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A Novel Fast Acquisition Method for L2C Code for GPS Based Radio Occulted Systems: A FPGA Based Implementation

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Abstract

L2C (L2 band carrier) is the second Global Positioning System (GPS) civilian signal to become available over the full constellation. Because of the unusually-long ranging codes used in L2C signal, the search space and the computational complexity for signal acquisition become huge. Software-based GPS (SGR) Receiver helps us processing the GPS signal at the lowest level of GPS raw signal data from the antenna. A software-based GPS receiver consists of a front-end device that converts the radio frequency signal from the antenna to an intermediate frequency in digital format. The signal thus converted is processed by high level programming language to compute position and velocity. The radio occultation (RO) technique, which makes use of radio signals transmitted by the global positioning system (GPS) satellites, has emerged as a powerful and relatively inexpensive approach for sounding the global atmosphere with high precision, accuracy, and vertical resolution in all weather conditions over both land and ocean. Basic measurements for the GPS Radio Occultation are excess carrier phase and carrier Doppler from the GPS satellites because of refraction. To measure these carrier phases and Doppler one has to acquire the signals, first. The time window of occulted signals will be very narrow. So one has to acquire the signal as soon as possible, otherwise we will miss the occultation. Conventional acquisition algorithms usually take 8 to 32 seconds for the acquisition of occulted signals, depending upon the received signal strength and Doppler. This paper aims at reducing the acquisition time in the range of 1 second to few milliseconds. GPS signals are transmitted at L1 as well as L2C frequencies. The paper will be aiming at acquisition of L2C signals.

Keywords: GPS, L2C, Radio Occultation, Software Defined Radio, GNSS, and Fast Acquisition.

Introduction

The discovery of navigation seems to have occurred early in human history. According to Chinese storytelling, the compass was discovered and used in wars during foggy weather before recorded history. There have been many different navigation techniques to support ocean and air transportation. Satellite-based navigation started in the early 1970s. Three satellite systems were explored before the GPS programs: the U.S. Navy Navigation Satellite System (also referred to as the Transit), the U.S. Navy's Timation (TIMe navigATION), and U.S. Air Force project 621B. The Transit project used a continuous wave (cw) signal. The closest approach of the satellite can be found by measuring the maximum rate of Doppler shift. The Timation program used an atomic clock that improves the prediction of satellite orbits and reduces the ground control update rate. The Air Force 621B project used the pseudorandom noise (PRN) signal to modulate the carrier frequency.

One common way to start an acquisition program is to search for satellites that are visible to the receiver. If the rough location (say Dayton, Ohio, U.S.A.) and the approximate time of day are known, information is available on which satellites are available, such as on some Internet locations, or can be computed from a recently recorded almanac broadcast. If one uses this method for acquisition, only a few satellites (a maximum of 11 satellites if the user is on the earth's surface) needs to be searched. However, in case the wrong location or time is provided, the time to locate the satellite increases as the acquisition process may initially search for the wrong satellites.

The other method to search for the satellites is to perform acquisition on all the satellites in space; there are 24 of them. This method assumes that one knows which satellites are in space. If one does not even know which satellites are in space and there could be 32 possible satellites, the acquisition must be

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performed on all the satellites. This approach could be time consuming; a fast acquisition process is always preferred.

The conventional approach to perform signal acquisition is through hardware in the time domain. The acquisition is performed on the input data in a continuous manner. Once the signal is found, the information is immediately passed to the tracking hardware. In some receivers the acquisition can be performed on many satellites in parallel.

When a software receiver is used, the acquisition is usually performed on a block of data. When the desired signal is found, the information is passed on to the tracking program. If the receiver is working in real time, the tracking program will work on data currently collected by the receiver. Therefore, there is a time elapsed between the data used for acquisition and the data being tracked. If the acquisition is slow, the time elapsed is long and the information passed to the tracking program obtained from old data might be out-of-date. In other words, the receiver may not be able to track the signal. If the software receiver does not operate in real time, the acquisition time is not critical because the tracking program can process stored data. It is desirable to build a real-time receiver; thus, the speed of the acquisition is very important.

A GPS L2C receiver must perform an exhaustive search to acquire the signal, due to the unusually long ranging codes used in L2C, consuming substantial resources at the very first stage of digital processing. A GPS based radio occultation receiver, on-board a LEO spacecraft provides a mechanism for surrounding atmosphere. The relative motion of the occulting GPS transmitter and LEO satellites lead to the slicing of the GPS signals through different vertical layers of the atmosphere over the course of an occultation event. The changes in carrier phase (Doppler shift) at GPS L1 and L2 frequencies have to be recorded, and the phase measurements have to be transmitted to the ground for further processing. These highly accurate measurements will be used to derive vertical profiles of the temperature, pressure, and humidity in the atmosphere, as well as profiles of electron content in the ionosphere.

The aim of GPS signal acquisition is to determine visible satellite, initial code phase and carrier Doppler frequency. It is 3-D search of satellite number, code phase and Doppler frequency domain. The traditional sequential search algorithm is directly to serial search existing satellite signal, carrier Doppler frequency and code phase in time domain [1]. This algorithm is simple and needs less resources, but computational complexity is large and acquisition time is long. In order to improve acquisition speed, we propose frequency domain L2C code parallel acquisition algorithm based on FFT which makes signal transformed from time domain to frequency domain using FFT; it realizes Doppler frequency and parallel search code phase [2]. This algorithm needs moderate hardware resources, but reduces computational complexity and acquisition time.

History of GPS

The launch of Sputnik in 1957 also marked the beginning of the era of satellite navigation. Initially, the U.S. Navy developed a satellite navigation system called Transit. In 1964 Transit became functional for U.S submarines and went commercial in 1967. However, the system could only be used to calculate the position of low velocity surface vehicles. To accommodate the need for high dynamic, high velocity vehicles such as aircrafts, GPS was eventually developed based on the concept of the Transit system.

Since the introduction of GPS, the system has integrated into people's lives. For civilian users, GPS is generally used as a navigation tool. Whereas, for military users, GPS plays a vital part in military operations that requires precise and definite location reading. Therefore, GPS usage is very wide and depends on the individual user's application. Civil receivers throughout the world are capable of using Standard Positioning Service (SPS) signal, while only authorized users can have Precise Positioning Service (PPS). GPS is the only system today that provides precise position information at anytime, anywhere, and in any weather conditions. Public transport nowadays uses GPS for navigation and receiving message from their control center.

The first GPS satellite was launched in 1978. The first ten satellites launched were developmental satellites, called Block I. From 1989 to 1997, 28 production satellites, called Block II, were launched. The last 19 satellites of this series of satellites were called Block IIA, which were the updated versions. The initial operational capability of GPS was established in December 1993. The primary system was completed with the launch of the 24th GPS satellite in 1994. In February 1994, the Federal Aviation Agency (FAA) declared GPS ready for aviation use [1]. The third-generation satellite, Block IIR, was first launched in 1997. These satellites are being used to replace the aging satellites currently in the GPS constellation.

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GPS system

The entire GPS system consists of three segments: the control segment, the space segment and the user segment [2]. The control segment consists of five GPS earth stations. The master control station is located at Falcon Air Force Base in Colorado Springs, CO. The main function of the earth stations is to monitor the performance of the GPS satellites. Each monitor station has two cesium clocks as reference for the GPS system time. Each of the five earth stations makes continuous pseudo range and delta range measurements to all satellites in view, every 1.5 seconds. These measurements are used to update the satellite's navigation messages.

The data collected from the satellites by the earth stations is transmitted to the master control station for processing. The master control station is responsible for monitoring GPS performance, generating and uploading the navigation data to the satellites to sustain performance standards, as well as promptly detecting and responding to satellite failure to minimize the impact.

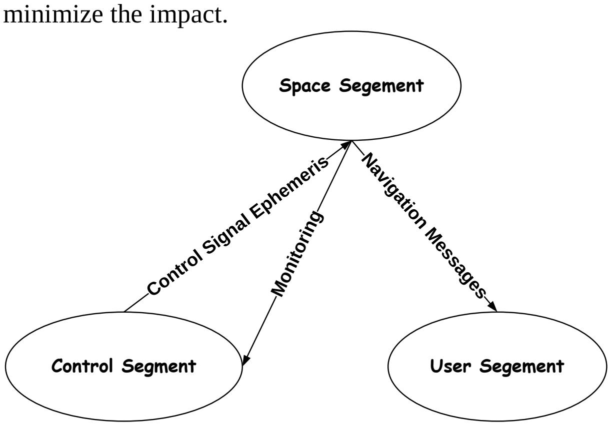

Figure 1: The Three Segments of GPS

Figure 1 is a graphical illustration of the three segments of the GPS system.

Basic GPS receiver

The basic GPS receiver is shown in Figure 1. The signals transmitted from the GPS satellites are received from the antenna. Through the radio frequency (RF) chain the input signal is amplified to proper amplitude and the frequency is converted to a desired output frequency. An analog-to-digital converter (ADC) is used to digitize the output signal. The antenna, RF chain, and ADC are the hardware used in the receiver.

After the signal is digitized, software is used to process it. Acquisition means to find the signal of a certain satellite. The tracking program is used to find the phase transition of the navigation data. In a conventional receiver, the acquisition and tracking are performed by hardware. From the navigation data phase transition the sub frames and navigation data can be obtained. Ephemeris data and pseudo ranges can be obtained from the navigation data. The ephemeris data are used to obtain the satellite positions. Finally, the user position can be calculated for the satellite positions and the pseudo ranges.

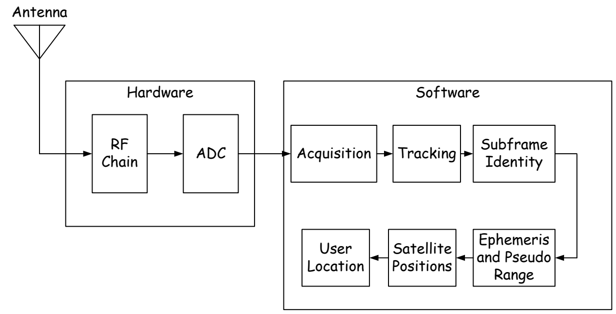

Figure 2: Basic GPS receiver

Basic GPS Concept

The position of a certain point in space can be found from distance measured from this point to some known positions in space. In Figure 3, the user position is on the x-axis; this is a one dimensional case. If the satellite position.

S_1 and the distance to the satellite x are both known, the user's position can be at two places, either to the left or right of S_1. In order to determine the user position, the distance to another satellite with known position must be measured. In this Figure, the positions of S_2 and x_2 uniquely determine the user position U.

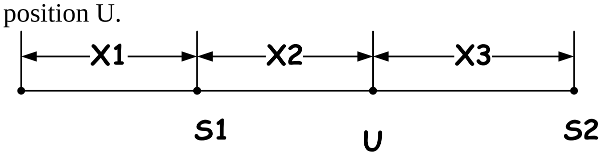

Figure 3. One dimension user position.

Figure 4 shows a two-dimensional case. In order to determine the user's position, three satellites and three distances are required. The trace of a point with constant distance to a fixed point is a circle in the two-dimensional case. Two satellites and two distances give two possible solutions because two circles intersect at two points. A third circle is needed to uniquely determine the user position. For similar reasons one might decide that in a three-dimensional case four satellites and four distances are needed. The equal-distance trace to a fixed point is a sphere in a three-dimensional case. Two spheres intersect to make a circle. This circle intersects another sphere to

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produce two points. In order to determine which point is the user position, one more satellite is needed.

In GPS the position of the satellite is known from the ephemeris data transmitted by the satellite. One can measure the distance from the receiver to the satellite. Therefore, the position of the receiver can be determined.

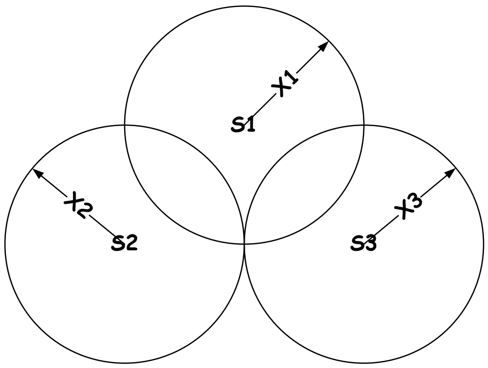

Figure 4. Two dimension user position

Method of finding the user position:

In this section the basic equations for determining the user position will be presented. Assume that the distance measured is accurate and under this condition three satellites are sufficient. In Figure 3.3, there are three known points at locations r_1 or (x_1, y_1, z_1), r_2 or (x_2, y_2, z_2), and r_3 or (x_3, y_3, z_3), and an unknown point at r_u or (x_u, y_u, z_u). If the distances between the three known points to the unknown point can be measured as r1, r2, and r3, these distances can be written as

$$\mathbf{r_1 = ((x_1-x_u)^2 + (y_1-y_u)^2 + (z_1-z_u)^2)^{0.5}}$$
$$\mathbf{r_2 = ((x_2-x_u)^2 + (y_2-y_u)^2 + (z_2-z_u)^2)^{0.5}}$$
$$\mathbf{r_3 = ((x_3-x_u)^2 + (y_3-y_u)^2 + (z_3-z_u)^2)^{0.5}}$$

Because there are three unknowns and three equations, the values of x_u, y_u, and z_u can be determined from these equations. Theoretically, there should be two sets of solutions as they are second-order equations. Since these equations are nonlinear, they are difficult to solve directly. However, they can be solved relatively easily with linearization and an iterative approach. In GNSS operation, the positions of the satellites are given. This information can be obtained from the data transmitted from the satellites. The distances from the user (the unknown position) to the satellites must be measured simultaneously at a certain time instance. Each satellite transmits a signal with a time reference associated with it. By measuring the time of the signal traveling from the satellite to the user the distance between the user and the satellite can be found.

GPS L2C Code Structure

The L2C code structure is shown in Figure 2. The L2c code is composed of 2 ranging codes L2 CM (moderate) and L2 CL (long).

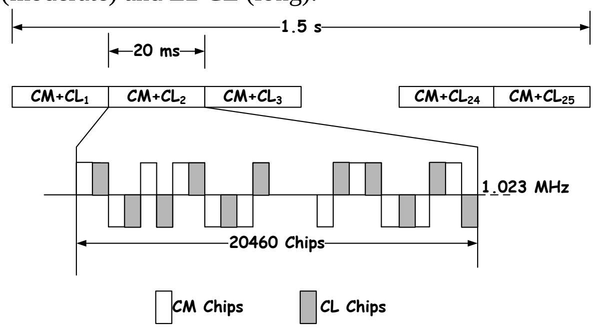

Figure 5: L2C Code Structure

The CM code is modulo-2 added to the data (i.e., it modulates the data) and the resultant sequence of chips is time multiplexed with the CL code on a chip-by-chip basis. The individual CM and CL codes are clocked at 511.5 kHz, whereas the composite L2C code has a frequency of 1.023 MHz code boundaries of CM and CL are aligned, and each CL period contains exactly 75 CM periods. This time multiplexed L2C sequence modulates the L2 (1227.6 MHz) carrier.

Signal Acquisition

Signal acquisition is the first stage of digital processing in a GPS receiver. Hence a signal must be "acquired" before it can be tracked and used. A desired satellite signal present at the IF stage of receiver is usually modeled as:

$$\boldsymbol{r(t) = \sqrt{2P_K d_K(t-\tau_k) c_k(t-\tau_k) \cos\left[2\pi\left(f_{IF}+f_{D,K}\right)t+\varphi_k\right]} + n(t)} \qquad (\mathbf{1})$$

where Pk is the received signal power (subscript kk identifies received satellite signals whereas local replica signals will be identified by subscript ii), $d_k(t)= \pm 1$denotes navigation data symbols, $c_k(t)$ is the spreading code while τ_k represents the phase or delay of the received code and f_{IF} is the IF carrier frequency. Due to continuous satellite motion and possible receiver dynamics, the signal frequency suffers from the Doppler Effect, incorporated as f_D,. Also, φ_k denotes the carrier phase and $n(t)$ is the thermal noise in the receiver, modeled as additive white Gaussian noise (AWGN) with two-sided power spectral density of $N_0/2$.

Signal acquisition is the process of finding the correct code delay and Doppler frequency (often simply denoted "Doppler") to match the desired

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signal in order to establish synchronization between the received and local signals. Hence an uncertainty range in both Doppler and delay dimensions needs to be searched. Each Doppler/delay trial combination is referred to as a "cell" and hence a bi-dimensional grid of cells constitutes the search space. A "bin" on the other hand refers to the individual Doppler or delay window.

GPS Radio Occultation

The Radio occultation concept is depicted in the Figure 6. This is a relatively new technique (first applied in 1995) for performing atmospheric measurements. It is used as a weather forecasting tool, and could also be harnessed in monitoring climate change.

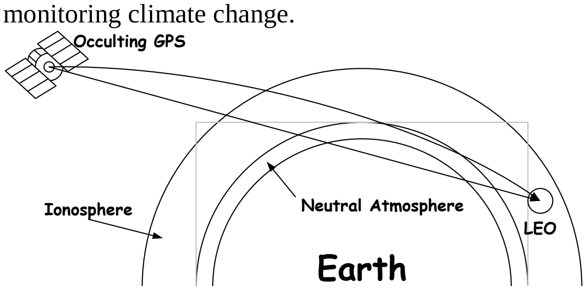

Figure 6: Radio Occultation Concept

This technique involves a low-Earth orbit satellite receiving a signal from a GPS satellite. The signal has to pass through the atmosphere and gets refracted along the way. The magnitude of the refraction depends on the temperature and water vapor concentration in the atmosphere. GPS Radio occultation amounts to an almost instantaneous depiction of the atmospheric state. The relative position between the GPS satellite and the low-Earth orbit satellite changes over time, allowing for a vertical scanning of successive layers of the atmosphere. GPSRO observations can also be conducted from aircraft or on high mountaintops.

GPS Existing Acquisition Methods:

Signal acquisition is the process of finding the signal of certain satellite. The goal of acquisition is to find the visible satellites, the L2C code delay and Doppler shift. The acquisition process is a 2-Dimensional search for Code phase and Doppler. Generally there are three methods are available for GPS Signal acquisition.

- Serial search in code phase and serial search in Doppler.
- Parallel search in code phase and serial search in Doppler
- Serial search in code phase and parallel search in Doppler.

For L2C signal the search space for code phase is 10230 chips and Doppler is around ±2 KHz preferably 20ms pre-detection integration time for weak signal acquisition. The Doppler range is reduced to 2 KHz from 50 KHz using almanac mode of acquisition. As per calculations, the first method will take around 136 minutes for acquisition. But by replicating 256 modules using massive correlators, one can reduce the acquisition time to 32 seconds (with reasonable resource utilization of 50%). The second method takes 0.8 seconds, but it requires 10230 point FFT and IFFT to be realized inside the FPGA which may take 80% of the resources. The third method will take 204.6 seconds and it will take 9% resource utilization.

Here the authors propose a novel method where the "Serial search in code phase domain and parallel search in Doppler domain", method is modified for parallel 256 search of code phase, so that the acquisition time comes down to 0.8 seconds with remarkable resource utilization of 36% , which is least among the methods for the same acquisition time.

Algorithm and Implementation

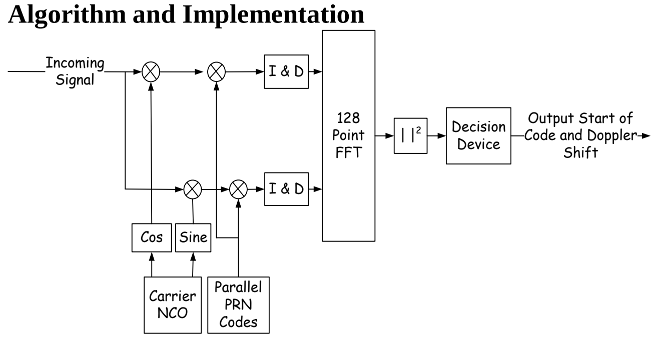

Figure 7. Parallel Search using FFT method

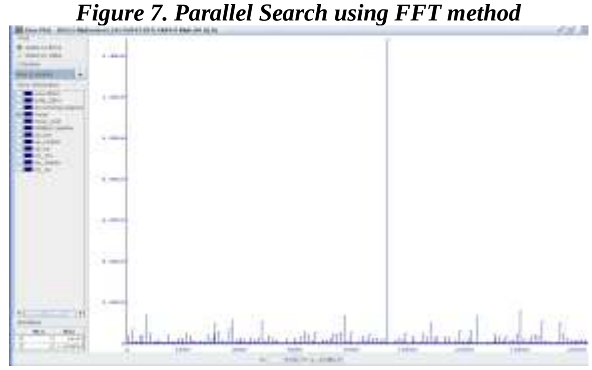

Figure 8. Chip Scope window showing acquired signal with high peak

The block diagram of the novel approach in mentioned in the following Figure 7. The "serial search in code phase and parallel search in Doppler

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domain" method is modified so that the 128 parallel code phase search is implemented in an efficient way. In order to track and decode the information in the GROS signal, an acquisition method must be used to detect the presence of the signal. Once the signal is detected, the necessary parameters must be obtained and passed to a tracking program. From the tracking program information such as the navigation data can be obtained.

Acquisition module is implemented on a single FPGA. The goal of acquisition is to find out the Doppler frequency and code start for each of the channels and pass this information to the tracking modules for further extraction of the navigation data.

The "serial search in code phase and parallel search in Doppler domain" method is modified so that the 128 parallel code phase search is implemented in an efficient way. The incoming signal is correlated with the carrier signal and is again correlated with the parallel PRN codes and then it is integrated and dumped or in simple accumulated and is fed as inputs to 128 point FFT. Norm of output of FFT is taken and is fed as input to a decision device where the norm of output of FFT is compared with the previously set Threshold and if the norm of output of FFT crosses the threshold then the signal is acquired and corresponding Doppler shift and the code phase is to be found.

Results

Xilinx ISE 12.2 is the software we used along with the Virtex-5 board, for VHDL development, synthesis and programming of the target board.

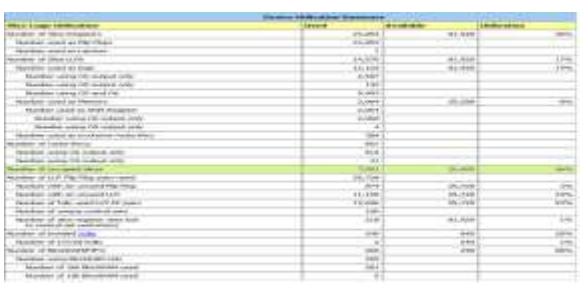

Figure 9. Device utilization generated by Xilinx 12.2.

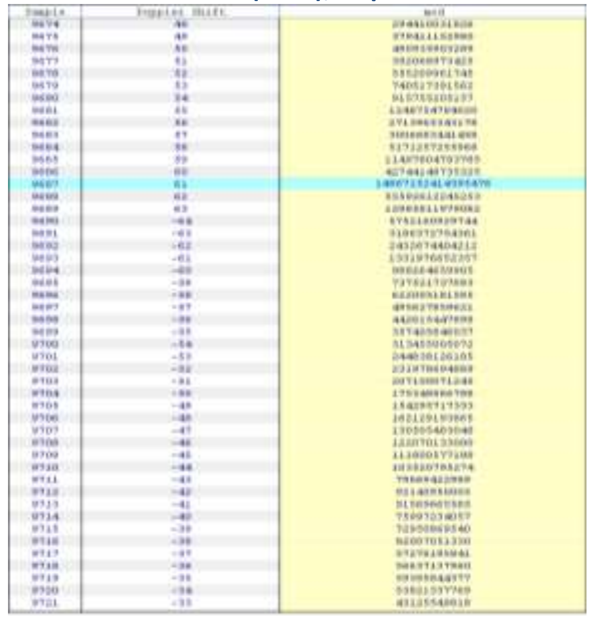

Figure 10. Chip Scope window showing acquired signal value in listing.

Conclusion

The algorithm was implemented in Xilinx Virtex-5 FX130T FPGA using ML510 development board and the signal is acquired at 1.6 sec with Doppler shift of 63 (what is the unit? Hz, or kHz, or MHz, or GHz) and with 36 % of FPGA resource utilization; this FPGA is the commercial equivalent of the space qualified FPGA. The efficiency of the algorithm has ensured the best possible resource utilization without compromising on the performance.

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