

Interference Performance of Ultra-High Rate (up to 40 Mchip/s) FQPSK Based W-CDMA

Experimental modem offers more robust performance against multi-tone interference than one with BPSK.

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This paper presents an experimental study of a ubiquitous Wideband Code Division Multiple Access (W-CDMA) system which can be operated with either relatively low or ultra-fast bit rate and chip rate for a clear mode (TDMA) or a W-CDMA system in narrowband interference (NBI) environment. The experimental modem and 2.4 GHz radio system can provide multiple modulation waveforms of BPSK, QPSK, OQPSK and nonlinearly amplified (NLA) power and spectral efficient FQPSK which is fully compatible with GMSK standardized by a GSM system and has a higher spectral efficiency than GMSK. The NBI environments are characterized as either a single-tone interference or as a multi-tone interference in our measurement. The NBI caused by other narrowband analog FM and digital PSK signals also has been carried out to evaluate the performance of the DS-SS system. We demonstrate that the W-CDMA system with FQPSK is more robust against multi-tone interference than the one with BPSK.

Introduction

W-CDMA implemented with Direct-Sequence Spread Spectrum (DSSS) signaling is one of the most promising multiplexing technologies for higher data rate cellular communications services because it maximizes system capacity. Several versions of CDMA have been proposed for cellular and personal communications service (PCS) applications, such as a frequency-hopping technique version and a narrowband direct sequence CDMA version. However, these versions mainly deal with small numbers of voice channels per cell and relatively low data transmission rates [1]. The ultimate goal of the PCS is to supply multiple services where speech, data, video and multimedia are transmitted. A

result of the demand for these integrated services is the appearance a wideband CDMA (W-CDMA) system. The W-CDMA system can provide great numbers of voice channels per cell and high-speed data transmission. Some W-CDMA systems are described for cellular mobile communications in References [1, 2, 3 and 4].

Another advantage of spread spectrum CDMA is the ability to reject interference that might prohibit useful communications. The two major sources of interference to CDMA systems are Narrowband Interference (NBI) and Wideband Interference (WBI). The former is a single-frequency interference, or narrowband signal interference where its energy is concentrated near one frequency, as in conventional communication of analog FM systems. It has been demonstrated that carrier wave (CW) interference represents a "worst-case" narrowband interference [1, 3, 4] while the frequency of the single-frequency interference is equal to carrier frequency of the received DSSS signal. The latter is created by another CDMA user having an approximately equal chip-rate with a different PN spreading function. But NBI is more dangerous to CDMA systems because the power density of NBI after correlation is higher than that of WBI. For this reason, this paper focuses on the impact of NBI on CDMA and W-CDMA performance.

Meanwhile, there is proof that the performance of a DSSS system in the presence of NBI can be enhanced significantly through the use of active NBI suppression techniques [5, 6] prior to a despreading operation. The content and behavior of the performance degradation of a DSSS system in the presence of NBI, however, should be experimentally demonstrated and evaluated because most research focuses on computer simulation.

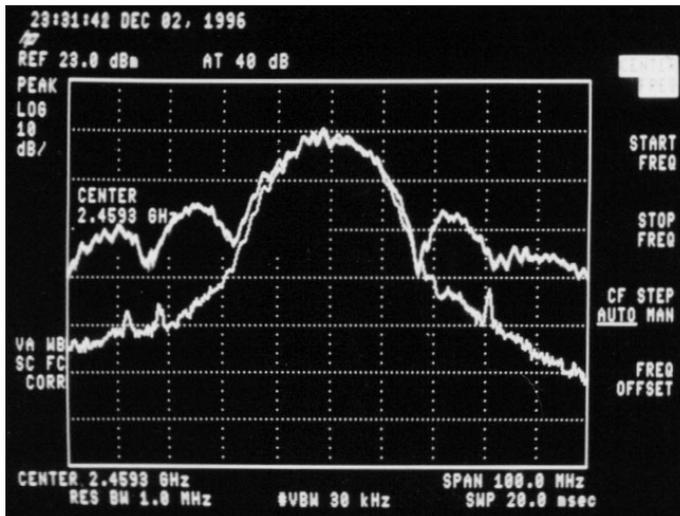
System	1. DDSS mode: BPSK, OQPSK, FQPSK 2. clear mode: BPSK, OQPSK, FQPSK
Data rate (Kbit/s)	256, 560, 660, 772, 1544, 2110
Chip rate (Mc/s)	16.984, 30.88, 30, 35
PN code	2^{16} length
Carrier recovery	decision-directed, phase difference approximation, digital phase shifter (i.e. vector rotator)
Convolutional coding and interleaver	Viterbi decoder
IF signal (MHz)	70

■ **Table 1. Features of a DSSS CDMA system evaluation board using FQPSK-GMSK, built by Lockheed Martin under the license of Feher et al., patented technologies [3].**

In this paper, a wideband DSSS system, which is the basis of the W-CDMA, is used to evaluate some fundamental characteristics and performance of the DSSS system in single- and multiple-tone interference environments. In particular, we used the EB200KF; FQPSK-GMSK Lockheed Martin system manufactured under license of Feher et al. patented technologies [3]. The purpose of this paper is to provide some measured results as useful references for future W-CDMA development.

Wideband DSSS system: Modulation/demodulation

A multiple mode wideband DSSS modem has been designed to transmit data rates up to 40 Msymbols/s and chipping rates from 1 Mcps to 40 Mcps. It can support BPSK, QPSK, OQPSK and FQPSK [3, 7] and GMSK operations with spread or clear (non-spread) mode to meet particular requirements of PCS and ultra-high rate W-CDMA. A NBI suppression technique and coherent detection have been implemented in the receiver.



■ **Figure 1. Spread spectrum of W-CDMA system in a nonlinearly amplified RF system. Upper trace: filtered QPSK, lower trace: FQPSK bit rate: 1.544 Mb/s, chip rate: 16.84 Mcps/s.**

The features of the digital DSSS system W-CDMA evaluation board are listed in Table 1. The RF spread spectrum of a nonlinearly amplified DS-SS system is given in Figure 1. It can be seen from Figure 1 that FQPSK has a tremendous spectral efficiency advantage over filtered QPSK and OQPSK in non-linearly amplified RF systems.

Narrowband interference rejection

As noted above, the NBI signal degrades the performance of CDMA systems. With NBI, the CW interference signal is defined as having the same frequency as the carrier signal of the received spread spectrum signal, that is, CW is an unmodulated carrier signal.

In the receiver, the down-converted IF spread spectrum signal overlapped by CW interference signal is given by

$$V_r(t) = \sqrt{2P_s}d(t)g(t)\cos(\omega_0 t + \theta) + \sqrt{2P_j}\cos(\omega_0 t + \theta) \quad (1)$$

where $d(t)$ is the information-bearing signal, $g(t)$ is the spreading pseudo-noise (PN) sequence at a chipping rate of $f_c = 1/T_c$. P_s is the received desired signal power at the receiver input. P_j is the power of a CW interference signal at the receiver input. ω_0 is the intermediate frequency (IF). θ is a random variable, uniformly distributed over 0 to 360 degrees.

The additive white Gaussian noise (AWGN) contribution is ignored because in our assumption $P_j \gg N_{AWGN}$, where N_{AWGN} is Gaussian noise power. The band-pass filter at the correlator output accepts the desired narrow bandwidth signal and rejects all of the CW interference lying outside the filter band, so the receiver processing gain [8] is

$$\begin{aligned} G_p &= \frac{\left(\frac{P_s + P_j}{P_j}\right)_{BPF-out}}{\left(\frac{P_s + P_j}{P_j}\right)_{BPF-in}} \\ &= \frac{BW_{RF}}{BW_{MOD}} \\ &\approx \frac{f_{chip}}{f_{bit}} \end{aligned} \quad (2)$$

where BW_{RF} is the RF bandwidth of the signal, BW_{MOD} is the modulated signal bandwidth, f_{chip} is the chip rate and f_b is the bit rate. In the following, the relationship between the average carrier to average interference power ratio (C/I) and the processing gain G_p will be derived.

The carrier-to-interference ratio [4] is

$$\frac{C}{I} = \frac{E_b}{I_o} \cdot \frac{f_b}{BW} \quad (3)$$

where E_b is the bit energy of the signal, I_o is the interference power spectrum density, f_b is the bit rate and B_W is the equivalent noise bandwidth of the receiver. Equation (3) can be expressed in decibels as

$$\left[\frac{C}{I} \right]_{dB} = \left[\frac{E_b}{I_o} \right]_{dB} - 10 \log \frac{B_W}{f_b} \quad (4)$$

When the single-side equivalent noise bandwidth of the receiver is equal to Nyquist frequency f_N , or the double-side noise bandwidth of the receiver $B_W = 2f_N$, equation (4) becomes

$$\begin{aligned} \left[\frac{C}{I} \right]_{dB} &= \left[\frac{E_b}{I_o} \right]_{dB} - 10 \log \frac{2f_N}{f_b} \\ &= \left[\frac{E_b}{I_o} \right]_{dB} - 10 \log \frac{2f_{chip}}{f_b} \end{aligned} \quad (5)$$

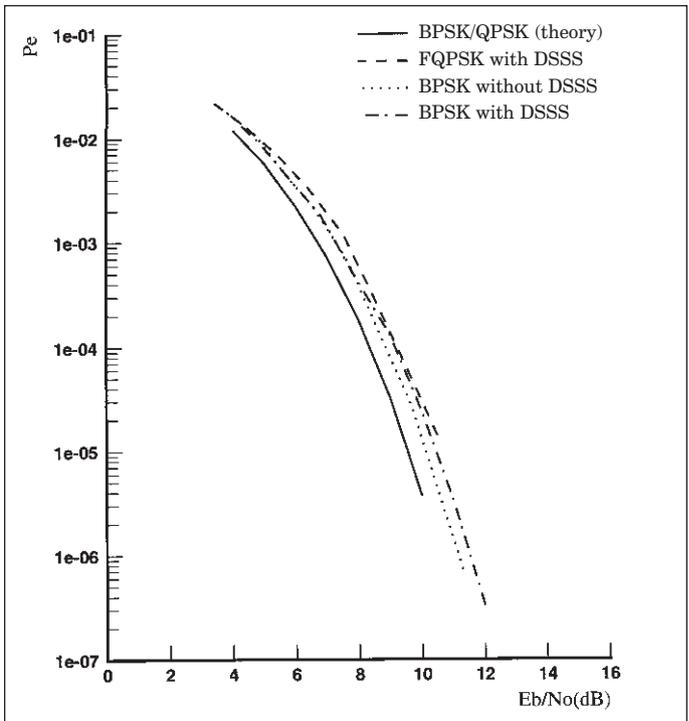
where Nyquist frequency $f_N = f_{chip}/2$ (Nyquist first theorem). Substituting (2) in equation (5) gives

$$\left[\frac{C}{I} \right]_{dB} = \left[\frac{E_b}{I_o} \right]_{dB} - [G_p]_{dB}$$

or

$$[G_p]_{dB} = \left[\frac{E_b}{I_o} \right]_{dB} - \left[\frac{C}{I} \right]_{dB} \quad (6)$$

When $f_{chip} \gg f_b$, the bandwidth BW_{MOD} of the band-pass filter at the output of correlator is narrower than the RF bandwidth BW_{RF} . In this case, after the NBI signal is spread by a local PN code with a chip rate of f_{chip} over a wideband range and then filtered by the band-pass filter with the bandwidth BW_{MOD} , the interference power density I_o is white noise within bandwidth BW_{MOD} . It has been demonstrated [1] that this interference noise at the output of the band-pass filter is Gaussian noise when $f_{chip} \geq 10f_b$. So $I_o = N_o$, and equation (6) can be rewritten



■ Figure 3. BER performance of a W-CDMA system in an AWGN channel.

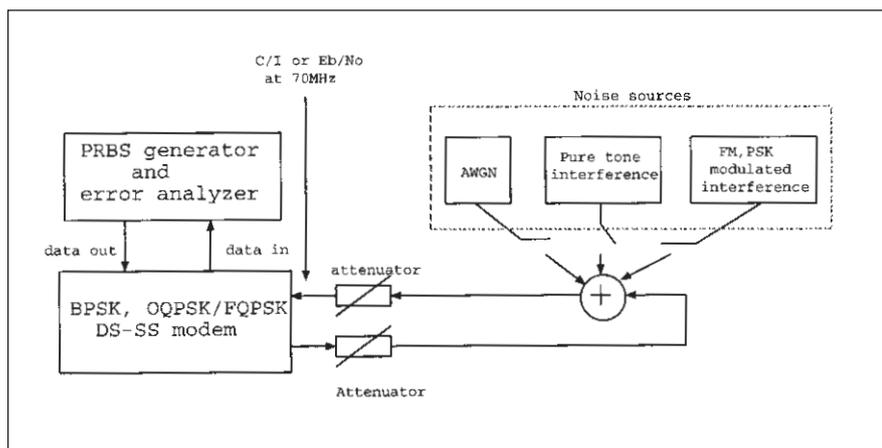
$$[G_p]_{dB} = \left[\frac{E_b}{N_o} \right]_{dB} - \left[\frac{C}{I} \right]_{dB} \quad (7)$$

where N_o is power spectrum density of additive white Gaussian noise. The equation (7) is identical to equation (1) of the reference [9]. So for the DSSS system, the processing gain can be interpreted as the decibel difference between the required E_b/N_o ratio in AWGN and the C/I ratio of the DSSS system in an NBI environment.

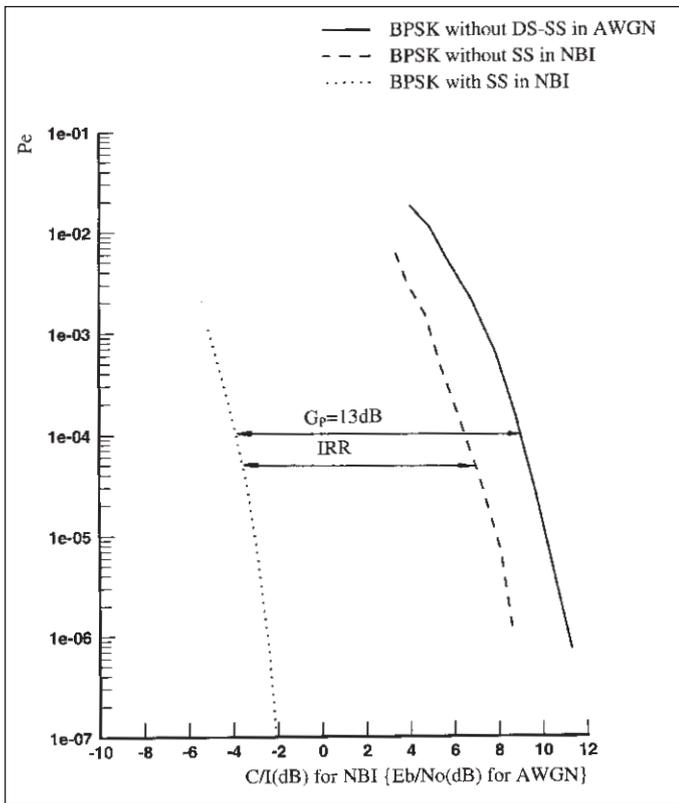
Performance evaluation

In our measurement, a wideband FQPSK and GMSK-based DSSS modem evaluation board manufactured by Lockheed Martin under Feher's patents was used to evaluate its BER performance and processing gain in the NBI environment where the NBI signals were characterized as either a single tone or multiple tone interference. The test block diagram of a DSSS system at the intermediate frequency (IF) band is shown in Figure 2. In the transmitter, multi-data and multi-chip rates can be chosen, and the function of spreading spectrum can be added according to practical applications.

The noise sources in the measurement are AWGN, pure sinusoidal tone interference and narrowband analog FM or digital $\pi/4$ -DQPSK interference.

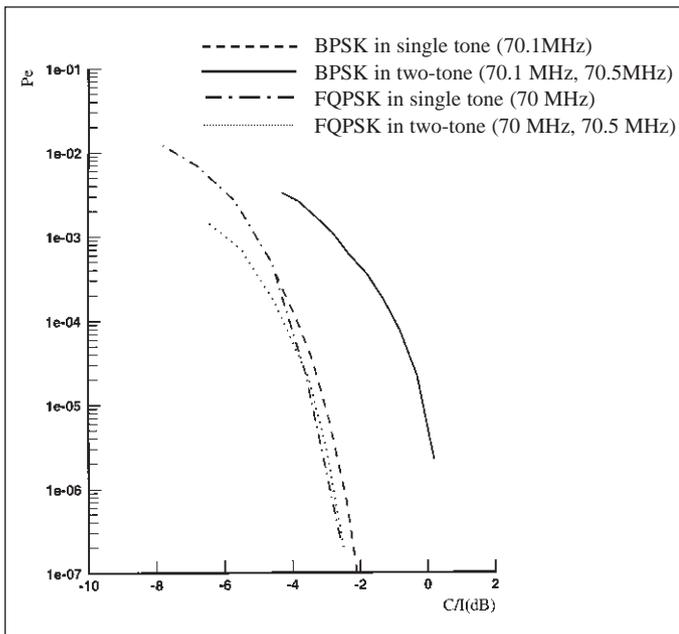


■ Figure 2. Measurement setup for a W-CDMA system.

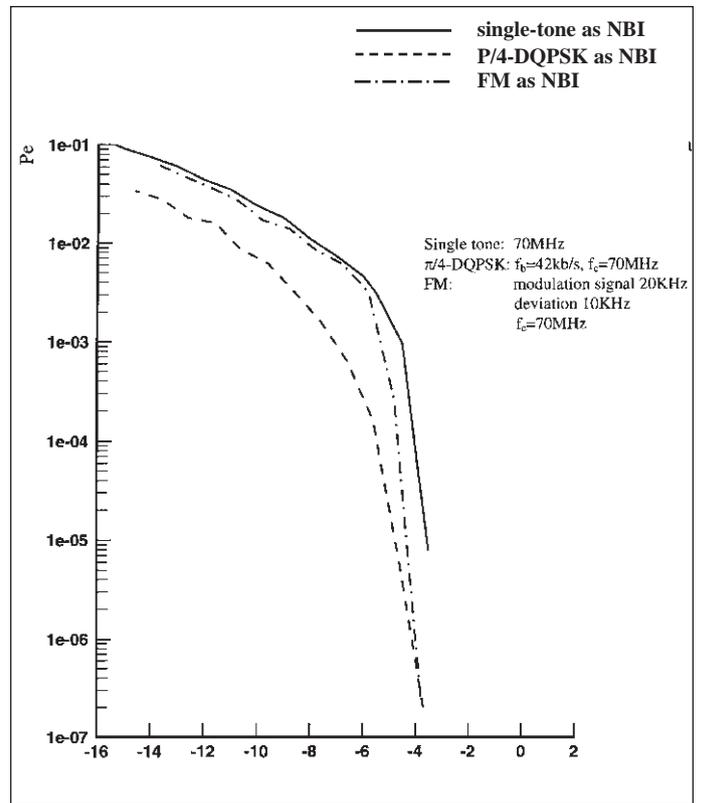


■ Figure 4. BER performance of a W-CDMA system in a single-tone NBI environment.

Analog FM and digital $\pi/4$ -DQPSK signals are used as NBI signals to evaluate their effects on the CDMA system because an analog FM system and a digital CDMA system will co-exist during the transition from analog to



■ Figure 6. BER performance of a W-CDMA system in a two-tone NBI environment.



■ Figure 5. BER performance of a W-CDMA system with FQPSK in NBI environments.

digital systems, and $\pi/4$ -DQPSK as the IS-54 standard and CDMA will be operated in parallel for PCS as the different standards.

A DSSS system in a AWGN channel

First, the BER performance of the wideband DSSS system is evaluated in an AWGN environment. The measured results are shown in Figure 3. The data rate and chip rate of a BPSK modem are 1.544 Mbps and 30.88 Mcps, and the data rate and the chip rate of the FQPSK modem are 1.544 Mbps and 16.984 Mcps. The performance of the spread spectrum BPSK and FQPSK is identical to one of the clear mode BPSK (non-SS). The required E_b/N_o is between 9-9.5 dB at $P_e = 1 \times 10^{-4}$, and the performance degradation is about 1 dB compared with theory performance. Meanwhile, it can be seen that the DSSS system does not combat AWGN, as does the clear mode of BPSK.

Single-tone NBI rejection and processing gain evaluation

In this measurement, BER performance of a DSSS system is evaluated in a NBI environment where single-tone, analog FM and digital $\pi/4$ -DQPSK signals are used as NBI, respectively. For the DSSS system with a BPSK modem of data rate $f_b = 1.544\text{Mb/s}$ and chip rate $f_{chip} = 30.88\text{ Mc/s}$, the theoretical processing gain from equation (3) is

1. Bit rate range	10 kb/s to 45 Mb/s (22.5 Mchip/sec)		
2. Data rate increments	N×8 kb/s (low rates), N×64 kb/s (medium rates), N×256 kb/s (high data rates), N=1,2,3,4,...		
3. Modulation	FQPSK or compatible enhanced efficiency GMSK or OQPSK		
4. RF amplification and transceiver	Modulation/demodulation must be suitable for NLA (Non-linearly Amplified (saturated) RF power efficient transceivers as well as for Linear Amplified (LIN) increased spectral efficiency RF applications.		
5. Integrated power spectral efficiency [b/s/Hz] requirements	For NLA (saturated; C-class) and for LIN operated transceivers the spectral efficiency will meet at least the following objectives:		
		<u>NLA transceivers</u>	<u>LIN transceivers</u>
		[b/s/Hz]	[b/s/Hz]
	99% occupied in-band power (-20dB integrated out of band)	1.2	1.8
	99.9% in-band power (-30dB integrated out of band)	0.9	1.6
	99.99% in-band power (-40dB integrated out of band)	0.7	1.5
6. Power spectral density (PSD) [b/s/Hz] minimal efficiency requirements relative to maximal in-band PSD		<u>NLA transceivers</u> [b/s/Hz]	<u>LIN transceivers</u> [b/s/Hz]
	-20dB	1.0	1.70
	-30dB	0.9	1.60
	-40dB	0.45	1.55
	-60dB	0.25	1.50
7. Probability of error performance (BER): BER=f(E _b /N _o) requirement (raw-uncoded) for both LIN and NLA systems specified in AWGN stationary environment		<u>E_b/N_o [dB]</u>	<u>BER better than</u>
		7	10 ⁻²
		9	10 ⁻³
		11	10 ⁻⁴
		13*	10 ⁻⁶
		15*	10 ⁻⁸
		* for systems above 300kb/s	

■ **Table 2. Specification/requirements of DoD's common RF data link standard FIRST. Physical Layer (PHY), Modulation/RF, data rates and performance highlights. FIRST Technical Working Group (TWG) Specification, Draft 1.0, Rev. 1, Dec. 9, 1996. Family of interoperable range system transceivers [11].**

$$\begin{aligned}
 G_p &= 10 \log \frac{f_{chip}}{f_{bit}} \\
 &= 10 \log \frac{30.88 \text{ Mc/s}}{1.544 \text{ Mb/s}} \\
 &= 13 \text{ dB}
 \end{aligned} \tag{8}$$

The measured BER performance of a DS-SS system in the single-tone environment is shown in Figure 4. The performance of a clear mode of BPSK in an AWGN environment also is given in Figure 4 to evaluate the processing gain. As mentioned before, the processing gain is the decibel difference between the E_b/N_o ratio in AWGN and the C/I ratio of a DSSS system in an NBI environment. The measured $[E_b/N_o]_{dB}$ and $[C/I]_{dB}$ values in Figure 4 are about 9.4 dB and -3.6 dB at $P_e = 1 \times 10^{-4}$ respectively. By replacing $[E_b/N_o]_{dB} = 9.4$ dB and $[C/I]_{dB} = -3.6$ dB in equation (7), we have

$$[G_p] = 9.4 \text{ dB} - (-3.6 \text{ dB}) \tag{9}$$

$$= 13 \text{ dB}$$

So the measured value of the processing gain is identical to the calculated value in the equation (8). It should be noted that about 10 dB difference between the C/I ratio of a DSSS system and the C/I ratio of a clear mode system at $P_e = 1 \times 10^{-4}$ can not be referred as the processing gain. This 10 dB difference for the same BER performance is defined as the interference-rejection ratio (IRR) [10].

Figure 5 shows the performance of the DSSS system with FQPSK modem in the NBI environment where analog FM and digital $\pi/4$ -DQPSK signals respectively were used as NBI. These narrowband interference signals have almost same impacts on the DSSS system except that the performance of the DSSS system is 2 dB better at the low C/I ratio range in the $\pi/4$ -DQPSK interference environment than in single-tone and analog FM interference environments when the bandwidth of these interference signals is narrower than the bandwidth of the DSSS system.

Two-tone NBI rejection

In this case, the total power level of two NBI signals with same power for each one is set equal to the power level of single-tone NBI. Figure 6 shows BER performance of the DSSS system with BPSK and FQPSK modems in a two-tone NBI environment. A DSSS system with a BPSK modem in a two-tone NBI environment shows a worse performance of 3 dB than in a single-tone NBI environment. Meanwhile the performance of a BPSK system does not continue to degrade with an increasing number of interference signals beyond two-tone. So a DSSS system with a BPSK modem is more sensitive to multi-tone interference signals than a single-tone interference signal.

It also has been shown that the performance of a DSSS system with a FQPSK modem in a two-tone interference environment has the same performance as the one in a single-tone environment. So a FQPSK modem is more robust than a BPSK modem in the multiple-tone environment. The robust FQPSK based W-CDMA as well as "clear mode" TDMA performance leads to numerous commercial licensed applications. The specification highlights of DoD's "FIRST" system [11] are presented in Table 2. Note that FQPSK is the only power and spectrally efficient modem/RF technology which can meet variable bit rate robust TDMA and CDMA requirements.

Conclusion

The BER performance and processing gain of a wideband DS-SS system with the multiple modulation modes in the NBI environments have been evaluated experimentally. The BER performance of the wideband DSSS system with BPSK in a two-tone NBI environment is worse than in a single-tone NBI environment. The wideband DSSS system with FQPSK is more robust than the one with BPSK in the multi-tone interference environment. The W-CDMA system with FQPSK is suitable for nonlinearly RF amplified PCS applications as well as commercial and military "dual-mode" technology applications in the NBI environment. ■

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3. K. Feher et al., U.S. Patents, Nos. 4,567,602; 4,339,724; 4,644,565 and 5,491,457. Exclusively licensed by Digcom, Inc. Dr. Feher and Associates, 44685 Country Club Drive, El Macero, CA 95618; tel. (916)-753-0738, fax. (916)-753-1788.

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