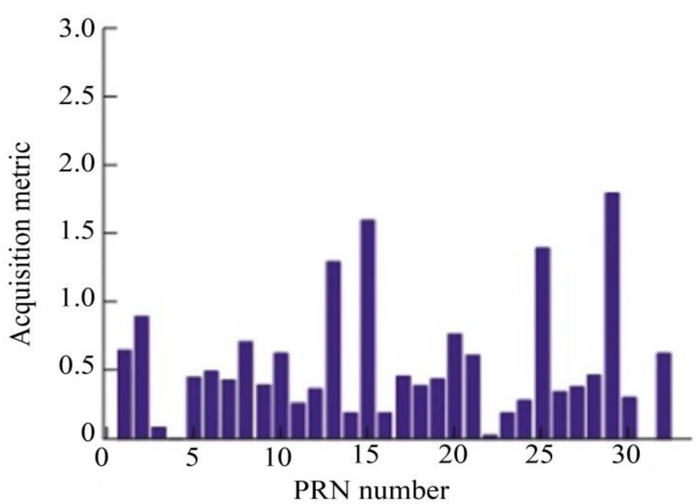

Fig. 8 Acquisition results

Table 1. Data packets loss comparison

Baseline Approach [27]			Proposed Approach		
Received Samples	Dropped Samples	Data Loss	Received Samples	Dropped Samples	Data Loss
5231160748	512027033	9.466	5301474434	193371915	3.328

5. Conclusion

This paper presents a novel methodology for the implementation of a GNSS receiver utilizing GNU Radio software. The approach capitalizes on the inherent flexibility and diversity of SDR technology. The system effectively generated and obtained GNSS signals through simulation, with a specific focus on receiving the L5 IRNSS signal. The adaptability of the design allows for seamless transmission and reception of signals across various navigation systems, hence offering a comprehensive framework. The GNSS system was successfully constructed and tested using QPSK modulation and demodulation techniques, resulting in satisfactory outcomes. The presence of channel noise was also noted, emphasizing the system's resilience in unfavourable circumstances. The utilization of a Costas loop enabled the detection of locked constellations, hence improving the performance of the receiver. GNU Radio facilitates signal replay and allows for experimentation with diverse processing techniques; nonetheless, it requires the use of substantial disc files. However, the configuration described in this study provides a solid foundation for future research, establishing the necessary framework for the advancement of real-time systems and the progress of GNSS receiver technology.

References

[1] Wolfgang Lechner, and Stefan Baumann, "Global Navigation Satellite Systems," *Computers and Electronics in Agriculture*, vol. 25, no. 1-2, pp. 67-85, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[2] Norman Bonnor, "A Brief History of Global Navigation Satellite Systems," *The Journal of Navigation*, vol. 65, no. 1, pp. 1-14, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[3] Fabio Dovis et al., "Recent Advancement on the Use of Global Navigation Satellite System-Based Positioning for Intelligent Transport Systems [Guest Editorial]," *IEEE Intelligent Transportation Systems Magazine*, vol. 12, no. 3, pp. 6-9, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] Dorijan Radočaj, Ivan Plaščak, and Mladen Jurišić, "Global Navigation Satellite Systems as State-of-the Art Solutions in Precision Agriculture: A Review of Studies Indexed in the Web of Science," *Agriculture*, vol. 13, no. 7, pp. 1-17, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[5] Oltjon Kodheli et al., "Satellite Communications in the New Space Era: A Survey and Future Challenges," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 70-109, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[6] Sharifah Mastura Syed Mohd Daud et al., "Applications of Drone in Disaster Management: A Scoping Review," *Science & Justice*, vol. 62, no. 1, pp. 30-42, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[7] Yuanxi Yang, Yue Mao, and Bijiao Sun, "Basic Performance and Future Developments of BeiDou Global Navigation Satellite System," *Satellite Navigation*, vol. 1, no. 1, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Haibo Ge et al., "LEO Enhanced Global Navigation Satellite System (LeGNSS): Progress, Opportunities, and Challenges," *Geo-Spatial Information Science*, vol. 25, no. 1, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[9] Mohinder S. Grewal, "Global Navigation Satellite Systems," *WIREs Computational Statistics*, vol. 3, no. 4, pp. 383-384, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[10] Atanu Santra et al., "Precision of Satellite-Based Navigation Position Solution: A Review Using NavIC Data," *Journal of Information and Optimization Sciences*, vol. 40, no. 8, pp. 1683-1691, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Haibo Ge et al., "LEO Constellation Optimization for LEO Enhanced Global Navigation Satellite System (LeGNSS)," *Advances in Space Research*, vol. 66, no. 3, pp. 520-532, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[12] Md Nazirul Islam Sarker et al., "Disaster Resilience through Big Data: Way to Environmental Sustainability," *International Journal of Disaster Risk Reduction*, vol. 51, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] Jessica R. Murray et al., "Regional Global Navigation Satellite System Networks for Crustal Deformation Monitoring," *Seismological Research Letters*, vol. 91, no. 2A, pp. 552-572, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[14] Todd Walter, *Satellite-Based Augmentation Systems (SBASs)*, Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications, vol. 1, pp. 277-306, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] Dimitrios Kafetzis et al., "Software-Defined Networking Meets Software-Defined Radio in Mobile ad Hoc Networks: State of the Art and Future Directions," *IEEE Access*, vol. 10, pp. 9989-10014, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[16] Thomas Pany et al., "GNSS Software-Defined Radio: History, Current Developments, and Standardization Efforts," *NAVIGATION: Journal of the Institute of Navigation*, vol. 71, no. 1, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[17] Daniel Egea-Roca et al., "GNSS User Technology: State-of-the-Art and Future Trends," *IEEE Access*, vol. 10, pp. 39939-39968, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Kuan-Ying Huang et al., "Efficient FPGA Implementation of a Dual-Frequency GNSS Receiver with Robust Inter-Frequency Aiding," *Sensors*, vol. 21, no. 14, pp. 1-20, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] M.A. Gómez et al., "GNSS Receiver Developed on a SDR Platform Withstands High Accelerations and Speeds," *Proceedings of the 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022)*, Denver, Colorado, pp. 3333-3339, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] Jinming Zhang et al., "A Low-Latency FPGA Implementation for Real-Time Object Detection," *2021 IEEE International Symposium on Circuits and Systems (ISCAS)*, Daegu, Korea, pp. 1-5, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[21] Nabiha Ben Abid, and Chokri Souani, "SDR-Based Transmitter of Digital Communication System Using USRP and GNU Radio," *Proceedings of the 8th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications (SETIT'18)*, pp. 373-381, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[22] Madhuri Gummineni, and Trinatha Rao Polipalli, "Implementation of Software-Based Communication System Using SDR and GNU Radio," *AIP Conference Proceedings*, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[23] Umberto Robustelli et al., "GNSS-SDR Pseudorange Quality and Single Point Positioning Performance Assessment," *Applied Geomatics*, vol. 15, no. 3, pp. 583-594, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] Matteo Cutugno, Umberto Robustelli, and Giovanni Pugliano, "Low-Cost GNSS Software Receiver Performance Assessment," *Geosciences*, vol. 10, no. 2, pp. 1-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[25] Xiangdong An, Xiaolin Meng, and Weiping Jiang, "Multi-Constellation GNSS Precise Point Positioning with Multi-Frequency Raw Observations and Dual-Frequency Observations of Ionospheric-Free Linear Combination," *Satellite Navigation*, vol. 1, pp. 1-13, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[26] Kanta Prasad Sharma, and Ramesh C. Poonia, "Review Study of Navigation Systems for Indian Regional Navigation Satellite System (IRNSS)," *Soft Computing: Theories and Applications*, pp. 735-742, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[27] B.P. Kumar, and C.S. Paidimarry, "Improved Real Time GPS RF Data Capturing for GNSS SDR Applications," *Gyroscopy and Navigation*, vol. 11, no. 1, pp. 59-67, 2020. [CrossRef] [Google Scholar] [Publisher Link]