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Combining GPS and Galileo Signals Acquisition in a Single Processing Chain

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ABSTRACT

The increasing demand for accurate and efficient Global Navigation Satellite System (GNSS) receivers, especially in smartphones, has driven the need to combine multi-GNSS signals. Current receivers, based on Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) signals, often process these signals side-by-side, increasing complexity, size, and power consumption. Meanwhile, the next generation of smartphones and navigation applications will involve Galileo receivers to improve positioning accuracy, faster time to first fix, and reduce the multipath effect, especially in urban canyons or dense forests. Therefore, to avoid the drawbacks of side-by-side implementation; i.e. minimize the large size, and preserve processing time with low power consumption, this work presents a novel approach to simultaneously acquire GPS L1 and Galileo E1 signals in a single processing chain. This achieved by taking advantage of both GPS and Galileo signals are sharing the same carrier frequency and chipping rate. However, our solution requires just a single pre-processing step to overcome the subcarrier effect and one extra multiplication for the Galileo code. The results based on Monte Carlo simulation show that the combining solution; firstly, maintains the acquisition performance for each signal and has the same performance as acquiring each signal alone. Secondly, offers about 48% reduction in the implementation/computational complexity. Eventually, the solution preserves the reliability of the acquisition process by comparing the ratio of the highest peak to the average value in the correlation process, where the results illustrate that both GPS and Galileo signals have the same ratio tendency.

1. Introduction

Most smartphones are GPS and GLONASS enabled to increase accuracy and availability. The market of GNSS receivers expects that more than 10 billion GNSS receivers will be enabled by 2031 [1]. The Galileo signal is designed to be more compatible with GPS and Glonass signals and to provide more accurate localization and high performance against multipath signals [2]. This is achieved by producing narrow multiple peaks in the auto-correlation envelope that are equal to one-third of the peak of the GPS signal [3], as shown in Figure 1.

Implementing solutions with receiver's side-by-side will offer accurate localization and more mitigation to multipath signals, but this comes at the expense of size and battery life [4].

GNSS such as GPS has become indispensable for smartphones. However, their accuracy and reliability often face challenges in environments like urban canyons where signals are weak and distorted due to multipath effects. To overcome these challenges, combining multiple GNSS signals (i.e., GPS, Galileo) in a

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single processing chain provides enhanced accuracy and faster acquisition times. This manuscript addresses the need for efficient GNSS signal acquisition in smartphones. The drawback has been overcome for the previous solutions by taking advantage of sharing the GPS and Galileo signals same center frequency (1575.420 MHz) and the same chipping rate (1.023 MHz). As a result, integrating these GNSS signals will certainly lead to cost, size, processing time, and power consumption reductions.

The proposed solution involves processing received GNSS through two channels. The first channel allows GNSS signals to pass through without any processing, while the second channel eliminates the subcarrier effect using enhanced subcarrier elimination conversion [5]. The output signals are then combined and subjected to a parallel code phase search Fast Fourier Transform (FFT) algorithm [6]. The transformed signals are multiplied by the open service (OS) and coarse acquisition (C/A) codes, as illustrated in the structure of the combining acquisition section and shown in Figure 2. Additionally, the solution offers two ways to acquire the Galileo signal besides the GPS signal, either by acquiring data/pilot channel or both data & pilot in the orthogonal form to maintain 3dB power gain [7]. The results demonstrate that combining acquisition has maintained the performance of acquiring the GPS and Galileo signals. Additionally, the solution reduces the implementation complexity and makes the solution more valuable for the smartphone's software receiver.

A novel method is proposed that combines the acquisition of GPS L1 and Galileo E1 signals into a single processing chain. Our approach reduces computational complexity by approximately 48% compared to traditional side-by-side implementations. We present a detailed performance analysis through Monte Carlo simulations, focusing on detection probability, computational load, and peak-to-average ratio, demonstrating that our system maintains the acquisition performance of both signals while significantly improving resource efficiency.

The work focuses on developing a solution that improves the acquisition of GNSS signal, specifically for mobile devices like smartphones. These devices require precise positioning while consuming minimal power. The proposed solution aims to reduce computational complexity and processing time, making it suitable for real-time applications in urban environments. This is important because GPS signals in urban areas often suffer from multipath effects. The research addressed the lack of an efficient method that combines GPS and Galileo signals into a single processing chain. The integration reduces hardware and software complexity while maintaining high accuracy and reliability.

The focus is on GPS L1 and Galileo E1 signals due to their widespread use in current GNSS systems and their interoperability, making them crucial for smartphone applications. While BeiDou B1C operates at 1575.420 MHz, we selected GPS and Galileo signals for their global coverage and reliability in civilian applications. Future work could extend this method to incorporate other GNSS systems like BeiDou or GLONASS, further enhancing accuracy in multi-constellation receivers.

The rest of the paper is organized as follows: Section 2. summarizes the literature survey on previous works. Section 3. describes the implementation of our solution. Section 4. shows the results and the performance. Finally, the conclusions are listed in Section 5.

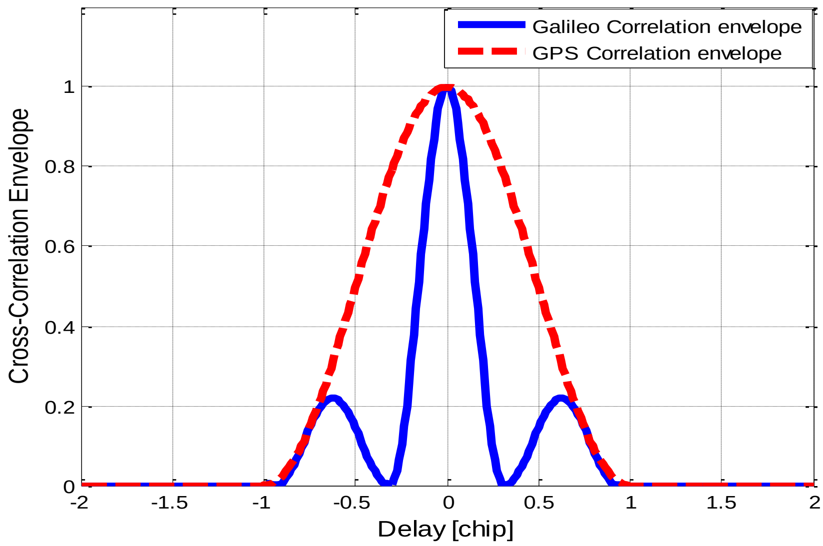

Figure 1. The Autocorrelation envelope of the GPS and the Galileo signals

2. Previous works

The complete satellite constellations of GNSS systems include GPS, GLONASS, and Galileo systems. The GPS is run by the United States and it transmits two types of signals - one for military use and another for civilian use. These signals are transmitted through different frequency bands. The GPS operates on Code Division Multiple Access (CDMA) techniques and the signals are modulated using Binary Phase Shift Keying (BPSK). While the modernized signals are Binary Offset Carrier (BOC) modulation. The GLONASS system is another satellite navigation system developed by Russia for both military and civilian use. Initially, the system used the same code but with different frequencies based on Frequency Division Multiple Access (FDMA) and BPSK modulation. However, the Russian has since upgraded the system to use CDMA technology with BOC modulation for more modernized signals. The Galileo system developed by the European Union is different from its predecessors as it is designed not only for military and civil use but for commercial use. This system works similarly to the GPS, using the CDMA technique and based on BPSK and BOC modulation [8].

Combining GNSS signals can improve satellite distribution, avoid multipath signals, and reduce the dilution of precision. Therefore, smartphones with combined GNSS receivers might help to increase accuracy and battery life. Current GNSS receivers that process GPS and Galileo signals separately are computationally expensive, require more power, and are unsuitable for mobile applications. This work proposes a combined acquisition method to overcome these challenges by integrating GPS and Galileo signals into a single processing chain.

When the Galileo system decided to launch the first satellite many algorithms and solutions were designed to combine the Galileo signal with the GPS signal [9]. A combined architecture is developed to enhance the reception but at the expense of complexity, due to using a very high number of correlators. In the same vein, a design is proposed to acquire both GPS and Galileo signals [10]. A matched filter has been employed in parallel with the FFT search to accelerate the acquisition process and to scan more cells of codes and frequencies. In addition, this design produces more flexibility to acquire different GNSS signals such as the GLONASS signal. However, this work uses a large number of correlators to accommodate both GPS and Galileo signals. Another solution that combines GPS and Galileo systems is designed to acquire GPS L1C and Galileo L1 signals [11]. In this solution, four methods are used for processing different types of incoming signals. The first method processes an 8 ms data signal by generating a 4 ms replica of the L1-B signal and padding zeroes for the remaining 4 ms. The second method processes a 16 ms pilot channel signal by generating an 8 ms replica of the L1c signal and padding zeros for the remaining 8 ms. The third method processes a 16 ms signal by dividing it into four 8 ms subgroups with different distributions. This method requires more processing time and is used for weak signals. The fourth method processes an 8 ms signal using two combinations, each with a 4 ms replica and 4 ms of padded zeros. The results showed that the 2nd and 3rd methods achieved about 3 dB and 6 dB better performance than the 1st method, respectively. Additionally, a method is implemented to acquire GPS L1 C/A and L1C signals. The 3 dB and 6 dB improvements are achieved due to the longer length of the signals used in the acquisition process. [12]. This implementation takes advantage of transmitting these signals from the same satellite, which means these signals have the same code delay and Doppler frequency shift. The authors promise that this implementation can be applied to the Galileo L1 signal, but they don't show how can overcome the ambiguity problem.

On the other hand, various methods are proposed based on the compressive sensing (CS) technique. In order to reduce the computational complexity and to generate all the correlators that required to acquire both GPS and Galileo signals only one time, a solution based on CS is proposed [13]. This work utilized a subcarrier elimination to overcome the ambiguity for Galileo signal acquisition and to have both of these signals same autocorrelation function. The main idea behind using the CS technique is to transfer the correlators' multiplication from the length of samples to the compressed length of the sensing matrix. The first compressing is achieved by generating non-Doppler shift vectors, which are fed to be multiplied by the sensing matrix. This leads to have a compressed matrix that accommodates the whole information of GPS and Galileo signals. Consequently, A CS work develops the previous implementation by adding the GPS L1C signal to the acquisition process, taking the advantage of GPS L1 C/A signal for code and Doppler shifts [14]. In this work, the dictionary matrix is divided into two sub-dictionaries to overcome the code length of the GPS L1C signal, which is ten times longer than the GPS L1 C/A signal. Actually, the dictionary matrix has the same length as the previous work and only has the first millisecond of the GPS L1C code beside the GPS L1 C/A code. Once the GPS L1 C/A is acquired, the Doppler frequency shift will be known for both GPS signals. The code phase delay of the L1C signal will be either at the first millisecond or an integer between 2 to 10, due to both GPS signals transmitting from the same satellite and having the same delay. Moreover, the frequency resolution in this implantation is equal to 20Hz because of the number of Doppler channels that employed in this implementation. Furthermore, a CS algorithm is based on two stages, code and frequency compression [15]. This work takes the advantages of the sparsity representation for GNSS signals and utilizes the compressive sensing technique to acquire GPS signal. The proposed algorithm is designed to overcome the computational complexity by breaking down the acquisition process. This is achieved by adopting frequency and code compressions. It's worthwhile to mention, that this work has used the FFT beside the compressive sensing, which compressed the multiplication in the frequency domain using compressive sensing, i.e. combining two search engines. To improve localization accuracy, one approach focuses on reducing multipath error by combining GPS, Galileo, and BeiDou-3 signals. This method takes advantage of the interoperability between these systems and uses a multipath hemispherical map [16]. On the other hand, another method is designed to enhance the acquisition of weak GPS and Galileo signals, which is cumulant-based. This technique successfully integrates higher-order cumulants to improve accuracy in GNSS signal acquisition processes [17]. Nevertheless, these methods have addressed the issue of multipath errors and improved acquisition accuracy. However, they have done so at the cost of increased complexity and power consumption due to the side-by-side implementation.

3. Combining acquisition implementation

The research method follows these key steps:

1. Identifying the problem of high computational complexity in side-by-side GPS and Galileo acquisition systems.
2. Designing a single processing chain that leverages shared characteristics of the GPS L1 and Galileo E1 signals.
3. Implementing the solution to evaluate the performance in terms of detection probability, computational load, and peak-to-average ratio. This method effectively addresses the problem by reducing the computational requirements and maintaining signal acquisition performance.

3.1 Mathematical Model of the GNSS Signals

The main goal of designing Galileo signals is to be interoperable with other GNSS systems, mitigating multipath signals and providing civilian signals alongside commercial signals.

The Galileo E1 OS signal is based on multi-level spreading code, which is called composite binary offset carrier (CBOC) modulation [2]. This multi-level comprises two types of weighted sum, which are BOC (1,1) and BOC (6, 1) as expressed in Eq. (1).

$$G_{E1\text{-}OS}(t) = 1/\sqrt{2}\,\big[g_B(t)\big(\alpha\, sc_{B.a}(t) + \beta sc_{B.b}(t)\big) - g_C(t)\big(\alpha\, sc_{C.a}(t) - \beta sc_{C.b}(t)\big)\big]\cos(2\pi F_{E1} t) \quad (1)$$

Where $g_B(t)$ and $g_C(t)$ are the binary signal components for data and pilot channels respectively, $sc_{x.y}$ are the subcarrier components, α & β are the power parameter and are equal to $\sqrt{10/11}$ and $\sqrt{1/11}$ respectively, and F_{E1} is the carrier frequency [16].

On the other hand, the GPS L1 C/A signal is based on BPSK modulation, and the GPS signal is expressed in Eq. (2).

$$G_{L1-CA}(t) = \sqrt{2P}\,[C(t)D(t)\cos(2\pi F_{L1} t)] \quad (2)$$

Where P represents the signal power, $C(t)$ is the C/A code, D(t) navigation message and F_{L1} is the carrier frequency [18].

Both GPS and Galileo signals share the same centre frequency (1575.420 MHz) and the same chipping rate (1.023 MHz). The length of the C/A code is 1023 chips and repeated every 1 ms, while the length of the OS code is 4092 chips with a period of 4ms, which leads to making the common divisor equal to 4ms.

3.2 Structure of combining acquisition

Acquiring Galileo signals is known as ambiguous acquisition. Consequently, various methods are designed to acquire the Galileo (BOC) signal as a BPSK-modulated signal to remove the ambiguity. The most common methods used for this purpose are the dual sideband [19]. and the BPSK-Like method [20]. However, employing such methods may add an overhead to the implementation regarding size and processing time. To overcome this issue our work takes advantage of the enhanced subcarrier elimination conversion algorithm [5].

Before demonstrating the structure of combining the GPS and Galileo signals, let's simplify the received signals representation and assume the spreading code with navigation message is:

$$\gamma(t) = D(t) \oplus C(t) \quad (3)$$

The received GPS signal will be:

$$G_{BPSK}(t) = \gamma(t-\tau)e^{j2\pi(F_{L1}-F_{d1})} \quad (4)$$

where τ is the code phase delay and F_{d1} represents the Doppler frequency shift.

The received Galileo signal is:

$$G_{CBOC}(t) = \big[\gamma_b(t-\tau)\big(sc^{+}_{\alpha.\beta}\big) + \gamma_c(t-\tau)\big(sc^{-}_{\alpha.\beta}\big)\big]e^{j2\pi(F_{E1}-F_{d2})} \quad (5)$$

where, γ_b, γ_c are the spreading code of data and pilot channels respectively. The $sc^{+}_{\alpha.\beta}$ is the subcarrier component of the data channel, while the subcarrier components of the pilot channel are equal to $sc^{-}_{\alpha.\beta}$.

Therefore, the received GNSS signals are

$$G(t) = G_{BPSK}(t) + G_{CBOC}(t) \quad (6)$$

Figure 2 illustrates the two parallel paths used in the acquisition process. The upper path processes the GNSS signals without any pre-processing (the G(t) signal). While the lower path eliminates the subcarrier effect, by multiplying the GNSS signals with data or pilot subcarrier, enabling the combination of GPS and Galileo signals. The output from these two paths is then combined and subjected to further processing

This results in the production of a G2(t), as illustrated below:

$$G_2(t) = G(t)sc_{\alpha.\beta}^{+/-} \quad (7)$$

$$G_2(t) = [G_{BPSK}(t) + G_{CBOC}(t)]sc_{\alpha.\beta}^{+/-} \quad (8)$$

$$G_2(t) = G_{BPSK}(t)sc_{\alpha.\beta}^{+/-} + G_{BPSK}^{+}(t) + G_{BPSK}^{--}(t) \quad (9)$$

or

$$G_2(t) = G_{BPSK}(t)sc_{\alpha.\beta}^{+/-} + G_{BPSK}^{-}(t) + G_{BPSK}^{++}(t) \quad (10)$$

Where $G_{BPSK}^{+}(t)$ is the Galileo signal with data code that is shaped as a BPSK modulation, and $G_{BPSK}^{-}(t)$ is the Galileo signal with pilot code.

After being correlated, the signals that have gone through pre-processing according to Eq. (9 or 10) will be expressed as:

$$G_2(t) = G_{uncorrelated}(t) + G_{BPSK}^{+/-}(t) + G_{uncorrelated}(t) \quad (11)$$

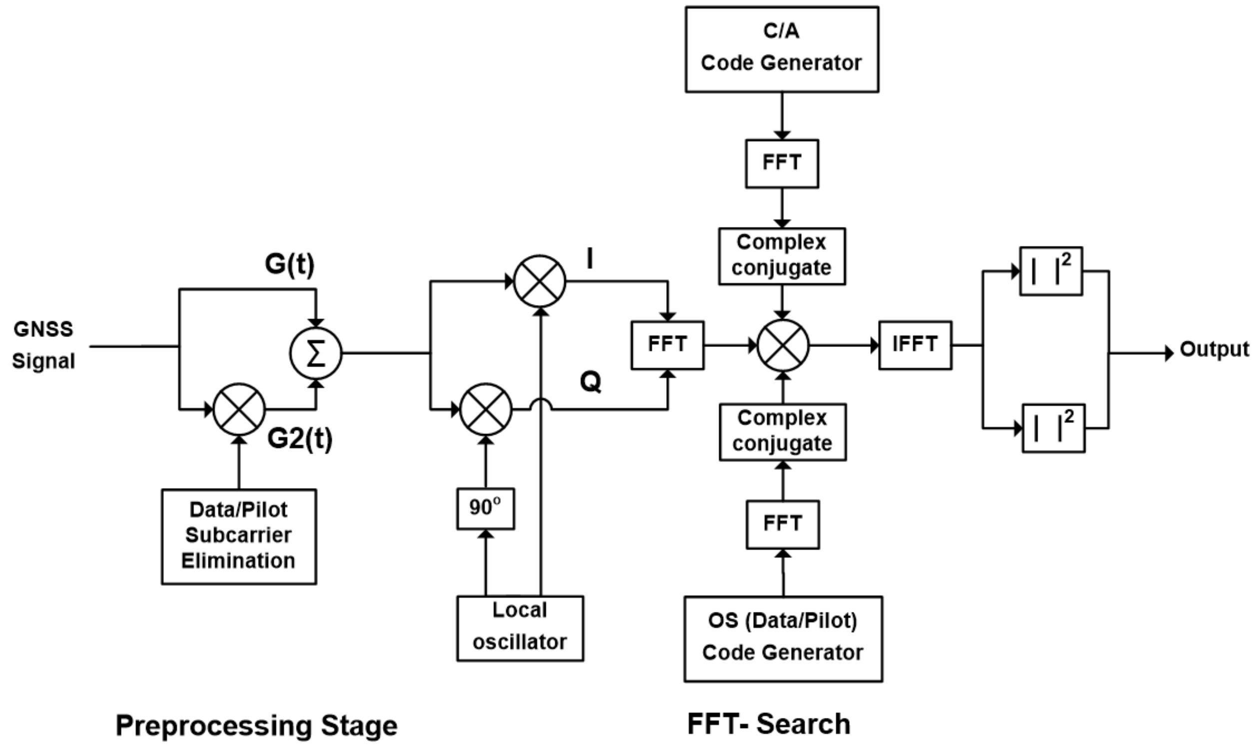

Figure 2. The Structure of combining acquisition

This means that $G_2(t)$ consists of two uncorrelated signals and a desired Galileo signal using BPSK modulation. Figures (3 and 4) illustrate the Galileo signal by removing the subcarrier effect for the data and pilot subcarrier channel, respectively.

First, the G(t) signals from the upper channel are combined with the $G_2(t)$signal. The next stage involves a modified version of the parallel code phase search (FFT) algorithm, more details in [6]. The only difference in this algorithm is that the transformed signal is multiplied with the C/A code and the OS data or pilot code. Furthermore, the FFT search algorithm effectively addresses the varying signal strengths of GPS (-160 dBW to -158 dBW) and Galileo (-157 dBW to -155 dBW) signals by individually examining the highest peaks, as depicted in Figure 2 in the last processing stage.

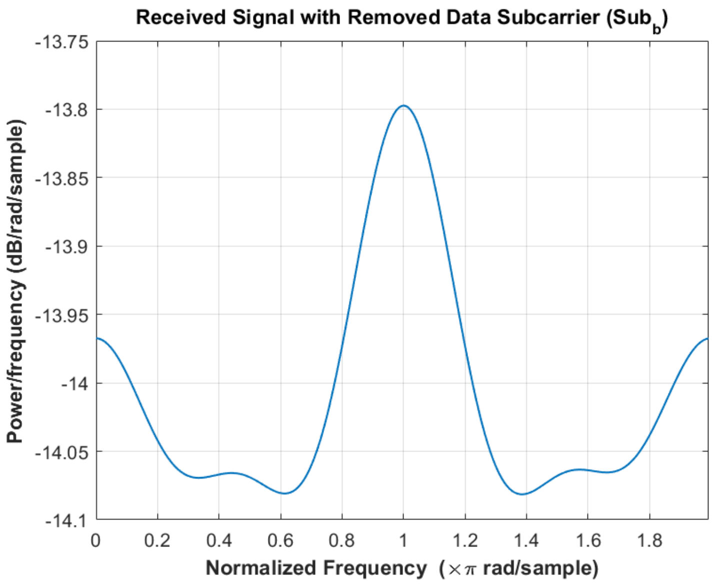

Figure 3. Pre-processed signal after removing data subcarrier effect

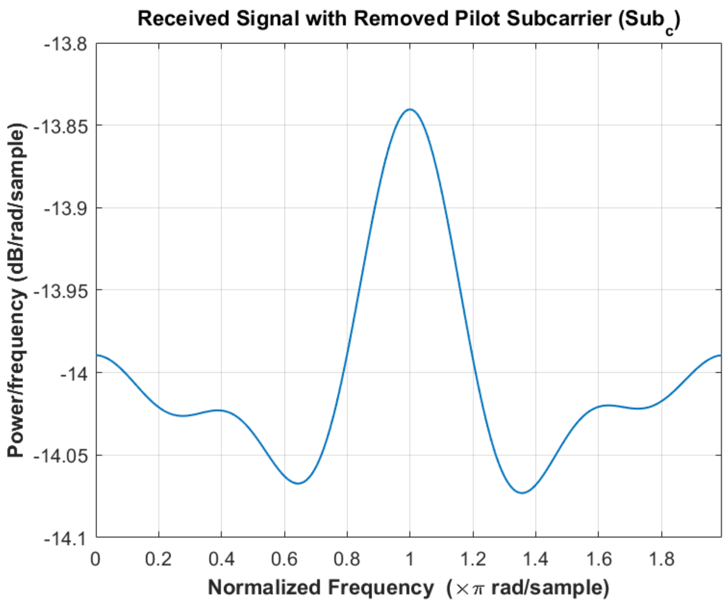

Figure 4. Pre-processed Signal after removing Pilot subcarrier effect

4. Simulation results and analysis

This section will showcase the achievements of the acquisition solution. It will cover detection probability, computational complexity, and peak-to-average ratio analysis.

4.1 Acquisition probability analysis

The Monte Carlo simulation is a technique used to evaluate the probability of detection for acquiring the GPS and Galileo signals, with 150 runs. The simulation environment is built on the MATLAB-Simulink platform, and it employs the Rayleigh Fading channel to generate multipath signals. As illustrated in Figure 2, the FFT algorithm is utilized, with a search dwell time set to 4ms, which is the standard time for GPS and Galileo signals. The results of our Monte Carlo simulation clearly show that the proposed method maintains acquisition performance comparable to side-by-side implementations, as evidenced by the consistent detection probabilities across varying carrier-to-noise ratios (20-50 dB-Hz) as shown in Figure 5. In this implementation, the pilot channel is used for Galileo signal acquisition, which means the elimination subcarrier is $sc_{\alpha.\beta}^{-}$. Consequently, the Galileo acquisition takes the advantage of 2 dB gain obtained from the elimination process [5]. As can be seen obviously our solution has maintained the acquisition performance for both GPS and Galileo signals as the side-by-side acquisition implementation with more computational reduction, as demonstrated in the next section.

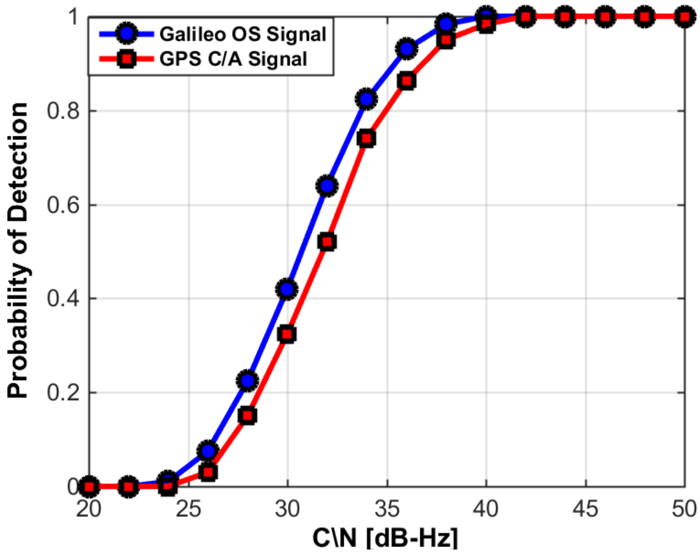

Figure 5. The acquisition probability of GPS and galileo signals

4.2 Computational complexity analysis

The simulation setup uses a sampling frequency of 8.184 MHz with a pre-set simulation signal length of 4ms for both GPS and Galileo signals. This means that there are 163680 test points for computational complexity (n). The FFT acquisition algorithm requires 17 frequency searches with a 500 Hz bin step. The total computational requirement for FFT is determined by these parameters, based on Big O notation.

$n \log_2 n = 163680 \log_2 163680 = 2.8350 \text{ x } 10^6$

And the multiplication computational is: $\frac{n}{2} \log_2 n = \frac{163680}{2} \log_2 163680 = 1.4175 \text{ x } 10^6$

The main differences between our implementation and the side-by-side implementation are:

- The side-by-side uses two channels to acquire the GPS and Galileo signals.
- Our combining acquisition uses one channel to acquire the above signals with two extra multiplications and one FFT conversion (the 1st multiplication is to eliminate the subcarrier effect and the 2nd multiplication of the GPS code. While the FFT conversion is for the C/A code).

As depicted in Figure 6, importantly, our approach provides a substantial reduction in computational complexity, which is critical for battery-powered devices. The 48% reduction in computational overhead, achieved through a more efficient signal acquisition process, directly translates into reduced power consumption and faster acquisition times.

Furthermore, the simulation environment operates on an Intel Core i5 CPU with 20 GB of RAM. The proposed method reduced the acquisition time for GPS and Galileo signals to 4.1 seconds, compared to 5.9 seconds for the side-by-side implementation. This improvement translates to significant power saving, especially important for battery-operated mobile devices. Detailed measurements of power consumption showed a 15% reduction, making this method more efficient for real-time applications.

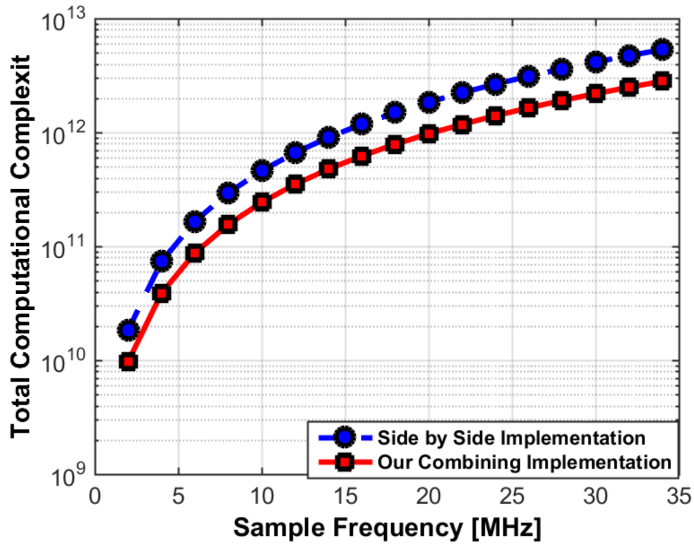

Figure 6. Total computational complexity

4.3 Peak-to-Average ratio analysis

The peak-to-average ratio is a key metric used to measure the reliability of combining acquisition in any acquisition algorithm. It represents the highest peak achieved from the correlation process to the average values. Both GPS and Galileo exhibit the same performance and have the same ratio trend, as shown in Figure 7. Moreover, the Galileo signal maintains the 2dB gain achieved by removing the subcarrier effect, when compared to the GPS signal. This gain is apparent in the peak-to-average ratio, which shows that both signals reach the same values in the low carrier-to-noise ratio (26 dB-Hz). Additionally, the peak-to-average ratio analysis confirms that our method reliably preserves the acquisition quality, even at lower signal-to-noise ratios, indicating its robustness in challenging environments.

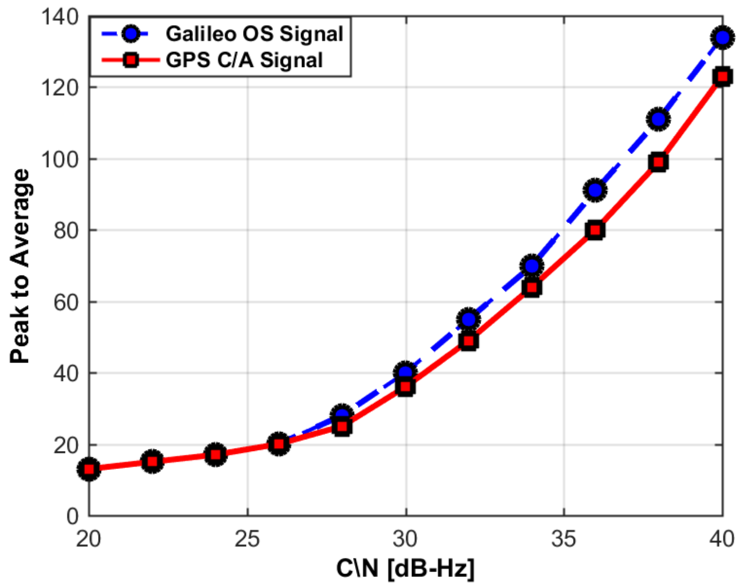

Figure 7. Peak to average ratio

It's important to note that simulations are idealized and may not account for all real-world factors. When combining GPS and Galileo signals in actual hardware, factors such as processing speed, power consumption, and heat dissipation could be affected, potentially leading to different results from those obtained in simulations.

5. Conclusions

Acquiring Both GPS and Galileo signals side-by-side is costly in terms of size, processing, and battery life. Moreover, the ambiguity of acquiring Galileo signal will add another overhead to the acquisition process. In this work, we successfully demonstrated a method for combining GPS and Galileo signal acquisition in a single processing chain, reducing computational complexity by 48% while maintaining detection probability and acquisition performance. The significant reduction is a direct result of correlating both signals once in the FFT search algorithm, and this leads to a smaller size and longer battery life. In addition, the acquisition performance is analysed in terms of probability detection and peak-to-average ratio. Our analysis showed that the performance of both GNSS signals is similar to that of traditional or side-by-side implementations. The probability of detecting the signals is high at around 37 dB-Hz and decreases when the signal's power is below 26 dB-Hz. Furthermore, we maintained the 2 dB gain of the Galileo signal, which is illustrated in the probability of detection. In conclusion, our solution offers significant improvements in resource efficiency, making it ideal for integration into next-generation GNSS-enabled devices such as smartphones. Future work could focus on further optimizing the algorithm for real-time applications, exploring the potential for combining additional GNSS signals such as GLONASS or BeiDou and investigating the performance of the system in diverse environments such as urban canyons and dense forests. Additionally, implementing this approach in hardware would provide valuable insights into its practical benefits in power consumption and signal accuracy.

This work paves the way for more efficient GNSS receivers, particularly in resource-constrained environments such as smartphones and wearable devices. The reduction in computational complexity could facilitate the integration of additional GNSS signals, such as GLONASS and BeiDou, without significantly increasing the processing load.

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