An Investigation to the Performance of Quantized DSSS in Mobile Wireless Communications under AWGN and Multipath Fading Channels

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Abstract

This paper presents an investigation to the performance of quantized direct-sequence spread spectrum system (DSSS) in mobile wireless communications systems. To obtain a real world value (RWV), the DSSS received signal is quantized to different levels of fixed-point values. These modes of quantization are evaluated by calculating BER under different channels environments (AWGN, Rayleigh, and Rician multipath fading). The effect of range of the represented values, the number precision and increasing in quantization noise on the performance of quantized DS in mobile wireless communications is also investigated. Based on simulation results, it is observed that quantized direct-sequence offers a trade-off between complexity and noise rejection compared to non-quantized DSSS and making a good representation of the digitized signals to implement the required DSSS in mobile wireless communications.

Keywords: mobile wireless communications, spread spectrum systems, direct-sequence, multipath fading, quantization, fixed-point conversion.

1. Introduction

Spread-spectrum techniques are used for RF communication to increase the information rate and confrontation to the interfering signals. A bandlimited signal is transmitted with bandwidth that is much greater than bandwidth of the signal. In another meaning, a signal of narrow bandwidth is expanded over a wide band using spread-spectrum methods. Therefore, the signal at a specific band is perceived as noise that enhance the flexibility to the interference from other signals [1]. One type of SS is direct-sequence spread spectrum system (DSSS) which contains a pseudo-noise generator (PN) codes that are termed chips. A sequence of chips is used to modulate the data bits to be sent. The chips have a much smaller time interval compared to data bit and each data bit is modulated with an amount of chips. As the rate of transmitted chip is greater than data bit rate, the bandlimited signal is spread over a large bandwidth. By shared the PN codes with receiver, DSSS signal can be interpreted or coded. The DSSS system has become the standard for wireless communications with the establishing of the IEEE 802.15.4 standard [2].

Most of mobile wireless communication channels places essential limits on the function of mobile communication structures. Multipath is a complaint where the transmitted signal is reflected by physical objects, producing multipaths between transmitter and desired receiver. These multipath signals could interfere with the wanted signal then prevent receiver to detect the transmitted signal. In addition, reduction in signal strength can be upraised when multipath signals are out of phase. This phenomenon of reduction in signal strength is called fading, and these multipath signals have both slow and fast fading [3].

The Rayleigh channel distribution is usually used to define the time-varying characteristic of the flat fading envelope of received signal, or the envelope of a single fading path component. It is assumed that channel induces amplitude in the model of Rayleigh, which fluctuates in time according to the Rayleigh channel distribution whose probability density function (PDF) is given by [4]:

$$f_{rayleigh}(x) = \frac{x}{\sigma^2}\exp\left(-\frac{x^2}{2\sigma^2}\right), \quad x \geq 0 \qquad (1)$$

where σ^2 is the variance of the in-phase and quadrature components and $\boldsymbol{x}$ is a random variable corresponding to the signal amplitude. It is assumed that all signals suffer nearly the same attenuation, but arrive with different phases.

In wireless communications, there is several path components between the transmitter antenna and receiver antenna. One is the dominant path or main line of sight and the others are diffused multipath components. In this situation, other components of faded signal are overlaid on the main component and the amplitude of resultant signal follows Rician distribution with the ratio between line of sight and the diffused components is known as the Rician factor (K) [5]. K (in dB) is equal to $10\log\left(\frac{A^2}{2\sigma^2}\right)$ where A is the amplitude of the signal of the dominant path. Doppler-shifted echoes with a Gaussian distribution cause Rician fading, but there is at all times a direct line from the transmitter antenna to the receiver antenna [6]. The Rician distribution has PDF is given by:

$$f_{rician}(x) = \frac{x}{\sigma^2} \exp\left(-\frac{(x^2+A^2)}{2\sigma^2}\right) I_0\left(\frac{Ax}{\sigma^2}\right) \qquad (2)$$

where $x \geq 0, A \geq 0$ and $I_0(\,)$ is the zero-order modified Bessel function of the first kind.

Usually the depth of fading is reduced by the main path, and in terms of bit error rate (BER), Rician fading model gives better BER performance compared with Rayleigh fading. The existing of line of sight component in fact depends on the cell size. Smaller cell gives higher probability of existing of line of sight path. When no dominant path exists, Rician PDF is considered a Rayleigh PDF. If the amplitude of the signal of the main path is greater than σ, the distribution can be considered as Gaussian distribution. Therefore, since Rician distribution covers also Gaussian and Rayleigh distribution, mathematically the Rician fading channel can be considered as general case [7].

In this paper, the performance of quantized DSSS in mobile communications is evaluated under different channels environments (AWGN, Rayleigh fading, and Rician multipath fading). To obtain a real-world value (RWV), the DS received signal is quantized to different levels of fixed-point values and comparing with non-quantized case (floating-point DS signal values).

2. Modeling of Non-quantized DSSS

DSSS spreads the baseband data by directly multiplying the data pulses with PN sequence. A single pulse of PN waveform is known as a chip. Figure.1 shows the model of DSSS with BPSK modulation.

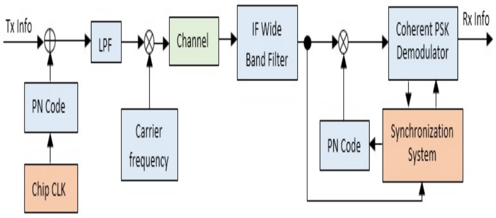


Figure.1 Model of transmitter and receiver of basic DSSS

The received spread spectrum signal for single subscriber can be represented as [8]:

$$r(t) = \sqrt{\frac{2E_s}{T_s}}\; m(t)\, p(t) \cos(2\pi f_c t + \theta) \qquad (3)$$

where E_s is energy of data symbol, T_s is the duration of data symbol, $m(t)$ is the data sequence, $p(t)$ is the PN spreading sequence, f_c is the carrier frequency, and θ is the carrier phase. An estimated amount of the interference rejection ability is given by processing gain defined as $PG = T_s/T_c$ where T_c is chip duration. The greater the processing gain of the system, the greater will be its ability to suppress in-band interference. The original PN code in the receiver part of Figure.1 is multiplied by the received signal then integrated over the time of data symbol. This process is called despreading. In multiple access systems, signals from other subscribers interfere with the desired signal at receiver antenna. In this situation, despreading makes an additional role of decorrelating the multiple access interference. The interfering signals have spreading codes that are orthogonal to the desired subscribers spreading code, and thus they are suppressed during despreading. One advantage of DSSS is the reduced receiver sensitivity to interference. This advantage is due to this fact that the despreading system acts as spreading system for any signal to which it is not matched. Figure.2 shows the Simulink model of DSSS that uses BPSK modulation for both data symbols and PN spreading code. The PN spreading code has 10 chips per bit that results $PG = 10\,dB$. AWGN is only included in this model, but no fading or interference exist in channel just to clarify DSSS characteristics.

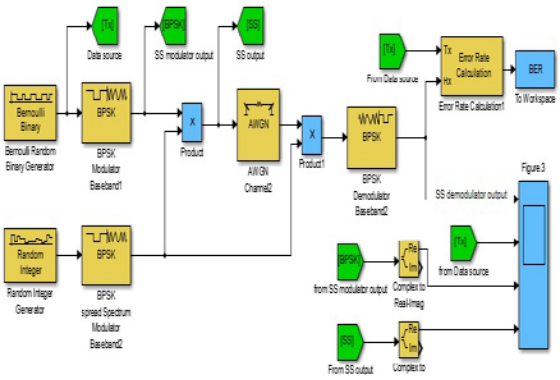


Figure.2 Simulink model of DSSS using BPSK modulation

The simulation of Figure.2 has the following parameters: simulation time=100 sec, sample time=1 sec, chip sample time=100 msec, and the range of $\frac{E_b}{N_o}$ from 0 to 8 dB. Figure.3 (a-d) shows the effect of PN spreading code on the modulated data with 10 chips per bit for 8 seconds period and for $\frac{E_b}{N_o} = 3\,dB$, while (e) shows the BER performance of DSSS. The theoretical BER for BPSK is given by [8]:

$$BER = \frac{1}{2}\, erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \qquad (4)$$

where $erfc(\,)$ is the complementary error function. The simulation gives BER=0.02097

(Figure.3e) for $\frac{E_b}{N_o} = 3\ dB$, while theoretical $BER = \frac{1}{2}\ erfc(10^{0.3}) = 0.0229$. Clearly, from this result it seems that the BER performance is not affected by spreading process.

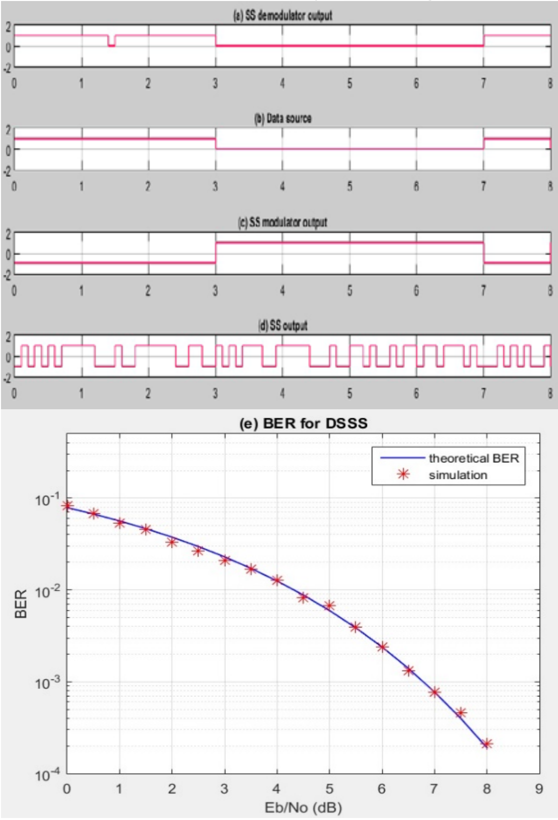


Figure.3 DS signals of 8 seconds Time scope and BER performance for 10 chips/bit DSSS

3. Modeling of Non-quantized DSSS with fading channels

In actual environment, the RF propagation effects are combined and leads to fading channels that generate multipath. Various signals will be received when there is many propagation paths and the resultant received signal level is just the summing of signals. These signals that incident to the receiver come from random angels. As a result, some of reflected signals are in-phase with the direct path and others are out-phase. Practically, fading is produced by different physical occurrence like Doppler shift, reflection, diffraction, and scattering. Based on the effect of multiple path, there are two types of fading [9]:

- Long-term fading: here the signal attenuation that determined by the physical context of the path causes the received signal power to be varied slowly.
- Short-term fading: here the fading results a fast variation in both signal phase and amplitude when the signal moves over a distance in the order of wavelength.

In this paper, only the short-term fading will be taken when simulate the quantized DSSS. In fact, many models describe the short-term fading. Out of these models, Rayleigh fading, and Rician fading.

- Rayleigh fading model: This model is mostly produced by multipath reception. It is considered as statistical model for effect of propagation environment on RF signal and it is most appropriate model when the transmitter and receiver do not have any line of sight between them.
- Rician fading model: Rician model is analogous to Rayleigh fading model, except that a strong component is present in Rician model.

AWGN model will also be taken into account throughout the simulation of quantized DSSS because it is normally simulates the background noise of channel.

The probability of error in the case of the BPSK under Rayleigh fading effect defined by [10]:

$$P_b = \frac{1}{2}\left[1 - \sqrt{\frac{\overline{E_b/N_o}}{1+\overline{E_b/N_o}}}\right] \qquad (5)$$

where $\overline{E_b/N_o}$ is the average SNR per bit. The PSD of the channel $S(f)$ characterizes the time varying of the channel.

$$S(f) = \frac{1}{\pi f_m \sqrt{1-(\frac{f}{f_m})^2}} \quad \ldots \ |f| \le f_m \qquad (6)$$

where f_m is the maximum Doppler frequency. In mobile communications, where an object travels at speed of v and carrier frequency is f_0, then $f_m = v f_0/c$ where c is the light speed.

A Rician model can be considered as a generalization of Rayleigh model where a strong component happens beside various reflected signals. If x_1 and x_2 are independent Gaussian random variables with variance σ^2 and mean μ, and if α is considered as distribution random variable for Rician model, then $\alpha^2 = {x_1}^2 + {x_2}^2$ is recognized to be non-central Chi squared with two degrees of freedom. The probability of error in the case of BPSK under Rician fading is defined by [10]:

$$P_b = Q(a,b) - \frac{1}{2}\left[1 + \sqrt{\frac{\overline{E_b/N_o}}{1+\overline{E_b/N_o}}}\right] e^{-(a^2+b^2)/2}\ I_0(ab) \qquad (7)$$

where $\overline{E_b/N_o}$ is the average value and equal to $E_b/N_o\ (2\mu^2 + 2\,\sigma^2)$, and

$$Q(a,b) = \int_b^{\infty} x e^{-(a^2+x^2)/2}\ I_0(ax)\ dx \qquad (8)$$

$$a = \sqrt{\frac{K\left[1+2\overline{E_b/N_o}-2\sqrt{\overline{E_b/N_o}(1+\overline{E_b/N_o})}\right]}{2\left[1+\overline{E_b/N_o}\right]}} \qquad (9)$$

$$b = \sqrt{\frac{K\left[1+2\overline{E_b/N_o}+2\sqrt{\overline{E_b/N_o}(1+\overline{E_b/N_o})}\right]}{2\left[1+\overline{E_b/N_o}\right]}} \qquad (10)$$

Where K is equal to μ^2/σ^2.

Figure.4 shows the Simulink model that used to compute BER performance of DSSS with Rayleigh fading. The Matlab fading model uses Simulink Jakes model [11] where Doppler shift is equal to $0.01\ Hz$. The AWGN block specifies one Watt input signal power with average SNR from zero to 25 dB. The math function $1/u$ after fading model is essential to follow time variation in the fading channel and works as automatic-gain control in DS receiver.

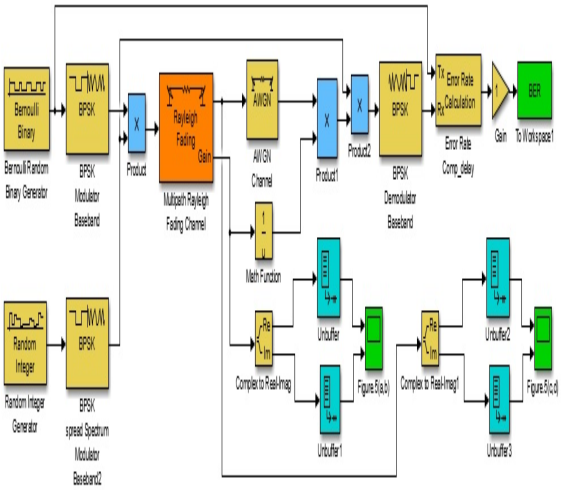


Figure.4 Simulink model of Non-quantized DSSS with Rayleigh fading channel

Figure.5 (a and b) shows the complex parts of the gain of main path in Rayleigh channel. Figure.5 (c and d) shows the real and imaginary parts of the Rayleigh fading channel output where the time-variation of the fading channel is visibly plain as a result of chosen Jakes fading model that be considered as flat (frequency non-selective) model.

BER performance of Non-quantized DSSS with Rayleigh fading can be shown in Figure.6. The performance shows the theoretical and simulated BER for Rayleigh fading channel along with the theoretical BER of Non-quantized DSSS with AWGN alone. The BER penalty with the existence of fading effect against AWGN performance is very clear in this figure.

For Non-quantized DSSS with Rician fading channel, the same Simulink model in Figure.4 is used but with Rician Matlab channel block instead of Rayleigh block. The parameters for this model are as following: frame-based with 20 samples per frame, 0.01 Hz Doppler shift, and the maximum diffuse Doppler shift is 0.01 Hz.

Figure.7 shows BER performance for Non-quantized DSSS with Rician fading channel and for different values of Rician factor (K).

The theoretical BER of Rayleigh channel is included in the Figure.7 for comparison with simulated values. The increasing of Rician factor from K=1 to K=2, puts forward high dominant received component which leads to an improvement in BER performance.

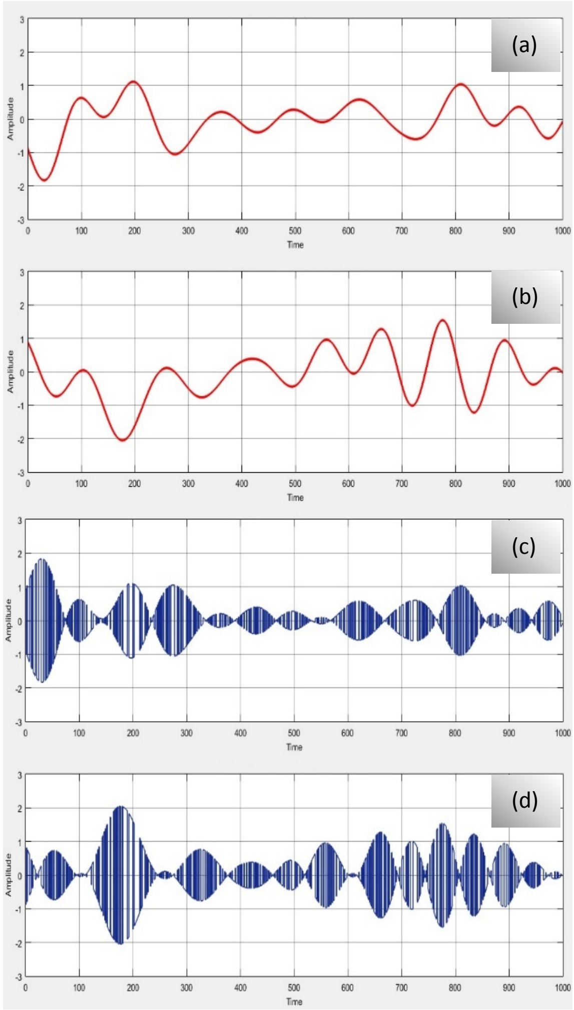


Figure.5 Real and Imaginary parts of Rayleigh fading channel in Non-quantized DSSS: (a, b) channel Gain, (c, d) channel output

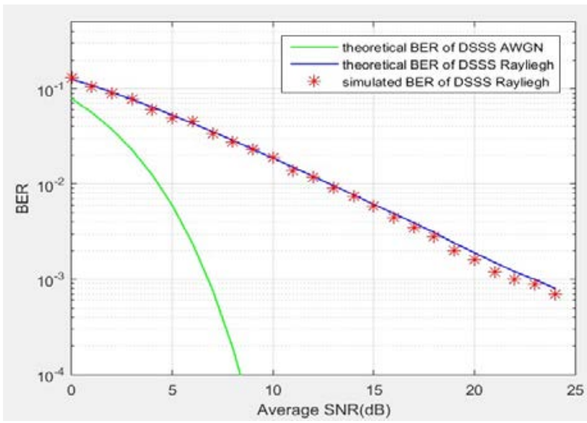


Figure.6 BER performance of non-quantized DSSS with Rayleigh fading and AWGN channels

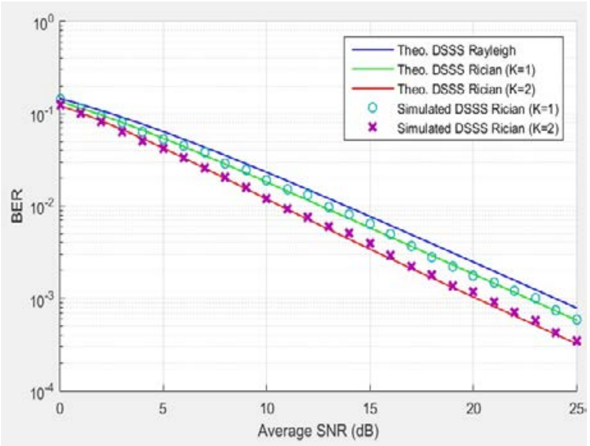


Figure.7 BER performance of non-quantized DSSS with Rician fading channel with K=1, 2

4. Modeling of Quantized DSSS (fixed-point performance)

In all previous models of DSSS, the performance evaluation has been done with floating–point operations. In the real world, these models are realized as an application-specific integrated circuit (ASIC) with finite values processing (discreet) such as digital signal processing (DSP) or field-programmable gate array (FPGA). So to obtain a real world value (RWV), the DSSS received signal is quantized to different levels of fixed-point values to evaluate the exact behavior and real-time performance. Fixed-point numbers in the Matlab are represented in binary form by the expression $fixdt(s, ws, n)$, where s is the sign bit, *ws* is the word length, and *n* is fraction length [12].

Figure.8 (a) shows the Simulink convert-block that converts the ADC floating-point to fixed-point which will be used to reevaluate DSSS performance under real-time applications, while Figure.8 (b) shows the structure of fixed-point representation.

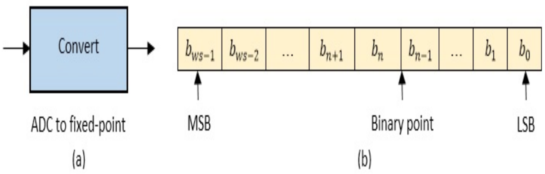


Figure.8 (a) Simulink convert-block, (b) Fixed-point representation

5. Simulation Results

The model of Quantized DSSS (10 chips/bit) with only AWGN channel can be shown in Figure.9. This Simulink model contains a convert-block that translates the received floating-point values into fixed-point precision for word size 8 and different quantization levels. The using of double-block that precedes the AWGN block is just to make the input to AWGN as floating-point value.

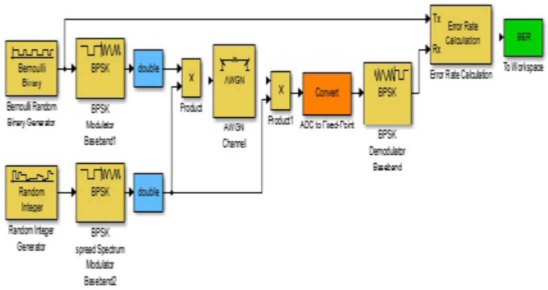


Figure.9 Simulink model of Quantized DSSS with AWGN channel

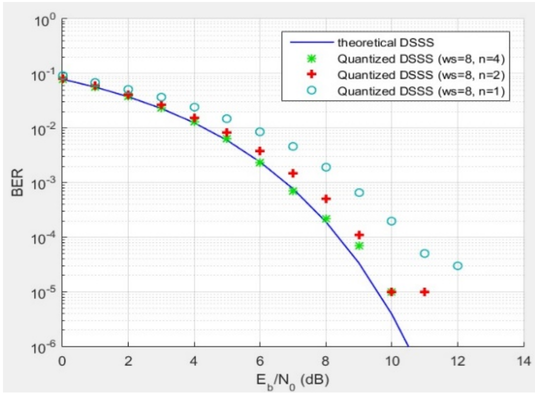


Figure.10 BER performance of Quantized DSSS with AWGN channel

The BER performance of Quantized DSSS for 100000 transmitted bits with word size 8 and fraction lengths of 4, 2, and 1 can be shown in Figure.10.

For SNR equal to 10 dB (Figure.10), BER for fraction length of four results in a little degraded performance compared to theoretical performance. This degraded is due to an insufficient time that required calculating BER rather than from errors added by quantized error. For other cases of fraction lengths ($n = 1,2$), the performance seems a high degraded due to increasing in quantization error. Values of fraction lengths that greater than four leads to a saturation in the model and reach to the theoretical performance. The choice of suitable word and fraction length in Quantized DSSS is a trade-off between system complexity and noise rejection. In addition, this compromise includes the range of the represented values, the number precision, and the quantized errors to make a good format of the digitized signals to implement the required DSSS in mobile wireless communications.

Figure.11 shows the Simulink model for estimating BER performance of quantized DSSS (10 chips/bit) with Rayleigh fading channel.

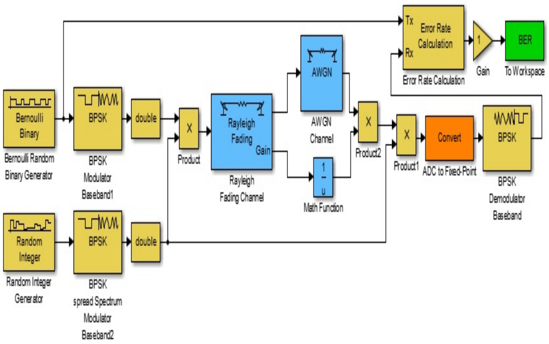


Figure.11 Simulink model of Quantized DSSS affected by Rayleigh fading channel

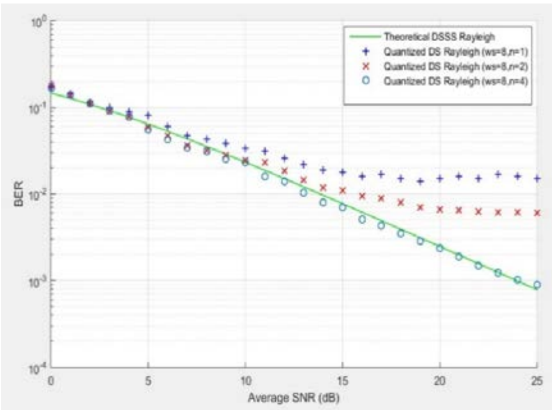


Figure.12 BER performance of Quantized DSSS with Rayleigh channel for different quantization levels

This model uses Jakes fading model for Doppler shift equal to 0.01 Hz. The AWGN block specifies one Watt input signal power with average SNR from zero to 25 dB. To apply different quantization levels, the convert-block is used here to translate the received floating-point values into fixed-point precision for a word size 8 and different fraction lengths. The BER performance of Quantized DSSS (Rayleigh fading channel) for 10000 transmitted bits with word size 8 and different quantization levels (fraction lengths of 4, 2, and 1) can be shown in Figure.12. For average $SNR = 15\ dB$, the BER performance which at low quantization levels (fraction lengths of 1 and 2) seems high degraded and saturated around $BER = 10^{-2}$ regardless of increasing in SNR values. This is because of an increasing in quantization noise at such low quantization levels. BER performance at quantization level of fraction length of four ($n = 4$) reaches the theoretical performance and seems a good choice for digitized signals to implement the required DSSS in mobile wireless communications that operates under Rayleigh fading channel environment.

Figure.13 shows the Simulink model for quantized DSSS (10 chips/bit) with Rician multipath fading channel for the following simulation parameters:

- DSSS (10 chips/bit) with BPSK modulation.
- Three levels of received signal quantization (n=1, 2, and 4).
- Two paths with delay vector {0 and 2} seconds and average paths gain {0, and -3} dB.
- Jakes fading model with maximum diffuse Doppler shift 0.01 Hz.
- The line of sight component has 0.01 Hz Doppler.
- Simulation time = 10000 sec and sampled-based (20 samples/frame) with 1 second sample time.

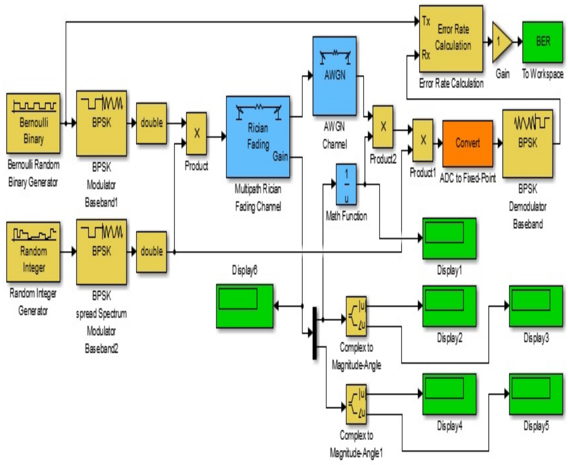


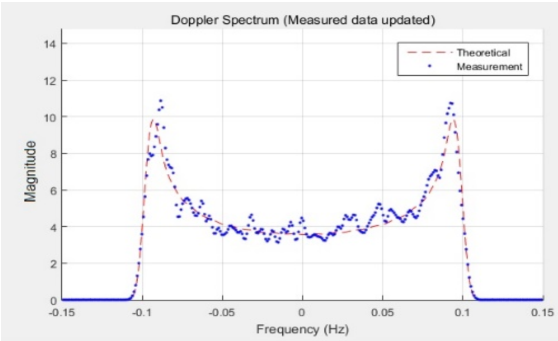
Figure.13 Simulink model of Quantized DSSS affected by multipath Rician fading channel

Before developing BER performance of quantized DSSS with Rician multipath fading channel, it is important to investigate the behavior of Rician channel using specific parameters. These parameters include Rician factor that denotes the ratio of signal power in the main component over the scattered power (for diffuse multipath components), the Doppler shift (for line of sight component), and the maximum Doppler shift (for diffuse multipath components). Figure.14 shows the Rician channel Doppler spectrum with multipath for Rician factor 3, where no multipath case (a) is setting at 0.1 Hz maximum diffuse Doppler shift.

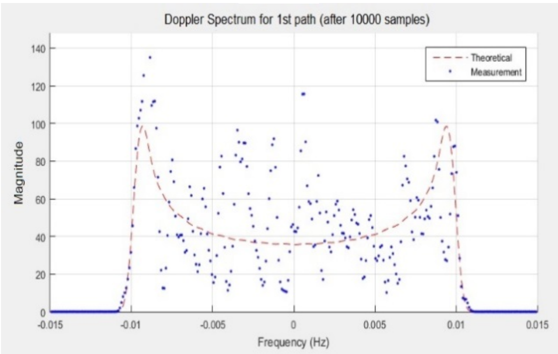
Comparing (a) with (b) and (c) in Figure.14, it can be seen that the time varying characteristic of fading channel consequences in worse estimation in Doppler spectrum. For two paths with delay = 0 second for first path and delay = 2 seconds for second path, Figure.15 shows the Rician channel frequency and impulse responses for Rician factor 3 and after 10000 samples.

The variation in frequency response is due to channel variation in time and taken after 10000 samples. It can be seen a null at 0.07 Hz in frequency response which resulted from the presence of multipath effect in the channel. This null occurred at about 0.23 Hz from the peak. The

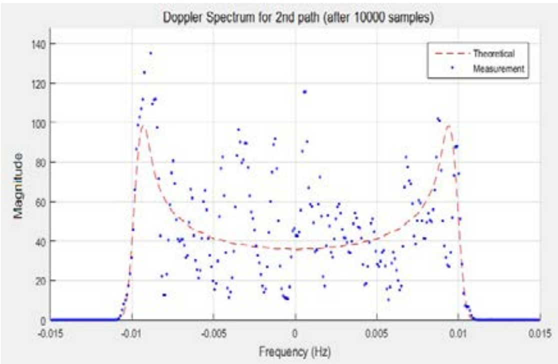
BER performance of Quantized DSSS (Rician multipath fading channel) for 10000 transmitted bits with word size 8 and different quantization levels (fraction lengths of 4, 2, and 1) and for Rician factors $(K = 1, 2)$ can be shown in Figure.16.



(a)



(b)



(c)

Figure.14 Rician channel Doppler spectrum for Rician factor=3 and after 10000 samples: (a) Doppler spectrum without multipath, (b) Doppler spectrum for 1st path, (c) Doppler

For both cases K=1 and 2 when average SNR=15 dB, the BER performance at low quantization levels $(n = 1 \; and \; 2)$ seems high degraded and saturated around $BER = 10^{-2}$ regardless of increasing in SNR values (as in case of Rayleigh BER). As mentioned before, this happens due to increasing in quantization noise at such low quantization levels. BER performance at quantization level of $n = 4$ reaches the theoretical performance until $SNR = 20 \, dB$ and seems a superior choice when implemented quantized DSSS in mobile wireless communications that affected by Rician multipath fading channel.

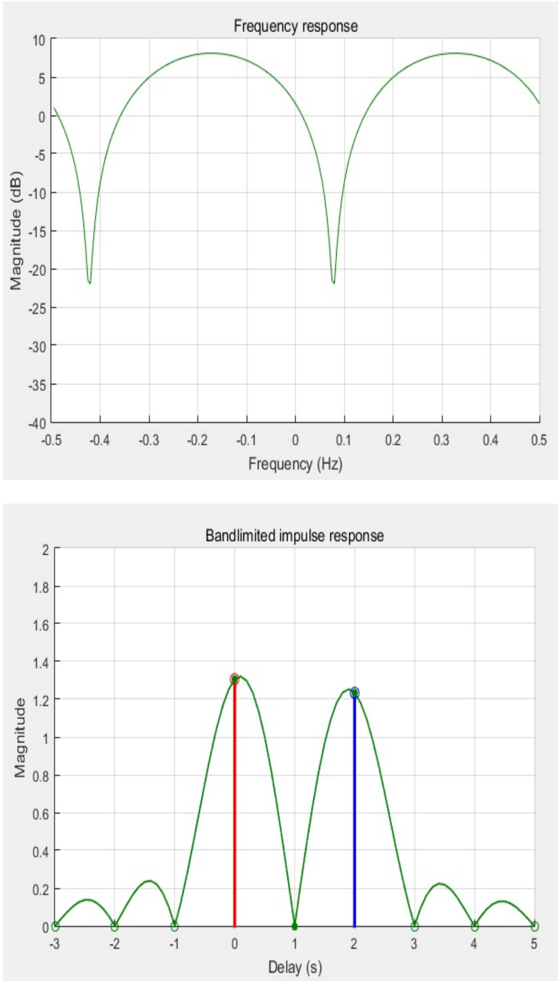
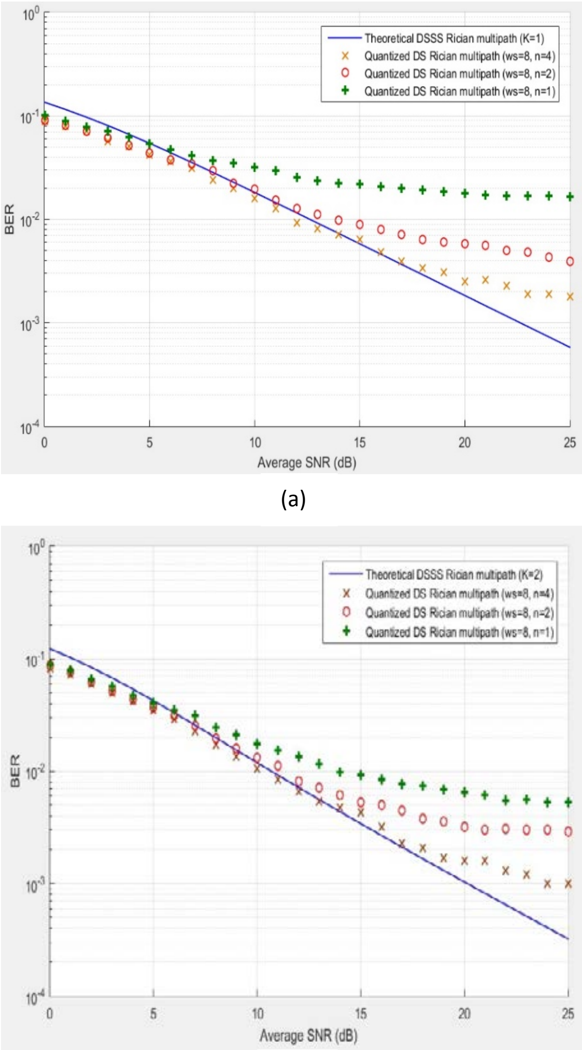


Figure.15 Frequency response and Impulse response of Rician multipath channel for Rician factor=3 after 10000 samples

Table.1 shows a comparison between the BER performance of non-quantized DSSS (floating-point) and quantized DSSS (fixed-point) along with related theoretical results for different channel types and for specific values of SNR and transmitted bits.



(a)

(b)

Figure.16 BER performance of Quantized DSSS with Rician multipath fading channel for different quantization levels (n=1, 2, and 4): (a) Rician factor K=1, (b) Rician factor K=2.

6. Conclusion

The performance of quantized DSSS for different channels (AWGN, Rayleigh fading, and Rician multipath fading) depends mainly upon the selection of the range of the represented values, the precision received value, and the quantization noise. From simulation results, it is found that at low level quantization (fraction length 1 and 2) the BER performance is high degraded due to increasing in quantization noise and insufficient time that required calculating BER rather than from errors added by quantized error. At the quantization level $n = 4$, the performance is slightly degraded and reaches to the theoretical performance and seems a good choice to make a better representation for digitized signals to implement the required DSSS in mobile wireless communications. It is also observed that the BER performance in all channel types behave in the same manner for both cases (floating-point and fixed-point) where BER of AWGN is better than BER of Rician and the latter in turn is better than BER of Rayleigh channel. The choice of suitable word and fraction length in Quantized DSSS is a trade-off between system complexity and noise rejection spatially when required implementation of fixed-point DSSS receivers in application-specific integrated circuit such as DSP or FPGA.

Table.1 Comparison between non-quantized and quantized DSSS for different channel models

Channel Model of DSSS	SNR (dB)	Trans. bits	BER				
			Theoretical value	Non-Quantized DSSS (floating-point)	Quantized DSSS (fixed-point)		
					Performance improvement →		
					n = 1	n = 2	n = 4
AWGN	8	100000	$2X10^{-4}$	$2.1X10^{-4}$	$2X10^{-3}$	$5X10^{-4}$	$2.2X10^{-4}$
AWGN + Rayleigh	15	10000	$5.8X10^{-3}$	$5.5X10^{-3}$	$2X10^{-2}$	$1.2X10^{-2}$	$7X10^{-3}$
AWGN + Rician ($Rician\ factor\ K = 1$)	15	10000	$6X10^{-3}$	$6.3X10^{-3}$	$2.2X10^{-2}$	$9.1X10^{-3}$	$6.4X10^{-3}$
AWGN + Rician ($Rician\ factor\ K = 2$)	15	10000	$3.4X10^{-3}$	$3.9X10^{-3}$	$9X10^{-3}$	$6X10^{-3}$	$5X10^{-3}$

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تحليل أداء نظام الطيف المنتشر الكمي (السلسلة المباشرة) في الاتصالات اللاسلكية المتنقلة تحت بيئة قنوات الضوضاء البيضاء المضافة والخفوت متعدد المسارات

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الخلاصة

يقدم هذا البحث تحقيقا لأداء نظام الطيف المنتشر-السلسلة المباشرة (DSSS) في الاتصالات المتنقلة. للحصول على القيمة الحقيقية، تم أجراء عملية التكميم على أشاره الطيف المنتشر بمستويات مختلفة من تمثيل النقطة الثابتة. وتم تقييم هذه الأوضاع من التكميم عن طريق حساب BER تحت بيئة قنوات مختلفة (AWGN،Rayleigh، Rician). وبناء على نتائج المحاكاة، لوحظ أن نظام السلسلة المباشرة الكمية توفر أداء وسط بين التركيب المادي للنظام ورفض الضجيج مقارنة مع نظام السلسلة المباشرة الغير كمية وجعل التمثيل ملائم للإشارات الرقمية لتنفيذ DSSS المطلوب في مجال الاتصالات اللاسلكية المتنقلة.