GPS Signal Jamming and Anti-jamming Strategy - A Theoretical Analysis

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GPS Signal Jamming and Anti-jamming Strategy - A Theoretical Analysis

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Abstract— **The weak strength of GPS signal makes it very vulnerable to jamming. This calls for appropriate modeling and implementation of GPS signal source and jammers that are used to jam GPS signal. The present work describes a simple and efficient way to simulate GPS signal using MATLAB® with focus on investigation of GPS signal jamming and devising an anti-jamming technique to counter different jamming scenarios besides Additive white Gaussian noise (AWGN). The jamming types influencing GPS Signal have been identified and suitable jamming scenarios have been modeled using MATLAB®. The effect of each jamming signal type on GPS signal has been quantified by estimation of Bit error rate (BER) for different jamming to signal (J/S) ratio. A background study of different anti-jamming techniques for GPS signal has been carried out and Turbo coding has been implemented as a suitable measure to counter the effect of GPS signal jamming.**

***Keywords*—Global Positioning System (GPS), Bit Error Rate (BER), Jamming to signal (J/S) ratio, Modulation, Additive white Gaussian noise (AWGN), Demodulation, Anti-Jamming, Turbo coding.**

I. INTRODUCTION

In present world, GPS technology has become an integral part of daily life. For example, it is used by natural resource managers to locate and map various features of interest along with important information about those features [1]. It is also an essential part of all navigation and tracking systems [2]. The utility of GPS is indispensable for defence organizations which use it for aircraft, ship and troops navigation [3-7]. It is also largely used by civilians through mobile devices such as smart phones, automobiles, etc. The accuracy of navigation, surveying and tracking systems depends on accuracy of GPS signal, but its distortion due to jamming is a serious problem. There are several reasons behind jamming of GPS signal which need to be investigated. Although there is much literature available on GPS technology and applications, but limited research work has been reported on analysing the detrimental effects of jamming on GPS signal. The effect of Pulse Jamming was analyzed by Ponoi et al. [8]. The effect of colored noise with small intensity on Mean time to Lose Lock of GPS receiver was done for optimum jammer design by Bobrovsky et al. [9]. GPS receiver performance and GPS signal structure was analyzed by Bangh'iDk et al. [10]. Behavior of some commercial GPS receivers to jamming attack was studied by Hunkeler et al. [11]. Hence, an extensive study of effect of different jamming scenarios on GPS signal is required to understand their effect. But, GPS signal generation requires sophisticated and costly resources, which is one of the reasons behind limited academic investigation on GPS signal jamming. A number of GPS signal simulators are currently available in the commercial market like Lab Sat by Racelogic [12], Accord GPS Correlator Simulator [13], GSG 6 Series multi frequency GNSS Simulator [14], Welnavigate GS 600 [15], CAST 1000 Satellite Signal Simulator [16], Spirent Multi-Channel GPS/SBAS Simulation System STR4500 [17], NI GPS Simulation Toolkit for Lab VIEW [18], GNSS Signal Architect Simulator Software [19]. But, their use has been limited to corporate companies developing GPS receiver because of their high cost. In this perspective, our work focuses on GPS signal simulation and quantification of loss of GPS signal accuracy due to jamming in terms of Bit Error rate (BER), as shown in Fig. 1. Besides this, a procedure based on Turbo coding has been devised to counter GPS signal distortion by jamming. The paper is divided into six sections. Section 2, describes the GPS Signal Structure and MATLAB® Model for simulation of GPS Signal. Section 3 and 4 discuss different GPS Signal jamming techniques and their implementation in MATLAB®. MATLAB® Simulation results depicting the effect of jamming on GPS signal is presented in Section 5. Section 6 discusses different methods for countering GPS signal jamming. Section 7 describes implementation of turbo codes and its effectiveness in two jamming scenarios. The last section summarizes the conclusions and further scope of work.

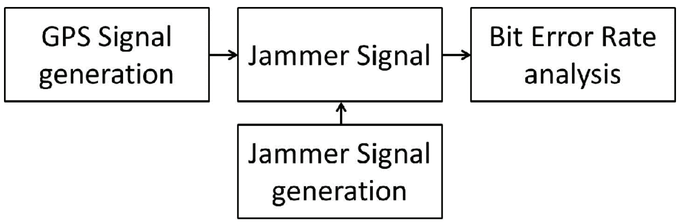

Fig.1. Block diagram of proposed GPS signal simulation, jamming scheme and jammed signal analysis

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II. GPS Signal Structure And GPS Signal Simulation

GPS consists of 24 satellites orbiting at an altitude of 20,183 km at known positions. The signals transmitted by the GPS satellites are direct-sequence spread-spectrum (DSSS). Position and the network data of each satellite is transmitted using Navigation message at a rate of 50 bits/s. The modulo-2 addition of navigation message is done with ranging codes. There are two types of ranging codes used in GPS: Course/Acquisition (C/A code) and Precision (P Code). Both ranging codes are pseudorandom binary sequence; C/A code is a 1,023 bit which is transmitted at 1.023 megabits per second (Megabits/s) and repeats every millisecond. P code is 6.1871×10^{12} bits long which is transmitted at 10.23 Megabits/s and repeats once a week. The modulo-2 addition of ranging codes and navigation message is done to get Pseudo-random number (PRN) sequence which is modulated onto a carrier frequency for transmission. There are two carrier frequencies: 1575.42 MHz (10.23 MHz × 154) called L1; and 1227.60 MHz (10.23 MHz × 120), called L2. The PRN sequence obtained on modulo-2 addition with C/A code is transmitted on the L1 frequency as a 1.023 MHz signal using a bi-phase shift keying (BPSK) modulation technique. The PRN sequence obtained on modulo-2 addition with P code is transmitted on both the L1 and L2 frequencies as a 10.23 MHz signal using the BPSK modulation [20], as shown in Fig.2.

GPS signal is simulated using MATLAB® Simulink. The navigation data of satellite is simulated at the rate of 50 bits per second. The actual 1500 bits of navigation data is reduced to 50 bits due to limitations of the processor (4 GB RAM, 2.2 GHz Intel Core 2 Duo CPU) speed and memory, used for simulation. This 50 bit/s navigation message of GPS is modulated on top of the C/A ranging code. C/A code is modulated on L1 signal. In our simulation only L1 signal is modeled because it is more susceptible to jamming and has widespread civilian use. The simulation is designed to generate GPS L1 signal having carrier frequency 1575.42 MHz. This simulation simulates 1 second of the actual GPS signal. The MATLAB routine consist of two parts, the first part is the spreading block in which 50 bits data is spreaded across the 1023 chips of C/A code. The result is a 1.023 Mega bits of data. An exclusive OR operation of spreaded GPS bits with the selected satellite C/A code has been done followed by BPSK modulation. A sinusoidal wave at the carrier frequency of 1575.42 MHz is sampled and the spreaded GPS signal bits modulate the sinusoidal wave by adding phase information according to BPSK modulation scheme (Table I), as shown in Fig. 3.

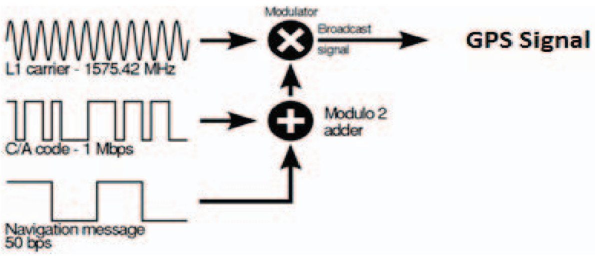

Fig.2. GPS signal simulation [21]

TABLE I. BPSK Modulation Scheme

Binary Bit	Phase (degrees)	Multiplication Factor
1	180	-1
0	0	1

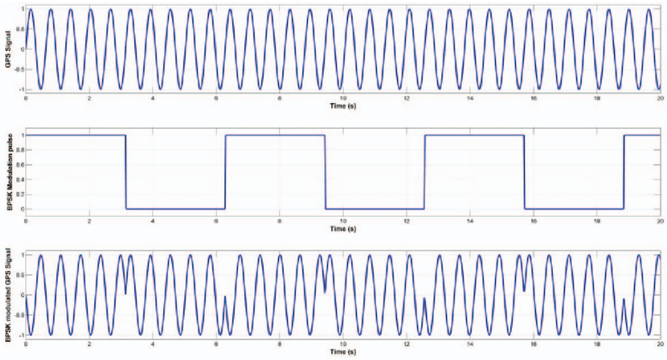

Fig.3. BPSK modulation of GPS signal carrier wave

III. GPS Signal Jamming

Jamming is intentional or unintentional radiation, re-radiation, or reflection of electromagnetic energy which impairs use of electronic devices, equipment, or communication systems [22]. This signal need not be very sophisticated or very powerful because the signals from the satellites are extremely weak. Hence the jamming signal can easily overcome the GPS receiver and suppress the legitimate signal which may cause severe damage.

It has been predicted that GPS signal jamming can cause a major accident in shipping industry within the next decade [23]. There are many different waveforms that can be used for jamming communications systems, though the most appropriate choice depends on the target system and level of jamming intended. For a GPS system, common types of jammers include Continuous Wave (CW), Pulse CW, Swept CW, Spot Noise, and Barrage Noise jammers. A CW jammer is a sinusoidal signal at a single frequency. A pulse CW jammer is a CW jammer that is turned on and off at a rate called the Pulse Repetition Frequency (PRF), where the percentage of on time to off time is called the duty cycle. The spot noise jammer is a noise jammer that has a narrow frequency band as compared to the GPS signal bandwidth, whereas the barrage noise jammer is a noise jammer that operates over the entire GPS signal bandwidth.

IV. Implementation Of Jamming Blocks

The GPS L1 signal is simulated as described in Sec.2, followed by addition of jamming signal and Additive White Gaussian Noise to it. The effect of four types of jamming signals namely: Continuous Wave, Pulse Continuous Wave, Spot Noise and Barrage Noise has been analysed and discussed in following section. All these jammers have been simulated using separate MATLAB® codes.

A. *CW Jammer:* Continuous Wave Jammer is single frequency signal with frequency same as carrier frequency. Its mathematical model is just a constant. Sinusoidal signal at ω_c, the frequency of GPS signal carrier frequency is generated by this jammer block with different J/S Ratio , in accordance with (1).

$$\varphi_{CWJ}(t) = A\cos(2\pi(\omega_c)t) \qquad (1)$$

where, A is varied in accordance with the desired J/S ratio.

B. *Pulse CW Jammer:* Pulse CW Jamming block generates pulse jamming signal which is pulse modulated by CW signal of ω_c (the frequency of GPS L1 signal) and for PRF 1.023 KHz to 102.3 KHz and for Duty cycle of 30%, 50% and 70% respectively. The PRF value of jamming signal is selected so that it matches PRF of modem radar [8]. General mathematical model of Pulse CW Jammer is defined by (2).

$$\varphi_{PCWJ}(t) = 1 \;\; for\; 0 \le t \le nT \qquad (2)$$

where, T is the period of the wave which is reciprocal of PRF (Pulse repetition frequency) and n(<1) varies according to the duty cycle.

C. *Spot Noise Jammer:* Spot Noise Jammer is spread on a small portion of the GPS signal bandwidth around the centre frequency (ω_c). It is a noise jammer that has a narrow frequency band as compared to the GPS signal bandwidth. It focuses power in 0.05 MHz bandwidth, that is, 5 percent of frequency range (ω_{cf}) around GPS carrier frequency. The mathematical model of Spot Noise Jammer is obtained using (3).

$$\varphi_{SNJ}(t) = (2A)\cos\big(2\pi\big(\omega_{cf}\big)t\big) \qquad (3)$$

where, A is varied in accordance with the desired J/S ratio.

D. *Barrage Noise Jammer:* The barrage noise jammer is also a noise jammer that operates over the entire 0.1 MHz GPS signal bandwidth that is, 10 percent frequency ($\omega_{c1}, \omega_{c2}, \omega_{c3}$) in vicinity of GPS carrier frequency (ω_c). Barrage Noise Jammer is spread across the bandwidth of the GPS Signal (i.e. 24 MHz), the baseband signal model is obtained as using (4).

$$\begin{aligned}\varphi_{BNJ}(t) = {} & (2A)\cos(2\pi(\omega_{c1})t) \\ & + (2A)\cos(2\pi(\omega_{c2})t) \\ & + (2A)\cos(2\pi(\omega_{c3})t)\end{aligned} \qquad (4)$$

where, A is varied in accordance with the desired J/S ratio.

V. RESULTS

The Bit Error Rate for different jammers as a function of J/S ratios (JSR) has been calculated. The simulated GPS signal is subjected to jamming signals followed by its demodulation to get the GPS signal bits. The Bit Error Rate (BER), as defined by (5) has been used to quantify loss of information for each jamming scenario.

$$BER = \frac{N_{error}}{N_{bits}} \qquad (5)$$

N_{error} is number of errors and N_{bits} is number of bits transmitted

A. *CW Jammer:* The simulation is done for JSR from 0 to 13 dB to estimate BER, as shown in Fig. 4. This clearly shows that the BER increases continuously with increase in JSR and most steep increase is observed in JSR interval of 1-4dB. It goes up to 15% at JSR of 13 dB and does not increase further with increase in JSR.

B. *Pulse CW Jammer:* The simulation is done for Pulse Repetition Frequency (PRF) varying from 1.023 KHz to 102.3 KHz and for Duty cycle of 30%, 50% and 70% respectively, as shown in Fig. 5. It can be observed that BER is almost constant for a particular duty cycle on varying PRF, which shows that BER is independent of PRF, but increases with increase in duty cycle.

C. *Spot Noise Jammer:* The simulation is done for JSR from 0 to 35.56 dB to estimate BER, as shown in Fig. 6. This clearly shows that the BER increases continuously with increase in JSR and increases most steeply in JSR interval of 5-25 dB. BER goes up to a maximum of 15% at JSR of 35.56 dB and saturates beyond it.

D. *Barrage Noise Jammer:* The simulation is done for J/S ratio from 0 to 40 dB to estimate BER, as shown in Fig.7. This clearly shows that the BER increases continuously with increase in JSR and most steep increase happens in JSR interval of 10-30 dB. But, BER does not increase further beyond JSR of 40 dB.

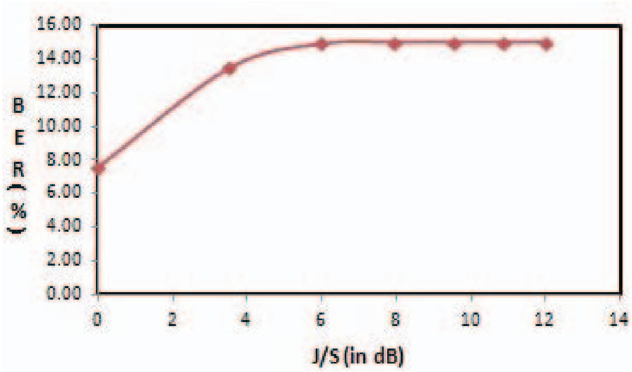

Fig.4. Bit Error Rate vs. J/S ratio for CW Noise Jammer

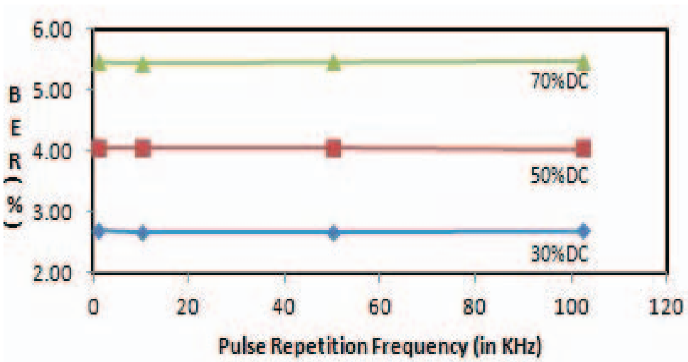

Fig.5. Bit Error Rate vs. PRF for Pulse CW Jammer

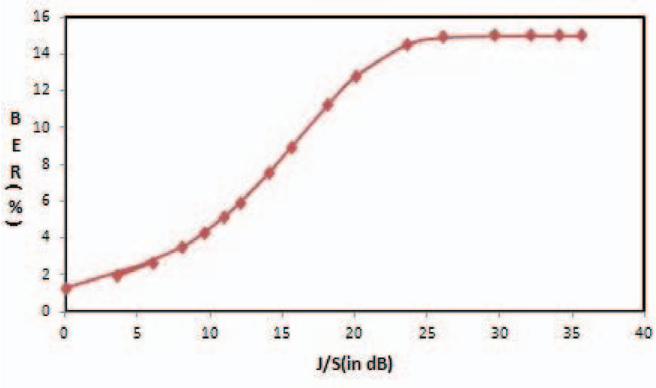

Fig.6. Bit Error Rate vs. J/S ratio for Spot Noise Jammer

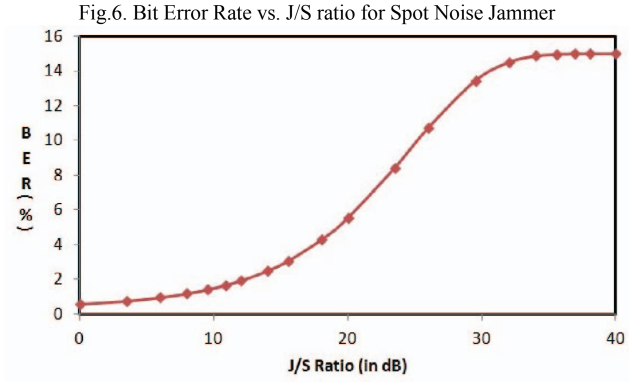

Fig.7. Bit Error Rate vs. J/S ratio for Barrage Noise Jammer

TABLE II. Comparison of Jamming signal type on BER

Jamming Signal Type	Bit Error Rate (%)
CW	15
Spot Noise	5
Barrage Noise	1.5

E. *Comparative analysis of different jamming scenarios*: A comparison of BER for JSR of 10 dB has been made, as shown in Table II. Evidently, CW jammer degrades the GPS signal accuracy the most for JSR of 10 dB.

VI. ANTI-JAMMING – AN OVERVIEW

Designers of military as well as commercial communication systems have developed numerous anti-jamming techniques through the years, to counter both unintentional and intentional interference. As these techniques become effective for interference removal and mitigation, jammers themselves have become smarter and more sophisticated, and generate signals, which are difficult to combat. GPS signals are direct-sequence (DS) spread spectrum signals and therefore provide a certain degree of protection against intentional or non-intentional jammers. The original satellite signal gets concentrated into a narrow bandwidth about the carrier frequency after de-spreading the received signal, whereas the lack of correlation of jamming signals with the pseudo-random code that encodes the satellite information results in spreading of jamming signal. The GPS signal tracking can be stable only if the jamming-to-signal ratio (JSR) is below the processing gain of the spreading code because a portion of the spread jamming signal still remains within the frequency band for the tracking loop with the satellite signal. Hence, the spreading gain might be insufficient to decode the useful data reliably [24] when the jammer power is much higher than the GPS signal. Thus, robust anti jamming techniques to protect the GPS signal accuracy at receiver end is an urgent requirement. There are several methods that have been proposed for interference suppression in DSSS communications [25-27]. But none of these methods guarantee to protect GPS Signal from distortion.

A. *Literature Review:*

There are a number of ways to counter the effects of jamming on GPS signal like techniques based on instantaneous frequency (IF) estimation, for non-stationary interference excisions [28], Smart Antennas [29], Filtering Techniques like Digital Excision Temporal Filter (DETF) [30]. The GPS Anti jamming techniques are broadly divided into following categories: (1) time domain filtering [31, 32], (2) frequency domain filtering [33, 34], (3) spatial filtering [35, 36], and (4) time-frequency filtering [37, 38]. The first two types of filtering are conventional. The third type employs adaptive nulling antenna, which is an array of antenna elements. Spatial filters with different amplification rates for signals from different directions of arrival (DOA) having adaptive nulling antenna can emphasize the desired GPS signal and reject jamming signals assuming that jamming signals and satellite signal have different DOA [35]. This technique is effective for both narrow-band and broad-band jamming signals. But, the adaptive antenna alone cannot counter jamming due to multi-path propagation of signals and the constraints associated with its size and power consumption [36]. The fourth type (time-frequency filtering) is based on the assumption that GPS signal and jamming signals have different time-frequency signatures. Time-varying notch filter [39] or subspace projection [40] can be used to counter jamming if instantaneous frequencies of jamming signal is estimated from the received signal. But the time-frequency filter blocks the frequencies occupied by jamming signals and thus subtract the power of satellite signal at those frequencies from the total power of the received signal. If substantial bandwidth of signal spectrum is occupied by jamming signals, the filtered GPS signal will have significant distortion. So, this method is more effective to counter narrow-band jamming [36]. The conventional code tracking loop employs delay-lock loop (DLL), but it has little protection against jamming and multipath. The robustness of DLL can be increased by including models (e.g., AR model) for jammer signal and multipath in the DLL. The resulting DLL can estimate the code delay using adaptive algorithms, e.g., Kalman filters and/or particle filters [39, 40]. Evidently, different techniques for anti-jamming have been proposed by researchers at different times but no technique can guarantee complete protection from jamming and subsequent distortion in GPS signal. The GPS signal is not only distorted by jamming signal but suffers interference from atmosphere while transmission. Hence, correction of received GPS signal is the one of the most viable methods to maintain accuracy of GPS based systems.

B. Proposed Solution:

Forward Error Control Coding has the capability to recover correct the GPS signal by detecting and correcting the errors. The traditional forward error correcting (FEC) code like block codes and convolution codes could not achieve the Shannon Limit, but Turbo codes developed in 1993 could get within 0·7 dB of the Shannon bound [41]. The Turbo codes are first practically implementable high performance codes, hence Turbo Coding has been selected for counter jamming in our work. The block diagram of possible methodology is shown in Fig. 8, where the original GPS data that carry the satellite information is encoded and both noise and jamming are present in the received GPS signal. The Turbo encoder at the transmitter encodes the signal and then the signal is modulated, passed over a noisy channel. The receiver demodulates the distorted GPS signal and then the Turbo Decoder decodes demodulated signal to retrieve the GPS signal.

VII. ANTI-JAMMING – IMPLEMENTATION OF TURBO CODING

A turbo encoder consisting of two ½ rate Recursive systematic convolutional encoders with a block interleaver before the second encoder has been implemented in MATLAB®. For decoding, APP (a posteriori probability) decoder with block interleaver and two de-interleavers have been used.

A. Barrage Noise Jammer: In this case, turbo encoding and decoding effectively reduces the BER for JSR up to 21 dB, beyond which it is not effective, as shown in Fig. 9.

B. Spot Noise Jammer: In this case, turbo encoding and decoding effectively reduces the BER for JSR up to 15 dB, beyond which it is not effective, as shown in Fig.10.

It is notable that turbo coding helps in eliminating BER for both barrage noise jammer and spot noise jammer up to JSR of 18 dB and 10 dB respectively, proving its appropriateness for GPS signal anit-jamming.

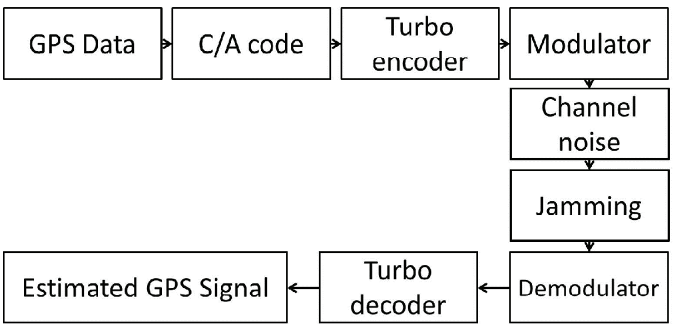

Fig.8. Block diagram of the proposed anti-jamming scheme using Turbo encoder and decoder

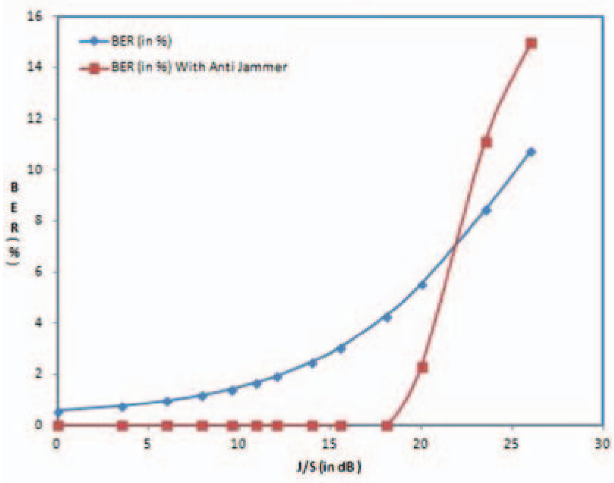

Fig.9. Graph showing BER of GPS in presence of Barrage Noise Jammer with and without anti jammer

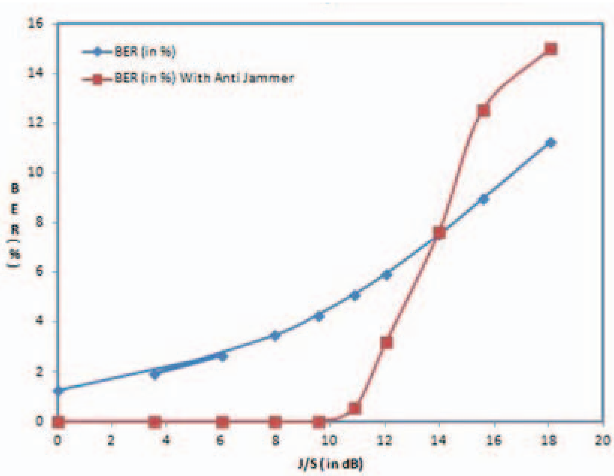

Fig.10. Graph showing BER of GPS in presence of Spot Noise Jammer with and without anti jammer

VIII. CONCLUSION

GPS signal simulation for Lab experimentation in real time is resource intensive. Through this work, a simple but effective method for simulation of GPS signal has been successfully devised. The low strength of GPS Signal makes it susceptible to jamming and subsequent distortion can hamper the accuracy of GPS based systems. The theoretical analysis of different jamming scenarios shows that BER greater than 10% has been found in the demodulated GPS signal. A quantitative comparison of different jamming scenarios shows that CW jammer causes most severe jamming of GPS signal followed by spot noise jammer and barrage jammer. In this perspective, different techniques to mitigate GPS signal jamming have been compared and Turbo coding has been been implemented, which is found to effectively reduce BER up to a certain J/S ratio, thus establishing its effectiveness. In near future, HDL implementation of Turbo codes followed by its hardware implementation would be carried out to realize a GPS signal anti-jamming system.

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