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Enhancing Orthogonal GPS L1C Signal Acquisition

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ABSTRACT

The Global Positioning System (GPS) represents a significant leap in global navigation satellite systems. This is achieved through continuous localization, reliable navigation, and precise timing for various uses, such as civilian, commercial, and military. Among the multiple signals sent by GPS satellites, the L1C signal greatly enhances structure and performance, boosting user reliability (by employing binary offset carrier modulation to reduce multipath effects) and accuracy (by lengthening the ranging code). It features data and pilot components, enhancing resilience against multipath interference and strengthening the signal under challenging conditions. In this work, an orthogonal single-channel acquisition algorithm for the GPS L1C signal is proposed, and it is utilized to reduce the complexity of a conventional side-by-side/dual-channel configuration. The proposed scheme mathematically combines the data and pilot portions into one orthogonal channel, which approach has been shown to achieve a 3dB gain in signal-to-noise ratio (SNR) with 34% gain in computation complexity over the conventional implementation. The MATLAB-Simulink environment was used to simulate the GPS L1C parameters with a sampling frequency of 16.368 MHz and a dwell time of 10 ms. The simulations were carried out across various SNR levels to evaluate detection probability, and processing time. The results show that the proposed solution preserves detection probability and dramatically increases resource utilization. This work provides the first single-channel orthogonal design for GPS L1C acquisition and is an efficient step towards low-power, high-performance GNSS receivers.

1. INTRODUCTION

The modernized GPS L1C and other L2 and L5 signals were developed to meet the requirements of the GPS services, among the current global navigation satellite systems (GNSS). The need to introduce the L1C signal enhances the current localization services provided by the legacy GPS L1C/A signal. In other words, it improves the localization accuracy by increasing the length of the ranging code and produces a more reliable signal by reducing the ionosphere delay effect [1]. Moreover, it presents an interoperable signal that is more compatible with other GNSS signals, such as the Galileo civilian signal.

The L1C signal is based on the binary offset carrier (BOC) modulation technique, which is the most commonly employed modulation in modern GNSS signals. This modulation has successfully proved the mitigation of the multipath effect in the urban canyon area [2]. As a result, increasing the code length and employing this modulation technique will produce more accurate localization in civilian applications [3]. The main reason for developing the L1C signal is the interoperability and compatibility with other modernized GNSS signals, like the Galileo E1 open service (OS) signal [4]. So, the signal structure, modulation technique, and coding increased the power reception by 1.5 dB over the power reception of the L1C/A signal [1]. Thus, this improvement in the reception performance will increase positioning accuracy in challenging environments. Furthermore, the next receiver design will move to have an L1C

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signal rather than the outdated L1C/A signal, especially for first aid applications. The L1C modulation is based on Time Multiplexed Binary Offset Carrier (TMBOC) modulation, which is part of the BOC family modulation [5]. Basically, the L1C signal consists of two carrier components, called data and pilot components. The pilot component is designed to be dataless, i.e., the navigation message is not spread with this component. Also, the power allocated to this component is more than the power on the data component, with a 3 dB improvement in the pilot compared to the data [1]. This led to the utilization of the pilot in the acquisition and tracking processes in most receiver designs. This allows GPS receivers to perform the L1C signal more effectively, improving navigation accuracy and sensitivity. As is known, the L1C signal in the L1 band frequency equals 1.57542 GHz, and the code length is 10230 chips, which is ten times the length of the C/A code used in the legacy GPS signal. The navigation message is spread on the data ranging codes, while the secondary code is spread by the pilot ranging codes [6]. Thus, the L1C signal acquisition could be accomplished by either using a single pilot or data component or combining both components, but at the expense of increasing the implementation complexity. This work has focused on integrating the pilot and data components to obtain a 3 dB improvement in acquisition performance. This combination is achieved by making these components orthogonal and introducing a 90-degree phase shift between them. The orthogonal design will fulfill the requirement for two channels to be used in the acquisition process, enabling these components to be processed within a single channel. The orthogonal acquisition technique in the L1C signal enhances the acquisition performance, increases the chance of detection probability, and improves the receiver sensitivity. Introducing this new principle of orthogonal channels will make a compelling case for ongoing research and applications, establishing a foundation for more resilient and versatile positioning solutions across various modern challenges. The orthogonal form is achieved by combining the received signal with the same signal shifted by 90-degree. Additionally, the generated pilot and data ranging codes are shaped into an orthogonal form by applying a 90-degree phase shift to either the pilot or the data component.

The L1C acquisition faced two main challenges: acquisition ambiguity and the selection of the pilot/data component to be acquired. This work has overcome the second challenge by organizing the data and pilot components in an orthogonal shape and utilizing a single acquisition channel. As a result, this enhanced technique retains the gains achieved from combining these components and maintains the acquisition performance, while reducing implementation complexity, as well as the processing time. Although dual-channel and side-by-side structures for GPS L1C acquisition have been examined in several works, the data- and pilot-component orthogonalization realization in one channel has not yet to be reported. This overhead restricts to optimized receive efficiency in the context of time and power consumption. Thus, it is desirable to develop an orthogonal single-channel acquisition scheme for the GPS L1C signal in order to enhance the probability of detection and reduce computational cost. The primary contribution of this paper is a lightweight orthogonality acquisition model as compared to the traditional approach.

The paper is structured as follows: Section 2 highlights the related works. Section 3 explains the mathematical model of the L1C signal and the mathematical representation of orthogonal acquisition. Section 4 demonstrates the detection probability performance results and the breakdown of computational complexity. Section 5 presents the conclusion of this work.

2. LITERATURE SURVEY

Recent research developments, especially regarding acquiring and tracking the L1C signal, have highlighted the achievement obtained by designing this signal. It showed the ability to reduce the effect of multipath signal and outstanding performance in various scenarios. In addition, the compatibility when integrated with GPS L1C/A and Galileo E1OS signals produces a fast time to first fix and more accurate positioning calculation. This section will highlight these research developments and clarify the algorithms' implementation and achievements.

A significant algorithm that combines three GNSS signals in one implementation is accomplished based on the compressive sensing technique. The GPS L1C/A and L1C signals are integrated with the Galileo E1OS signal. This algorithm takes advantage of these signals' transmitting on the same carrier frequency and having the same chipping rate [7]. The use of compressive sensing has generated a high-frequency resolution of about 50 Hz in the acquisition process and reduced the implementation to one-third. The use of compressive sensing maintains the acquisition performance as the traditional implementation In the same vein, another algorithm successfully combines multi-GNSS signals in a software receiver. The algorithm can acquire either L1C/A and E1OS signals or L1C and E1OS signals [8]. Acquiring L1C/A & E1OS signals is achieved because both signals share the same carrier and chipping rate. While the second combination (L1C &

E1OS signals) is obtained because both signals are based on BOC modulation, they also have the same carrier and chipping rate. This algorithm utilizes various lengths of generated codes, such as 4 ms, 8 ms, and 16 ms, to accommodate the different code lengths of incoming signals. The combination based on 16 ms shows higher performance than other signal lengths, but at the expense of high processing time. The author recommended using 4 ms when the received signal is strong, while employing 16 ms for a weak signal. Similarly, another implementation combines the acquisition and tracking of the GPS (C/A & C) signals [9]. The implementation takes advantage of both signals transmitting from the same satellite, which means they have the same propagation condition for Doppler frequency and code phase delay. For the L1C signal, the implementation combined both data and pilot components. The length of the replica code for both signals is set to 10 ms according to the length of the L1C signal. In this implementation a three channels are required, one for the GPS C/A signal, and two channels for the pilot and data ranging code of L1C signal. This work needs a high memory size to accommodate the pilot and data codes. Likewise, an acquisition model is developed for modern GNSS signal structure. The coherent combination of GPS L1 C/A and L1C signals can effectively enhance reflectometry as well as acquisition reliability [10], indicating the feasibility of implementing such design philosophy in the paper.

On the other hand, acquiring the Galileo E1OS signal is accomplished based on an orthogonal channel for data and pilot components [11]. A Hilbert transform is employed to make these components orthogonal. So, the acquisition process involves overcoming the side-by-side implementation. The use of Hilbert transform helps to shape data and pilot component in an orthogonal form, and reduce the number of correlators. A study of the multi-GNSS signal using a low-cost receiver and antenna is introduced [12]. The low-cost receiver allows the acquisition of GPS, Glonass, and Galileo signals, with specific carrier frequencies. Although using a low-cost antenna, the GNSS signals are still acquired. The study advises that the next generation of receivers and antennas will be based on low-cost implementation, allowing developers and researchers to implement their algorithms easily. Another solution is proposed to overcome the ambiguity when acquiring BOC modulation for Galileo signals [13]. The solution depends on the cumulative method, which allows the removal of the effect of the multiple side peaks that appear in the acquisition process and reduces the error, but at the expense of increasing the computation complexity. It's worthwhile to mention that this solution can also acquire the GPS L1C/A signal to overcome the acquisition ambiguity. A high-sensitivity GNSS receiver is implemented to acquire a Galileo E1OS signal using a field-programmable gate array platform [14]. The receiver's sensitivity is achieved by employing a 100 ms length of the received signal, which means hundreds of thousands correlators are required. This enables the receiver to acquire weak Galileo signals. Additionally, an implementation is focused on modifying a real-time Cinematic GNSS (RTK) in challenging scenarios [15]. The RTK-GNSS proves the localization sensitivity and reliability compared to the commercial GNSS receivers. Eventually, a software receiver is proposed that can combine tracking L1 signals, L1C/A, and L1C [16]. The software receiver can also handle other GNSS signals like Galileo and Beidou. However, the combination is implemented side-by-side. Additionally, a software-defined receiver for the GPS L1C signal has been designed [17]. This receiver is capable of receiving, acquiring, and tracking the L1C signal. For the signal acquisition process, both the data and pilot components are implemented side-by-side. The ranging codes for both components are stored in memory to speed up the acquisition process. Although several implementations have successfully acquired the L1C signal. Some are focused on acquiring the L1C signal alone, either employing a pilot component or combining data and pilot components. Others integrate the acquisition with other GNSS signals, taking advantage of the similarity of sharing carrier frequency and chipping rate. Furthermore, other acquisition algorithms are designed to solve the acquisition ambiguity. Although a significant improvement in the acquisition process is achieved but at the expense of size and implementation complexity, or still depends on side-by-side or dual-channel architectures. Existing GNSS acquisition methods have recently developed towards higher flexibility and real-time adaptability by means of software-defined radio (SDR) approaches. Several SDR-based GNSS front-ends have been proposed in recent years, which offer better flexibility and near real-time processing possibilities [18], [19]. Recent SDR realizations have further considered the reduction of interference with the use of spatial diversity methods [20], indicating that low-cost GNSS receivers are becoming even more flexible. Table 1 summarizes most relevant acquisition methods presented in the literature, focusing on signal type, methodology, performance, and computational complexity. While an orthogonal method exists for Galileo E1OS [11], this paper is the first to propose and validate such an orthogonal single-channel acquisition method for the GPS L1C signal.

Table 1. Comparison of prior methods with the proposed method

Ref.	Signal(s)	Method / Technique	Performance / Findings	Computational Complexity	Limitation / Note
[7]	GPS L1C/A, L1C, Galileo E1OS	Compressive sensing	High freq. resolution, 1/3 implementation reduction	Moderate	Still requires multi-channel setup
[8]	GPS L1C/A, E1OS, L1C	Multi-GNSS software acquisition	Flexible code lengths (4–16 ms)	High for long codes	Trade-off between sensitivity and processing time
[11]	Galileo E1OS	Orthogonal using Hilbert transform	Reduced correlators	Medium	Only applied to Galileo
[12]	GPS, Glonass, Galileo	Multi-GNSS receiver	Functional acquisition on low-end hardware	Low	Limited sensitivity
[13]	Galileo (BOC modulation)	ambiguity mitigation	Reduced false peaks	High	Increased computational cost
[14]	Galileo E1OS	FPGA-based high-sensitivity	Handles weak signals (100 ms integration)	Very high	Hardware demanding
[15]	GNSS (RTK)	Real-time cinematic GNSS	High reliability	Medium	Needs precise setup
[16]	GPS L1C/A, L1C, Galileo, Beidou	Software receiver	Multi-system tracking	High	Side-by-side combination
[17]	GPS L1C	Software-defined receiver	Fast acquisition (pilot + data)	High	Dual implementation; no orthogonalization
Prop. Work	GPS L1C	Orthogonal single-channel	Fast acquisition , smaller size	Low	First to combine pilot/data orthogonally

3. ORTHOGONAL ACQUISITION IMPLEMENTATION

This section presents the mathematical model of the L1C signal and explains its modulation technique. The second part of this section will highlight the acquisition implementation that achieves a single orthogonal acquisition channel.

3.1 Mathematical Model of the L1C Signal

The L1C signal is classified as interoperable because its modulation is compatible with the Galileo E1OS signal. This compatibility allows a receiver to process both signals effectively. The L1C signal is also more efficient due to its longer length than the GPS L1C/A code and Galileo E1OS code signals, improving positioning accuracy. As a result, software-defined receiver technology is essential for fully utilizing the capabilities of the L1C signal [21].

The L1C signal comprises two channels: the data channel and the pilot channel, which does not carry data. The data channel employs BOC (1,1) modulation, where the subcarrier frequency and the chipping rate are set at 1.023 MHz. In contrast, the pilot channel uses TMBOC modulation, which combines BOC (1,1) and BOC (6,1). In the BOC (6,1) spreading symbols, the subcarrier frequency is (6 × 1.023) MHz [22, 23]. Figure 1 shows the structure of BOC modulation, which highlights the key differences between BOC (1,1) and BOC (6,1) components used in the GPS L1C signal.

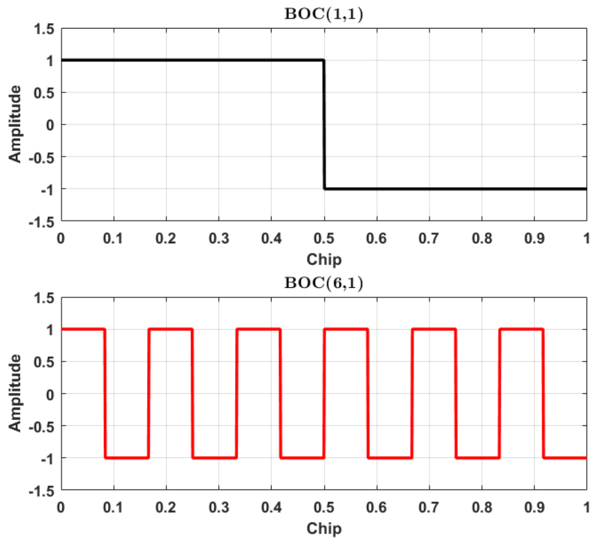

Figure 1. BOC (1,1) and BOC (6,1) Modulation

Eqs. 1 and 2 represent the BOC (1,1) and BOC (6,1) spreading symbols, respectively [10].

$$BOC\ (1,1) = sign\left(\sin\left({}^{2\pi t}/_{T_c}\right)\right) \tag{1}$$

$$BOC\ (6,1) = sign\left(\sin\left({}^{12\pi t}/_{T_c}\right)\right) \tag{2}$$

Where T_c is the code chip duration

The equations for the subcarriers of data and pilot channels (SC_D, SC_P) are presented in Eqs. 3 and 4.

$$SC_D = \sin BOC(1,1)\ (t) \quad (3)$$
$$SC_P = TMBOC_{\left(6,1,\frac{4}{33}\right)} \quad (4)$$

Where (6,1) denotes the BOC (6,1), and 4/33 indicates that the BOC (6,1) is positioned at four pre-selected chips within a 33-chip period. [24].

The data channel ($L1C_D$) includes navigation messages spread by a data ranging code, as shown in Eq. 5.

$$L1C_D = \sqrt{1/2}\, D(t).\, C_D(t).\, SC_D(t) \quad (5)$$

Where D represents the navigation message, and C_D denotes the data ranging code. The mathematical expression for the pilot channel ($L1C_P$) is presented in Eq. 6.

$$L1C_P = \sqrt{3/2}\, C_{sec}(t).\, C_P(t).\, SC_P(t) \quad (6)$$

Where C_{sec} is the secondary code and C_P denotes the pilot ringing code.

The L1C signal (G_{L1C}) can be represented as shown in Eq. 7.

$$G_{L1C} = (L1C_D + L1C_P)\cos(2\pi F_{L1} t) \quad (7)$$

The F_{L1} is the L1 carrier frequency 1.57542 GHz.

3.2 Orthogonal Acquisition Structure

The L1C signal is more reliable than GPS signals on the L2 and L5 bands, primarily because it is less affected by ionosphere conditions [1]. This reliability is achieved by distributing the power of the L1C signal across the principal components (data and pilot), with 75% of the power allocated to the pilot channel and 25% to the data channel [25, 26].

Consequently, more solutions are being developed to acquire the L1C signal using only the pilot channel, enabling faster detection while reducing implementation complexity.

This work addresses the drawback by formatting the received and generated signals orthogonally.

Figure 2 illustrates the acquisition strategy structure, where the received signal is shifted by 90 degrees and combined with the original received signal for the acquisition process. The structure remains the same as that of a single channel; the main difference is the 90-degree shift of the data ranging code, which is then added to the pilot ranging code. This combination allows the generated codes to be combined orthogonally, ensuring the acquisition of both channels in a single attempt, as shown in Figure 3.

The mathematical representation of the orthogonal acquisition is outlined step by step below.

1- Shaping the orthogonal received signal

The received signal passed through two channels. First channel comprises the original signal, while the second channel is responsible for adding the phase shift and then combining to shape the orthogonal signal. The orthogonal combination is given by:

$$G_{orth}[nT_s] = G_{L1C}[nT_s] - jG_{L1C}[nT_s] \quad (8)$$

Where G_{orth} represents the orthogonal signal, n denotes the number of samples, and T_s signifies the sampling period.

By substituting Eq. 7 into Eq. 8 and accounting for the code phase delay and Doppler frequency shift, the orthogonal signal becomes:

$$G_{orth}[nT_s] = \big(L1C_D(nT_s - \tau) + L1C_P(nT_s - \tau)\big)e^{j(2\pi(F_{L1}+F_{dop})nT_s)} - j\big(L1C_D(nT_s - \tau) + L1C_P(nT_s - \tau)\big) \quad (9)$$

Where τ is the code phase delay and F_{dop} represents the Doppler frequency shift.

2- Removing Doppler frequency Shift

During the acquisition process, the receiver generates frequencies corresponding to the received signal's frequency. When alignment occurs between the received and generated frequencies, the Doppler effect is eliminated from Eq. 9, rewriting it as follows:

$$G_{orth}[nT_s] = [L1C_D(nT_s - \tau) + L1C_P(nT_s - \tau)] - j[L1C_D(nT_s - \tau) + L1C_P(nT_s - \tau)] \quad (10)$$

3- Generate orthogonal ranging codes

This step is essential as it produces the replica data and pilot ranging codes (G_{orth_gen}) in an orthogonal format. The replica codes are represented as follows:

$$C_{orth\_gen}[nT_s] = L1C_P(nT_s - \tau) + jL1C_D(nT_s - \tau)] \quad (11)$$

The correlation output is obtained by taking the Fourier transform and multiplying the orthogonal replica codes (G_{orth_gen}) with the output from the previous step G_{orth}, as shown in Eq. 12.

$$G_{orth} = (NL1C_P.NL1C_D) + NL1C_P - j(NL1C_P.NL1C_D) - jNL1C_P - jNL1C_D + NL1C_D \quad (12)$$

Where multiplying ($L1C_P\,.L1C_D$), consider as an uncorrelated signal and can be neglected. Eventually, the square complex output for both data and pilot results in a 3 dB gain in the correlation process, as expressed in Eq. 13.

$$L1C_{Corr}(\tau, F_{dop}) = 4N^2 L1C_P + 4N^2 L1C_D \quad (13)$$

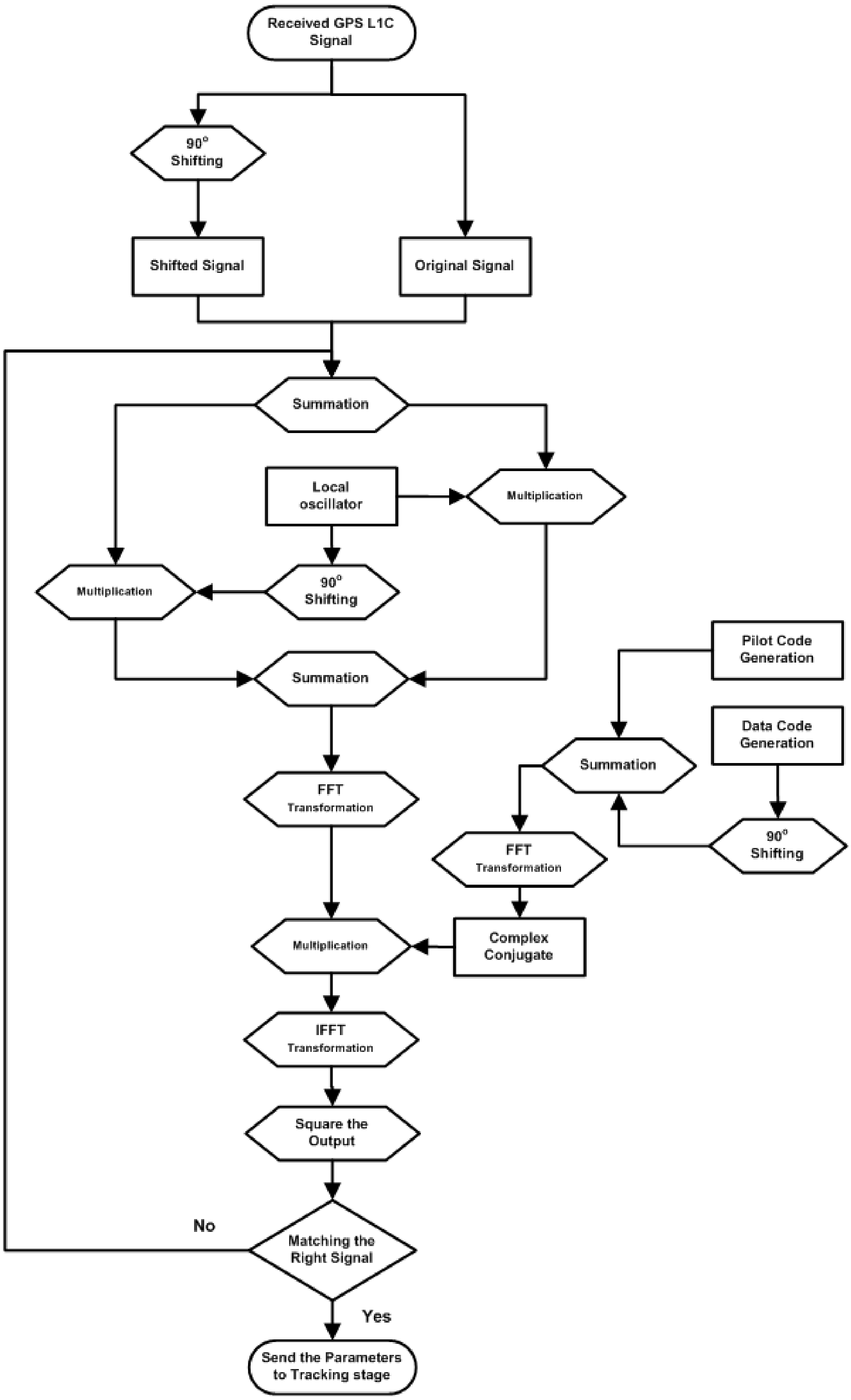

Figure 2. Flowchart of overall acquisition strategy

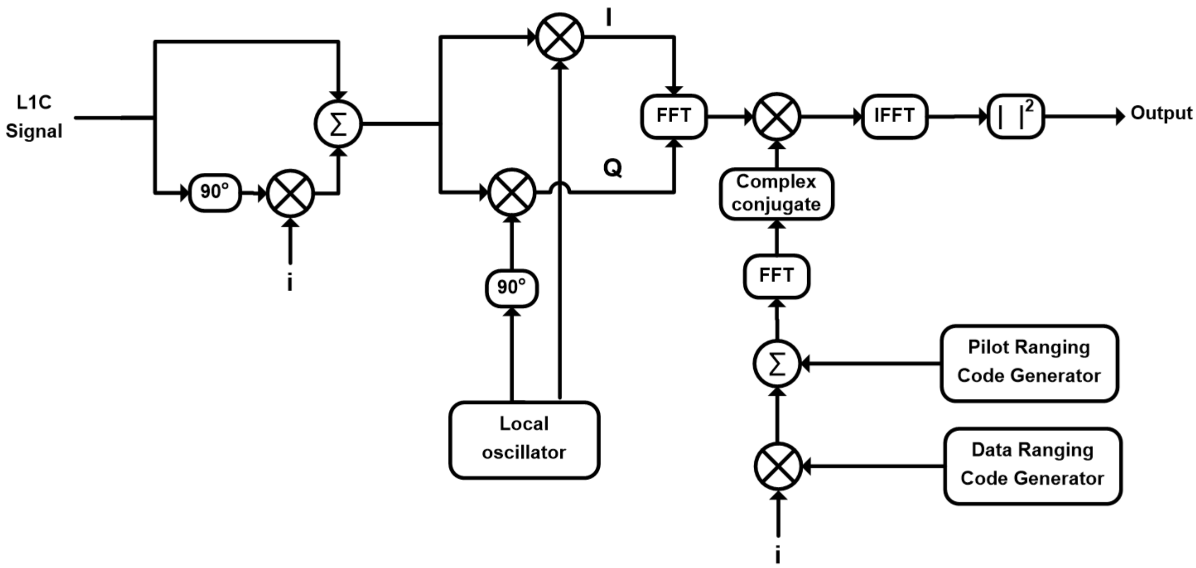

Figure 3. Orthogonal acquisition structure

To clarify the acquisition process, Algorithm 1 summarizes the key steps involved in acquiring the GPS L1C signal. It starts with receiving the signal, creating an orthogonal signal, then searches across Doppler frequency bins, aligns the code phase delay, and finally checks for correlation peaks. This pseudocode illustrates the framework used in the acquisition functions.

Algorithm 1: Pseudocode of the acquisition process

```
START
// Step 1: Receive the L1C Signal
Input_signal = Receive_L1C_signal()
// Step 2: Create an Orthogonal Signal
Original_signal = Input_signal()
Shifted_signal  = shift_phase(Input_signal , 90_deg)
Orthogonal_signal = combine_signals
(Original_signal, Shifted_signal)
// Step 3: Generate Local Oscillator Signals
Local_oscillator = generate_local_oscillator()
I_signal = mix(Orthogonal_signal , Local_oscillator)
Q_signal = mix(Orthogonal_signal ,
shift_phase(Local_oscillator, 90_deg))
// Step 4: Perform FFT on IQ-signal
IQ_freq = FFT(combine_iq(I_signal, Q_signal))
// Step 5: Generate Orthogonal Reference Code
Pilot_code = generate_pilot_ranging_code()
Data_code = generate_data_ranging_code()
Data_code = shift_phase(Data_code , 90_deg)
Reference_code = combine_codes(Data_code,
Pilot_code)
// Step 6: Perform FFT & Take Complex Conjugate of
Reference Code
Ref_freq = FFT(Reference_code)
Ref_conj = complex_conjugate(Ref_freq)
// Step 7: Multiply Complex Conjugate with FFT IQ
Multiplied_freq= mix(Ref_conj , IQ_freq)
// Step 8: Perform IFFT to Obtain Correlation Result
Correlation = IFFT(Multiplied_freq)
// Step 9: Compute Magnitude Squared
Output = abs(Correlation)^2
// Step 10: Determine Doppler frequency shift and
Code phase delay
Result = find(Dop_freq, Cod_del)
// Step 11: Send Result
Send_result (Dop_freq, Cod_del)
END
```

4. SIMULATION RESULTS AND DISCUSSION

The simulation result is obtained from the following setup. The L1C signal is generated using the MATLAB-Simulink platform, as shown in Figure 4. The simulation environment utilizes a Rayleigh fading channel and additive white Gaussian noise (AWGN) for the simulated environment, as depicted in Figure 5. Multipath scenario as urban and obstructed environments are the cases where GNSS receivers operates, we consider a Rayleigh fading channel to simulate multipath phenomenon. This model provides a pessimistic benchmark to assess acquisition performance in realistic fading.

The sampling frequency in our simulation setup is set to 16.368 MHz.

The results focus on two primary technical issues: the probability of detection and the computational complexity of implementation, highlighting the achievements produced by the orthogonal acquisition.

The simulation settings (detection probability, computational complexity, processing time, and comparative summary) are well--aligned with the simulation outcomes to keep the description of parameters closely linked to the discussion.

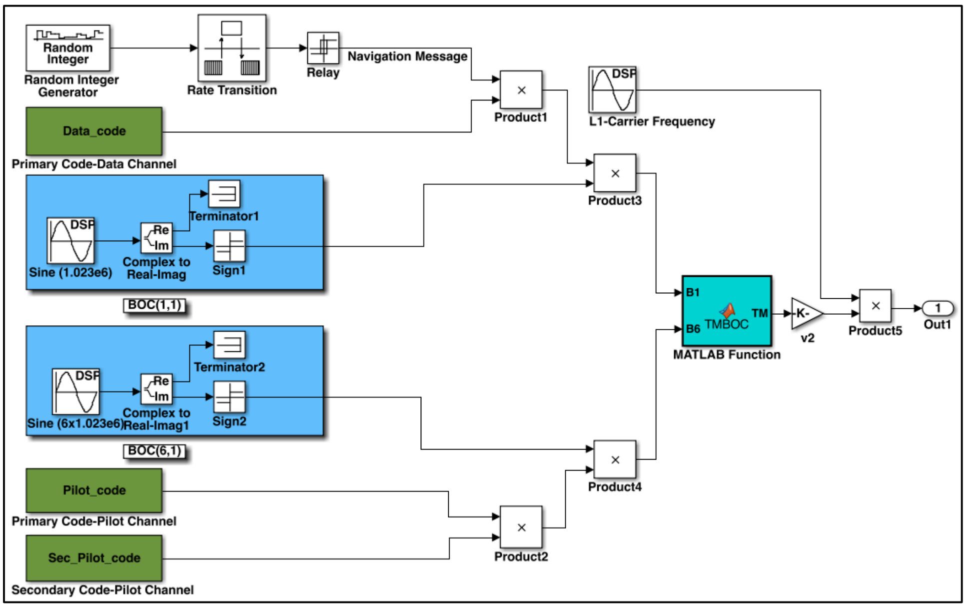

Figure 4. GPS L1C signal generation

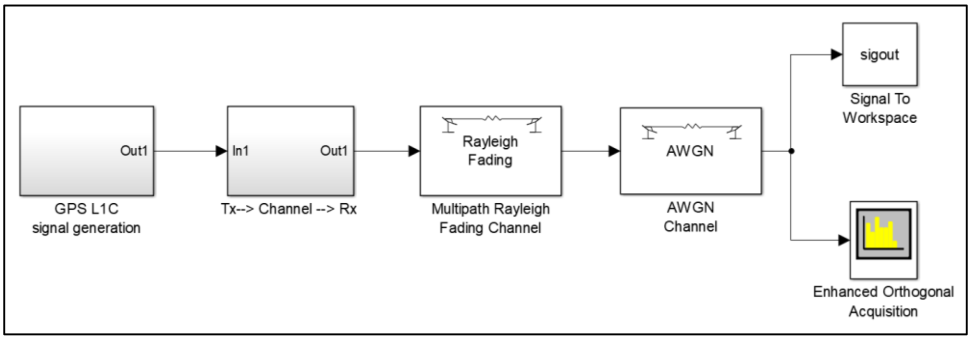

Figure 5. Transmitting-Receiving simulated environment

4.1 Detection probability

The experimental testing is conducted on the MATLAB-Simulink platform, utilizing a Monte Carlo simulation to assess the detection probability over 100 runs. The search dwell time is configured to 10 ms, aligning with the duration of the L1C codes. Figure 6 shows approximately a 5 dB difference between the acquisition of data and pilot channels, which is attributed to the power distribution across these channels [24]. Additionally, the performance of the joint pilot and data channels in an orthogonal configuration exceeds that of the pilot channel alone, suggesting that orthogonal acquisition maintains the 3 dB gain achieved through their combination [11]. It also shows that the orthogonal implementation outperforms the side-by-side implementation by about 1 dB through combining the data and pilot channels.

The gain obtained by the proposed combination of data and pilots in the orthogonal channel. The 90° phase shift between the two components makes the correlation functions independent, which preserves the total signal power for each component. This orthogonal alignment results in a theoretical 3 dB gain in the signal-to-noise ratio compared to single-component acquisition. In other words, the results indicate a 3 dB gain, which is in line with the theory that suggests combining two orthogonal components of equal power. This is because the signal power doubles while the noise levels stay the same, confirming that our simulation results align well with the theoretical model.

Furthermore, it enhances receiver sensitivity under low-SNR conditions and reduces computational load by eliminating the need for dual-channel correlation. Consequently, the orthogonal design provides a more efficient and robust acquisition scheme for GPS L1C signals.

It should be mentioned that the impact of navigation data bits and Neumann–Hoffman (NH) secondary code on convergence analysis were taken into account in this study. The duration of the coherent integration time is 10 ms, which is shorter than the navigation bit period 20 ms; therefore, data bit transitions do not interfere with detection. Also, the NH secondary code is deterministically cancelled before coherent summation to avoid phase reversals and to achieve a correct signal alignment that contributes to the reliable detection probability.

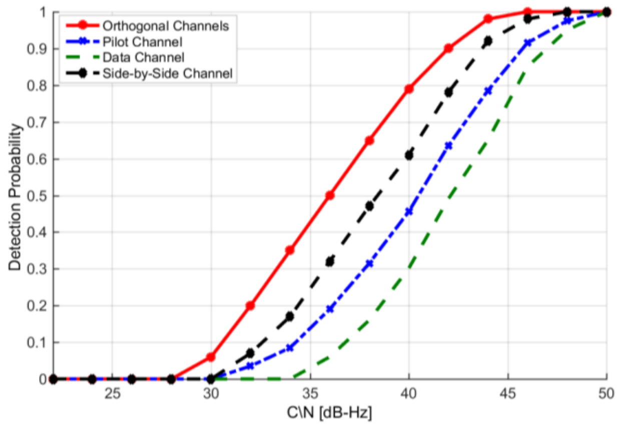

Figure 6. Detection probability for the GPS L1C signal

Comparison of receiver operating characteristic curves is shown in Figure 7. The detection probability is plotted as a function of the false alarm probability for the Pilot, Data and Side-by-Side channels to that of the proposed Orthogonal channel. Comparisons of the results reveal that compared with the method, the proposed Orthogonal approach has better detection performance over all false alarm rates and it is more immunity and sensitive to the other methods.

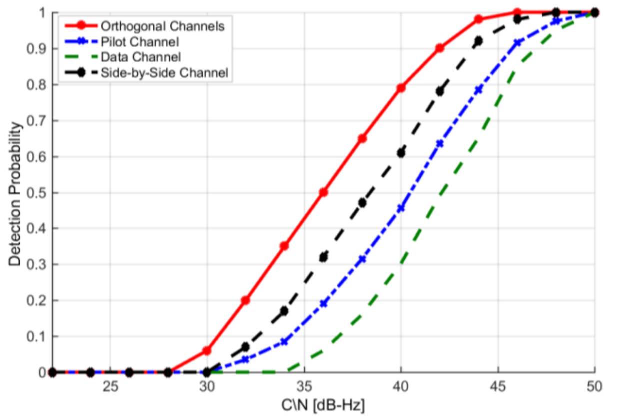

Figure 7. Detection probability vs. false alarm probability

4.2 Computational complexity

The sampling frequency is 16.368 MHz, meaning 16 samples represent each code chip. The Doppler frequency bin step is 500 Hz, which allows for 17 bins in a Doppler frequency search range of ±4 kHz. The implementation computational complexity of utilizing the FFT search method, as shown in Figure 3, is described using Big O notation.

It's worth mentioning that selecting a Doppler bin spacing of 500 Hz fits perfectly with the typical coarse acquisition process found in most conventional GNSS receivers, especially for static or low-speed applications [27]. Moreover, this spacing provides a balanced compromise between reliable signal detection and manageable computational complexity, enabling efficient acquisition without adding unnecessary processing overhead.

Table 2 outlines the acquisition steps and breaks down the computational requirements for both the orthogonal acquisition method and the side-by-side implementation method. In this context, 'n' represents the total number of samples, calculated as follows: 16 (samples) * 10 (ms) * 10230 (code length).

From Table 2, both designs have one $O(n^2)$ step for Doppler wipe-off. However, during the correlation step, the orthogonal performs one $O(n^2)$ code-matching, whereas the side-by-side requires two. Hence, the dominant quadratic step is 2 (orthogonal) vs. 3 (side-by-side).

Based on the number of samples discussed:

Addition O(n): $n = 1{,}636{,}800$

Multiplication O(n^2): $n^2 = 2.679 * 10^{10}$

Transformation (n $\log_2$ n):

$$n\, log_2 n = 1636800 \log_2 1636800 = 10 * 10^6$$

For orthogonal implementation:

$2 * O(n) + 2 * O(n^2) + 3 * n\, log_2\, n$

which approximately = 5,358,261,753,600

While for side-by-side implementation:

$2 * O(n^2) + 5 * n\, log_2\, n$

which approximately = 8,037,392,720,000

The quadratic terms take precedence, resulting in an overall orthogonal/side-by-side ratio of ≈ 0.667 (i.e., ≈ 33 % reduction). This theoretical reduction aligns with the processing-time improvements noted in Section 4.3.

As shown in Figure 8, the orthogonal implementation has a lower computational burden, requiring only two additions: one for adding the received signal to the shifted signal and another for performing operations with the data and pilot code orthogonally. In contrast, the side-by-side implementation requires double the multiplications and double the Fourier transformations and inversions. Consequently, the reduction achieved with the orthogonal implementation is 34% compared to the side-by-side implementation.

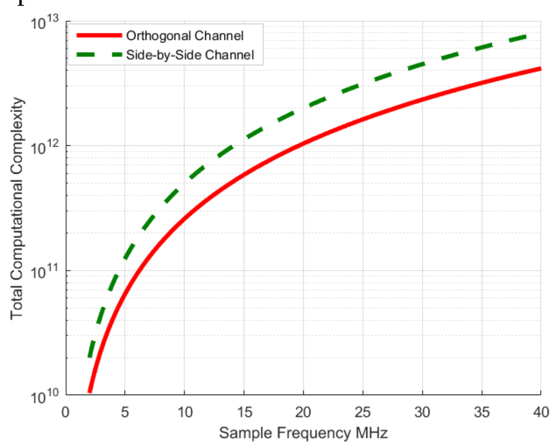

Figure 8 Computational complexity

Table 2. Orthogonal vs. side-by-side implementation steps

Steps	Big (O) operation	Orthogonal	Side-by-Side
Receiving	Addition	O(n)	--
Removing the Doppler shift	Multiplication	$O(n^2)$	$O(n^2)$
FFT	Transformation	$n \log_2 n$	$n \log_2 n$
Code generation	Addition	O(n)	--
FFT	Transformation	$n \log_2 n$	$2(n \log_2 n)$
Code Matching	Multiplication	$O(n^2)$	$2(O(n^2))$
IFFT	Transformation	$n \log_2 n$	$2(n \log_2 n)$

Where the shaded cells represent the lowest computational complexity cost.

4.3 Processing Time

Table 3 illustrates the decrease in processing time achieved by using an orthogonal implementation compared to a side-by-side implementation. In other words, the reduction in computational complexity is significantly reflected in the performance, as evidenced by the processing time required to accomplish the acquisition process. In this comparison, the processor is Intel(R) Core (TM) i5-6300U CPU @ 2.40GHz 2.50 GHz, and the RAM is equal to 4 GB. The acquisition-time values obtained are in agreement with the latter calculations with recent analyses on multi-GNSS receivers reported in [28].

Table 3. Processing time of Orthogonal vs. side-by-side implementation

Implementation	Processing Time
Orthogonal	7.217 sec.
Side-by-Side	11.088 sec

Although the power consumption was not directly measured in this work, the reduction obtained in both computational complexity and processing time led to a proportional decrease in energy usage. In SDR, power consumption is mainly influenced by correlation and FFT operations. Therefore, reducing the number of arithmetic operations leads to a measurable decrease in power consumption [29].

4.4 Comparative summary

Moreover, a comparative study with recent works has been carried out in order to verify the improvement in performance of the designed orthogonal single-channel acquisition scheme. Performance comparison Key performance indicators of related works including cumulant acquisition-based methods, joint correlator estimation, and hardware-based receivers as well as a former orthogonal method [11] are summarized in Table 4. Comparison reveals that the proposed L1C implementation gains 3 dB signal-to-noise ratio enhancement with 34% less computational complexity and is the minimum processor time-wise among the considered techniques. These results corroborate that the model developed offers a more efficient and realistic solution for the new generation GNSS receivers.

Eventually, the orthogonal implementation maintains acquisition performance and reducing the computational complexity. However, it’s still depends on maintaining accurate phase orthogonality between the data and pilot components.

Table 4. Comparative summary

Study (Ref.)	Signal	Method / Technique	Detection Probability	Computational Complexity	Key Observation
[11] Albu-Rghaif et al., 2015	Galileo E1OS	Orthogonal Data–Pilot Acquisition	High	Medium	Demonstrated orthogonal concept for Galileo signal
[13] Wang et al., 2024	Galileo E1OS	Cumulant-Based Acquisition	High	High	Ambiguity resolved but high complexity
[14] Majoral et al., 2024	Multi-GNSS (FPGA)	High-Sensitivity Hardware Receiver	Very High	Very High	FPGA-based, resource demanding

[23] Guo et al., 2022	GPS L1C/B1C	Joint Correlator Combination	High	Medium	Requires multi-channel setup
Proposed Work	GPS L1C	Orthogonal Data–Pilot (Single Channel)	High	Low	Achieves 3 dB SNR gain with reduced complexity

5. CONCLUSIONS

This paper was motivated to improve the performance of the GNSS signal acquisition with less computations. The proposed method obtained about 3 dB performance gain with 34% complexity reduction, the improvement of efficiency and accuracy is balanced in stage. One of the main contributions of this work is the simplified and single-channel orthogonal architecture, which offers better performance and implementation cost when compared to conventional side-by-side designs. This makes the method very attractive for the low-power and multi-GNSS receiver, where power consumption is a critical issue.

The experimental results demonstrate that the presented approach is capable of achieving a comparable or even better detection probability to current algorithms with much less computation, thus indicates its superiority and practical value. Future work will focus on validating this approach using an SDR with real-world dynamic datasets under realistic multipath conditions. Additional extensions will focus on the compatibility with GPS L1C/A and Galileo E1 OS signals.

In conclusion, this approach represents a promising path toward the development of future GNSS receivers, offering an effective balance between performance and implementation simplicity. By reducing processing complexity while maintaining high detection probability, to enable more efficient and adaptive positioning systems.

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