DSSS System with OQPSK-Spread FSK: Sutudy on Characteristics of Low Envelope Fluctuation and Bit Error Rate Due to Narrow-Band Interference

Yusuke Akiyoshi, Makoto Taromaru, and Mai Ohta
Department of Electronics and Computer Science, Graduate School of Engineering, Fukuoka University
8–19–1, Nanakuma, Jonan-ku, Fukuoka, 814-0180 Japan
http://w3.tl.fukuoka-u.ac.jp/e_contents/content_1.html

***Abstract*—This paper proposes a transmission system suitable for short range radio systems of small wireless devices using direct sequence (DS) spread spectrum (SS) modulation. FSK and OQPSK are employed as the primary and spreading modulations respectively. FSK, $\pi/4$-DQPSK, or OQPSK modulations having constant or low-fluctuation envelope are favourable because small wireless terminals/devices, such as sensor nodes, require high efficiency of power amplifiers and simplicity of circuits due to limited power sources. SS modulation is a promising technique for the use of ISM bands because SS transmission can mitigate interference from the other radio systems that are asynchronous to each other. However, BPSK or QPSK, which has conventionally been used for spreading modulations, makes high envelope fluctuations no matter what the primary modulation is. On the other hand, the transmitted signal of the proposed system has low envelope fluctuation since OQPSK is employed to spread the primary-modulated signal with constant envelope. Therefore, the transmitter and the receiver can employ high efficiency RF (radio frequency) power amplifiers and limiter amplifiers respectively. Because OQPSK spreading is a linear modulation, high capability of immunity against interference can be maintained in the same manner of common DS-SS systems. Simulation studies show the basic properties: good eye patterns in condition without interference or noise, low envelope fluctuation, and sufficient bit error rate performance due to narrowband interference.**

I. Introduction

Spread spectrum (SS) modulations are now widely employed not only for 3G (third generation) cellular systems, but also for cordless telephones and other short-range communication systems/devices. These are operating in industrial, scientific and medical (ISM) bands, such as 2.4 GHz and 900 MHz. In ISM bands, most of wireless communication systems are usually unlicensed, and they have to avoid or mitigate interference autonomously to/from the other radio devices. It is another important feature of ISM bands that all the systems/devices are operating independently and asynchronously unlike cellular systems in their licensed bands. IEEE802.11 WLAN, IEEE802.15.4 (ZigBee), and some other systems avoid interference by carrier sense, *listen-before-talk*, and some of them can scan the band to look for and change frequency to one of the available channel. However, it sometimes takes rather long time to establish the link channel. By contrast, SS systems such as Bluetooth, and some cordless telephones of slow frequency hopping SS (FHSS) systems can commence communication and emit a radio wave immediately without carrier sense. This is because SS radio transmission generally has higher tolerance to cochannel or overlapped-spectrum interference than narrow band systems [1]. However, the slow FHSS is not suitable for wireless sensor network, because it has to transmit a data packet using at least several slots for error correction even though the data length is very short. Therefore, direct sequence spread spectrum (DSSS) transmission is the most promising technique for ISM wireless devices because DSSS can also mitigate the interferences from the other radio systems or radio devices that are asynchronous to each other. For such a short range wireless communication system, power efficiency and circuit simplicity are very important issue. High-efficiency power amplifiers and simple radio circuits are required. Hence, the following modulations are favourable since their envelope is constant or fluctuates less: FSK, $\pi/4$-DQPSK, or OQPSK (offset QPSK). On the other hand, BPSK or QPSK modulation has commonly been used for spreading modulation in conventional DSSS systems; however, it results in high envelope fluctuation no matter what the primary modulation is.

From these view points, the authors proposed to adopt the DSSS transmission to the short range wireless systems that employs GFSK (Gaussian-filtered FSK) and OQPSK for the primary and spreading modulations respectively [2]. The transmitted signal of the proposed system has low envelope fluctuation since (G)FSK, having constant envelope, is spread by OQPSK. Therefore, it can employ high efficiency RF (radio frequency) power amplifiers and have high capability of interference reduction. Similar technologies have already been studied: OQPSK spreading [3]–[7], chirp spread spectrum FSK [8], and phase-rotation spread FSK [9], for example. However, these conventional OQPSK spreading have large envelope fluctuation since they used PSK or QAM for the primary modulations; no studies on OQPSK-spread FSK are found. Though the latter two literatures used FSK for the primary modulation, their immunity to interference is clearly limited because the spreading modulations are not linear operation of their spreading codes. In other words, it cannot mitigate the interference even if the codes between desired and undesired signals are orthogonal to each other. Additionally, [8] must have the problem similar to slow-hopping FHSS systems since it chirps in long-term of several symbols. In this paper, we propose to adopt a DSSS transmission system for short range wireless devices. To make the envelope fluctuate as little as possible maintaining the robustness to the interference, we employ GFSK and OQPSK as primary and spreading

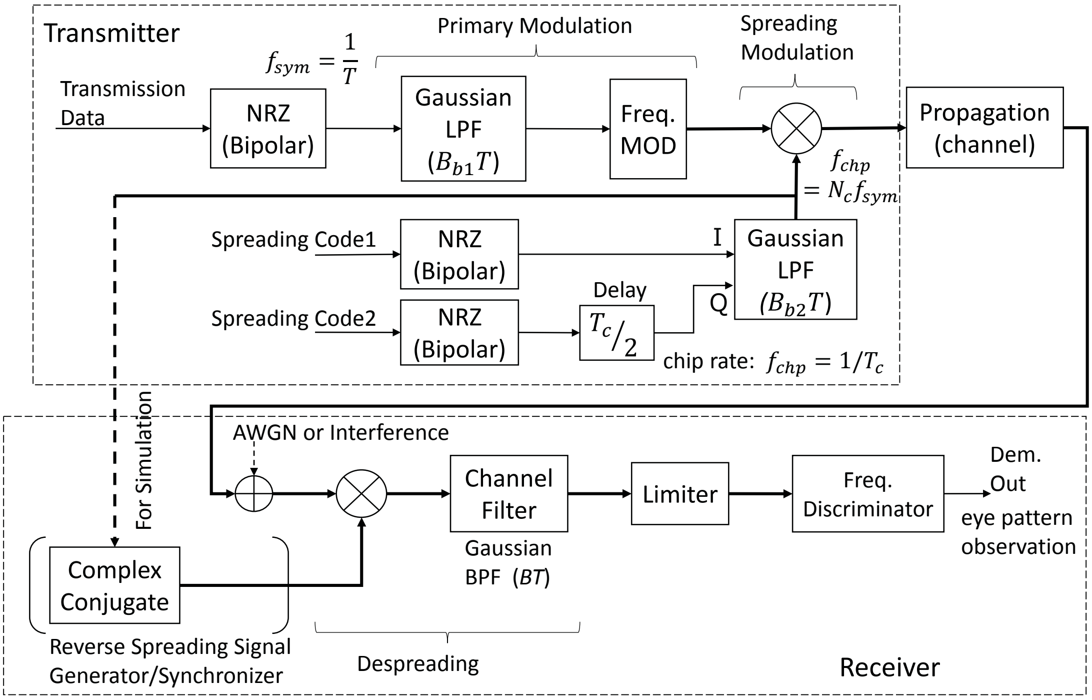


Fig. 1. Transmission system of OQPSK-spreading FSK

modulations respectively. The baseband I-Q signals of the spreading modulation are NRZ pulse trains shaped with a Gaussian filter with the cut-off frequency around the chip rate.

This paper is organized as follows. First, section II describes the SS transmission system. Section III gives the numerical results of the envelope fluctuation characteristic, eye patterns without interference or noise, and bit error rate (BER) performance due to narrowband interference at the same centre frequency. Finally, our conclusions are given in Section IV.

II. Transmission System of OQPSK-Spreading FSK

A. *Architecture of Transmission System*

Figure 1 shows the DSSS system that we studied. The transmission data is converted to bipolar NRZ pulse train and shaped/bandlimited with a Gaussian lowpass filter (LPF). The FM modulator modulates the carrier wave with the Gaussian-filtered pulses and outputs the GFSK signal, where we intend to set the modulation index $h = 0.5$(GMSK) –0.7. This is continuous phase FSK that is normally produced by a PLL (phase locked loop) circuit. Hereafter, let the symbol rate of the GFSK and the 3dB cutoff frequency of the Gaussian filter be $f_{sym} = 1/T$ and B_{b1}, respectively. Thick lines in the figure mean complex baseband signals or modulated RF signals, whose mathematical equations are expressed in complex form.

The spreading signal is made of a couple of the pseudo random number (PN) sequences (code) that are different to each other. These sequences are converted to bipolar NRZ pulse trains of chip rate $f_{chp} = 1/T_c$, and they are bandlimited with Gaussian LPF of cutoff frequency B_{b2}. The quadrature component of the spreading signal is T_c (half-chip) delayed to produce OQPSK signal. The time period of the PN sequences are equal to T, the symbol duration of the GFSK, and $f_{chp} = N_c f_{sym}$ where N_c denotes the length/period of the PN sequences.

The GFSK signal from the frequency modulator is multiplied by the spreading signal in complex and modulated with an orthogonal modulator. This modulator is usually made of a couple of Gilbert cells and a $\pi/2$ phase shifter. The output is commonly amplified to a necessary power level and transmitted into the air. The bandwidth of the transmitted signal becomes the sum of those of the GFSK and the spreading signal spectra. If the spreading signal were of NRZ pulses without the LPF, the occupation bandwidth would be exceed the band edges because its spectrum is expressed as *sinc function* and does not converge to zero sufficiently even at the frequency around $\pm f_{chp}$ apart from the carrier frequency. This is why we employ the Gaussian filters. Accordingly, the spreading signal is bandlimited within about f_{chp}. The normalized cutoff frequency ($\mathrm{B_bT}$ product) $B_{b2}T_c$ is typically around 0.5–2, and that of the LPF for GFSK modulation $B_{b1}T$ should be designed at least 1–2 so that it may not produce inter-symbol interference (ISI) degrading the BER performance.

B. *Receiver Architecture and Despreading Operation*

First, the receiver despreads the received signal by multiplying it by the complex conjugate, i.e., the reverse phase signal of the band limited spreading signal in the transmitter, as is shown in the lower part of Fig. 1. This processing is implemented with a Guilbert cell mixer or a balanced mixer, a kind of analogue multiplier. Then it passes through the BPF having the passband nearly equal to the bandwidth of the GFSK before spreading, i.e., the bandwidth of the primary modulation. In this paper, this BPF is assumed to

TABLE I. SUMMARY OF THE SIMULATION PARAMETERS

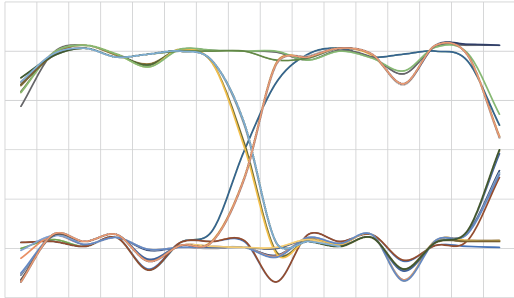
Primary modulation	GFSK (GMSK, $h = 0.5$), Normalized cutoff frequency of Gaussian filter: $B_{b1}T = 2$
Symbol rate	$f_{sym} = 1$ [kHz]
Spreading code	M-sequence PN codes (2047 chips)C Different codes between In phase and Quadrature phase
Chip rate	$f_{chp} = 1/T_c = 2047$ [kHz]
Spreading modulation	OQPSK by NRZ pulse of the PN codes bandlimited w/Gaussian filter
LPF for spreading signal	Gaussian, normalized 3dB cutoff frequency: $B_{b2}T_c = 2$
Propagation channel	Static, frequency-flat, phase shift ϕ
Despreading output BPF	Gaussian, normalized 3dB bandwidth $BT = 2$

have Gaussian characteristics, whose 3dB passband is denoted by B, and these processings are supposed to be in the IF (intermediate frequency) stages or by the mixer producing the IF signal in a super heterodyne receiver. Note that this BPF is not the matched filter but the channel filter, so the characteristics does not have to be Gaussian; Butterworth or other characteristics must be acceptable as well as the group delay ripple is little in the passband. The bandwidth should be designed as $BT = 0.7$–1.0 to give good BER performances due to thermal noise in case of common narrow GMSK systems [10], and it has to be increased proportional to the modulation index h if $h > 0.5$. These BPF and mixer work together as the despreading circuit, and the normal GFSK signal is obtained from the BPF.

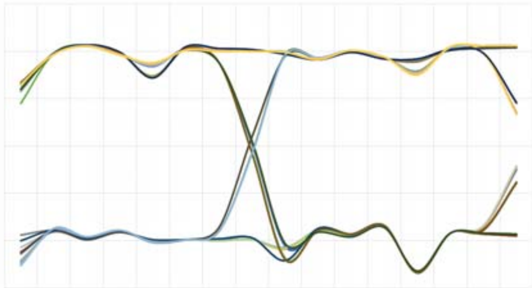
It is clear that the phase rotations due to spreading is removed from the received spread signal by the mixer/multiplier, so the instantaneous phase or frequency completely recovers to the original GFSK signal when thermal noise is ignored. However, envelope fluctuation due to spreading and despreading is remaining at the output of the mixer, and this signal can be seen amplitude-modulated (AM) by $|c_{ss}(t)|^2$, where $c_{ss}(t)$ is the spreading signal in complex form. Since $|c_{ss}(t)|^2$ becomes a periodic signal of the chip-rate frequency f_{chp} and has the DC component, the original GFSK signal is completely recovered after the BPF removes the AM's sidebands due to spreading/despreading, i.e. $\pm f_{chp}$ and its harmonics components. Nevertheless, it should be noted that the BPF arise ISI because the frequency characteristics is not entirely flat within its pass band or the occupation band of GFSK spectrum: this is the same as common (G)FSK transmission case. Apparently, the immunity against interference signals must be the same as the conventional DSSS systems because the spreading modulation is linear operation. The interference remaining in the despread signal depends on the cross correlation between the spreading signal/codes or pulse waveforms of the desired and the undesired signals in the same manner as the conventional ones. This point and other basic properties are evaluated in the following section.

III. SIMULATION RESULTS

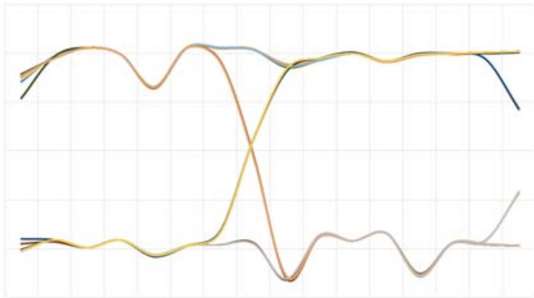
Table I shows the simulation parameters. In this study, we verified the principle of transmission system and evaluated the properties shown below without thermal noise for simplicity.



(a)



(b)



(c)

Fig. 2. Eye patterns at frequency discriminator output, w/o integration: (a) $\phi = 0$, (b) $\phi = \pi/8$, (c) $\phi = \pi/4$.

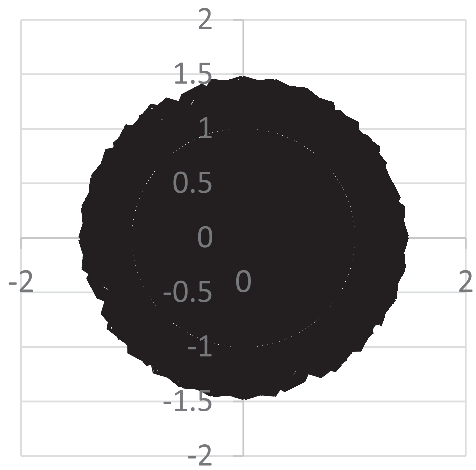


Fig. 3. I-Q trajectory of transmitted signal.

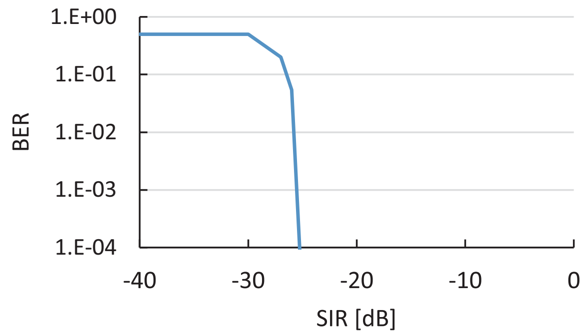


Fig. 4. BER performance due to narrowband interference.

Figure 2 shows the eye patterns of the output of the frequency discriminator,i.e. FM demodulator, where the horizontal axis is two symbol duration. Phase shift due to propagation channel is set to three values: zero, $\pi/8$, and $\pi/4$. From this figure, it can be seen that the same BER performance as common (narrowband) GMSK/GFSK is expected though some light ISI effects are seen. Note that this ISI is due to the Gaussian filters for GFSK baseband signal in the modulator and the BPF of the despreading block.

The I-Q trajectory of the transmitted signal is shown in Fig. 3. A clear space is seen around the origin of the I-Q coordinate, and the trajectory is gathering within a toric area in the radius range of the $\pm 20\%$ from its average. This is because the spreading is done by OQPSK to the constant envelope signal, a continuous phase FSK. Therefore, the envelope is fluctuating only in $\pm 20\%$; the peak-to-average power ratio (PAPR) is seen to be at most 10%, i.e., only $0.4\,\mathrm{dB}$.

Figure 4 shows the BER performance due to a narrow band interference signal assumed as a carrier wave on the same frequency for this simulation. This figure indicates that about $32\,\mathrm{dB}$ process gain is obtained with this system. It can be seen that a non-spreading (narrow band) GMSK system becomes error-free to co-channel interference at the signal-to-interference ratio (SIR) greater than around $6\,\mathrm{dB}$ while this one becomes error-free when $\mathrm{SIR} > -26\,\mathrm{dB}$. On the other hand, the spreading factor can be calculated as $f_{chp}/f_{sym} = 2047$; the process gain in dB is $10\log_{10} 2047 \approx 33\,\mathrm{dB}$. Therefore, this transmission system is confirmed to have the same immunity against interference in this condition and expected to have the immunity to the other kinds of interference, such as DSSS signals spread with other codes or other modulated signals.

IV. Conclusion

In this paper, we propose to adopt the direct sequence spread spectrum (DSSS) transmission system to short range wireless systems. To make the envelope fluctuate little maintaining interference robustness, we employ GFSK and OQPSK for primary and spreading modulations respectively. Our simulation study shows the basic properties of this system: good eye patterns with ISI as light as common non-spread GFSK, PAPR as little as $0.4\,\mathrm{dB}$ of the transmitted signal, and the same immunity to interference. Evaluation of BER performance due to additive white Gaussian noise (thermal noise) and other kinds of interference is our future work. Performance evaluation under frequency selective fading, rake receivers, synchronization and tracking methods of the despreading signal are also going to be studied.

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