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저전력, 저가격 무선통신을 위한 DSSS-FSK 신호의 동기 및 반동기 상관 검파

(Coherent and Semi-Coherent Correlation Detection of DSSS-FSK Signals for Low-Power/Low-Cost Wireless Communication)

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요 약

본 논문에서는 송신기와 수신기의 구현에 있어서 많은 장점을 제공하는 직접 확산-주파수(DSSS-FSK) 변조를 제안한다. 주파수 변조를 사용하여, 직접 확산 통신에서도 주파수합성기(PLL)를 이용한 송신기의 구현이 가능하므로 저전력, 저가격이 가능하다. 또한, 반송파 인접 대역에 정보를 전송하지 않아서 직접변환방식 수신기(DCR)의 구현을 용이하게 한다. 한편, DSSS-FSK 신호를 위한 최적 동기 검파와 반동기 상관 검파 구조를 제안하고 그 성능을 분석한다. 매우 큰 반송파 주파수 오프셋에서도 우수한 비트오율성능을 가지기 위해서, 분할 반동기 상관 검파 구조를 제안하고 성능을 분석한다.

Abstract

For the low power and low cost transceivers, direct sequence spread spectrum frequency-shift keying (DSSS-FSK) is proposed. A transmitter of the DSSS-FSK signal can be implemented by a simple direct modulation using the phase locked loop. Since the DSSS-FSK signal has negligible power around the carrier frequency, low cost direct conversion receiver can be used. Optimum coherent and semi-coherent correlation detection methods for the DSSS-FSK signal are proposed and analyzed. Segmented semi-coherent correlation detection method is proposed to improve the bit error rate performance in the large carrier frequency offset.

Keywords : DSSS, FSK, coherent detection, non-coherent detection, carrier frequency offset.

I. Introduction

Owing to its low implementation cost and high power efficiency, frequency shift keying (FSK) is still widely used in simple and low cost wireless communication systems. The FSK signals can easily be generated by a simple direct modulation using the phase locked loop (PLL), which eliminates the phase and amplitude mismatch in I/Q modulator. For the receiver, both the simple non-coherent detection and high performance coherent detection methods are used. And, since the FSK signal has negligible power around the carrier frequency, direct conversion receiver (DCR) can be used. DCR eliminates external filters and enables to single chip integration.

In this paper, direct sequence spread spectrum (DSSS) of FSK signal (DSSS-FSK) is proposed for a system operating in industrial science and medical (ISM) band. Optimum coherent and semi-coherent correlation detection methods for the DSSS-FSK signal are proposed and analyzed. In addition, segmented semi-coherent correlation detection method is proposed to reduce the performance degradation caused by the large carrier frequency offset.

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DSSS-FSK signal is proposed in Section Ⅱ. In Section Ⅲ, detection methods for the DSSS-FSK signal are proposed. These are optimum coherent detection, semi-coherent correlation detection, and segmented semi-coherent correlation detection. The bit error rate (BER) performances of the DSSS-FSK signal with proposed detection methods are evaluated and compared. Section V presents the conclusion.

Ⅱ. DSSS-FSK Signals

A modulation index of the DSSS-FSK signal must be greater than 1 to have negligible power around the carrier frequency[1]. However, a large modulation index must not be used to prevent wide power spectral density (PSD). Furthermore, the modulation index of the DSSS-FSK signal must be non-integer in order to maintain the characteristics of signal spectrum spreading.

A FSK signal is written as

$$\begin{aligned} s(t) &= \sqrt{2E_b/T_b}\cos(\omega_c t+\phi(t)) \\ &= \sqrt{2E_b/T_b}(\cos(\phi(t))\cos\omega_c t-\sin(\phi(t))\sin\omega_c t) \\ &= \sqrt{2E_b/T_b}(I_B(t)\cos\omega_c t-Q_B(t)\sin\omega_c t),\quad nT_b<t<(n+1)T_b \\ \phi(t) &= 2\pi h\sum_{k=-\infty}^{\infty} I_k q(t-kT_b),\ I_k=\pm 1 \\ q(t) &= \begin{cases} 0 & ,t<0 \\ 1/2\cdot t/T_b & ,0<t<T_b \\ 1/2 & ,t>T_b \end{cases} \end{aligned} \tag{1}$$

Since the phase smoothing response q(t) is equal to 1/2 after t=T_b, the phase of the carrier is then written as

$$\phi(nT_b) = m\pi h,\ m: integer \tag{2}$$

where h denotes the modulation index. If h is a integer, the phase transition during the T_b interval becomes equal to the multiples of π. Hence, $I_B(t)$ in (1) becomes a sinusoidal wave such that the half of the signal power is concentrated in the carrier. Taking these into account, 1.5 is chosen as the optimum modulation index of the DSSS-FSK signal. By the half integer part in the modulation index, the phase of the carrier is equal to 0 or π at every $2T_b$ such that a demodulator can be simplified.

Let us take DSSS-FSK example spreaded using 11-chip Barker code, which is written as

$$\begin{aligned} s(t) &= \sqrt{2E_b/T_b}\cos(\omega_c t+\phi_a(t)),\quad nT_b<t<(n+1)T_b \\ \phi_a(t) &= 2\pi h\sum_{n=-\infty}^{\infty}\left(a_n\sum_{i=0}^{10} b(i)q(t-nT_b-iT_c)\right),\ a_n=\pm 1 \\ q(t) &= \begin{cases} 0 & ,t<0 \\ 1/2\cdot t/T_c & ,0<t<T_c \\ 1/2 & ,t>T_c \end{cases} \end{aligned} \tag{3}$$

where $b(i)$ is the i-th component of 11-chip Barker code [-1 1 -1 -1 1 -1 -1 -1 1 1 1]. T_c denotes the chip period, and is equal to T_b/11. The PSD of the DSSS-FSK signal is shown in Fig. 1. In order to

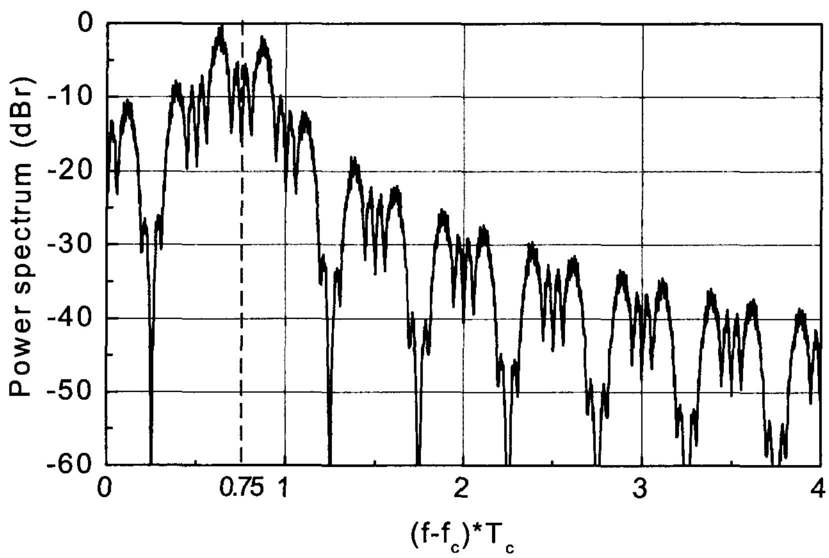

그림 1. DSSS-FSK 신호의 PSD.
Fig. 1. PSD of the DSSS-FSK signal.

calculate the PSD, the method proposed by Anderson and Salz is used. Note that the bandwidth of the DSSS-FSK signal is 11 times wider than that of the non-DSSS FSK signal.

Ⅲ. Receivers for the DSSS-FSK Signals

The proposed DSSS-FSK signal is orthogonal in T_b, which can be shown as below.

$$\begin{aligned}&\int_0^{T_b}\sqrt{2E_b/T_b}\cos(\omega_c t+\phi_i(t))\cdot\sqrt{2E_b/T_b}\cos(\omega_c t+\phi_j(t))dt\\&=E_b/T_b\int_0^{T_b}\cos(\phi_i(t)-\phi_j(t))dt\\&=E_b/T_b\int_0^{T_b}\cos\left(2\pi\left(2h\sum_{k=0}^{10}b(i)q(t-kT_c)\right)\right)dt\\&=E_b/T_b\int_0^{T_c}\cos(6\pi b(0)q(t))dt\\&=E_b/T_b\int_0^{T_c}\cos(\pm 6\pi q(t))dt=0.\end{aligned}\tag{4}$$

The phase of the DSSS-FSK signal at $t=mT_b$ (m:*integer*) is $k\pi/2,(k:\mathit{interger})$ since the phase transition during T_b for this particular example is equal to $\pm 3\pi/2$.

The optimum coherent detection of the DSSS-FSK signal is the Viterbi algorithm based sequence detection[3]. Note that it is complex. However, it should be noted that the phase of the DSSS-FSK signal at $t=2mT_b$ is always $k\pi$, which enables the use of simple matched filter of $2T_b$ period for optimum coherent detection of the DSSS-FSK signal. This is very analogous to the symbol matched filtering in GMSK[4]. The optimum coherent correlation detection of $2T_b$ period for the DSSS-FSK signal is shown in Fig. 2. In Fig. 2, $\phi_{ij}(t),(i,j:0,1)$ denotes the modulated signal's phase of consecutive 2 bit data {i,j}. Since the DSSS-FSK signal is orthogonal in T_b, which is described in (4), the BER performance is identical to that of the optimum coherent detection of the FSK signal.

In general, a coherent detection has a better BER performance than that of the non-coherent detections. However, the BER performance of the coherent detection is greatly dependent on the accuracy of the carrier phase synchronization scheme. This requires that the coherent receiver maintains increased processing power and hardware complexity. The phase noise, caused by oscillators and frequency synthesizers, and Doppler spread, may increase the synchronization time. On the other hand, non-coherent detection methods do not require a

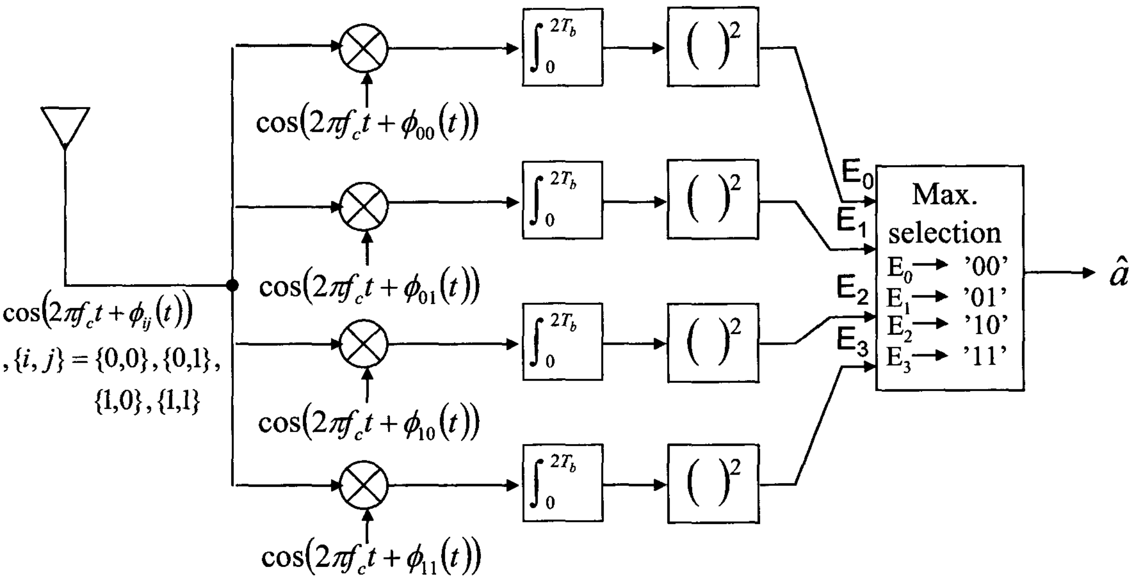

그림 2. DSSS-FSK 신호의 최적 동기 검파기. 정합 필터링은 2Tb 단위로 이루어진다.

Fig. 2. Block diagram of simple optimum coherent correlation detection of the DSSS-FSK signal. Matched filtering is done during 2Tb period.

carrier phase recovery scheme. Therefore, the achievement of the simple and low-power receivers is possible. For the semi-coherent correlation detection, the phase cancellation is added to the coherent detection of the DSSS-FSK signal[5,6]. It is written as:

$$\text{Output of semi-coherent correlation detection} = Max.\{\, C_{ij} \;\; i,j=0,1\}$$

where

$$\begin{aligned} C_{ij} = & \left(\int_0^{T_b} s(t)\cdot\cos(\omega_c t+\phi_{ij}(t))dt\right)^2 \\ & +\left(\int_{T_b}^{2T_b} s(t)\cdot\cos(\omega_c t+\phi_{ij}(t))dt\right)^2 \\ & +\left(\int_0^{T_b} s(t)\cdot\sin(\omega_c t+\phi_{ij}(t))dt\right)^2 \\ & +\left(\int_{T_b}^{2T_b} s(t)\cdot\sin(\omega_c t+\phi_{ij}(t))dt\right)^2 \end{aligned} \quad (5)$$

The BER performance is identical to that of the semi-coherent correlation detection of the non-DSSS FSK signals. In large carrier frequency offset, however, the BER performances of both coherent and semi-coherent detections are severely degraded[5]. However, the semi-coherent correlation detection of the DSSS-FSK signal can have the better BER performance than the semi-coherent correlation detection of the non-DSSS FSK signal. While the matched filter of the non-DSSS FSK signal requires T_b for the orthogonality, the DSSS-FSK signal needs only T_c. Because matched filtering time of the DSSS-FSK signals is in the order of T_c, which is much shorter than T_b, the transient phase change during this time by the carrier frequency offset is much smaller. In this paper, we propose a segmented matched filtering in $2T_c(=2T_b/11)$ period. The segmented semi-coherent correlation detection is shown in Fig. 3 and written as:

$$\text{Output of segmented semi-coherent correlation detection} = Max.\{\, C_{seg,ij} \;\; i,j=0,1\}$$

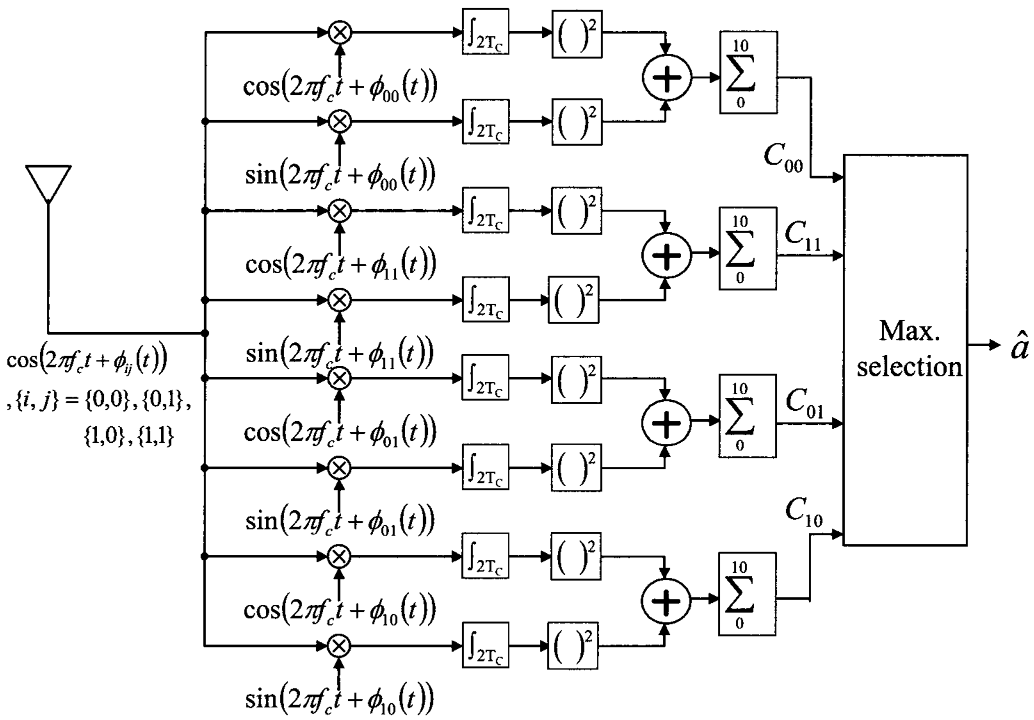

그림 3. DSSS-FSK 신호의 분할 반동기 상관 검파기. 정합 필터링은 2Tc 구간 단위로 이루어지고, 2비트의 상관값을 얻기 위해서 합해진다.

Fig. 3. Block diagram of segmented semi-coherent correlation detection of the DSSS-FSK signal. Matched filtering is done during 2Tc period that is then summed up to get correlation value for 2bit.

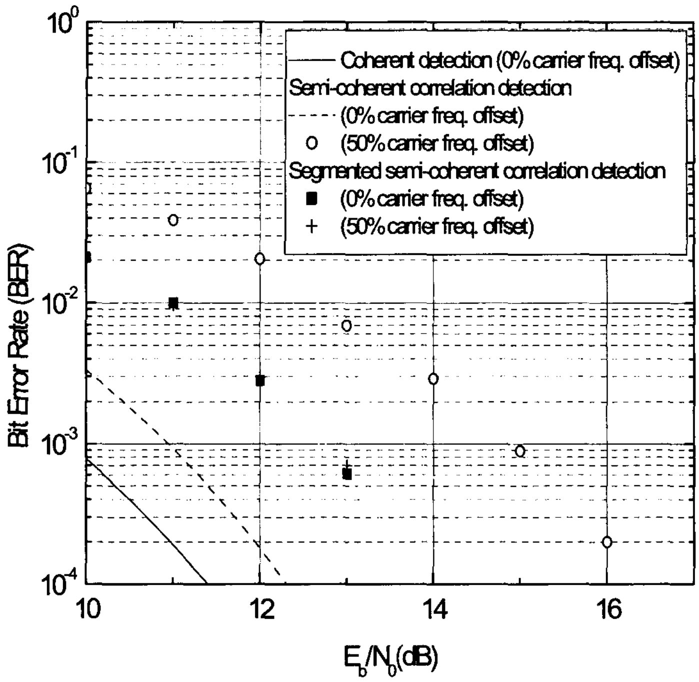

그림 4. 제안된 검파기를 사용한 DSSS-FSK 신호의 비트오율 성능. 실선: non-DSSS FSK 신호와 DSSS-FSK 신호에 대한 동기 검파의 zero 반송파 주파수 오프셋 환경에서의 이론적 성능, 점선: non-DSSS FSK 신호와 DSSS-FSK 신호에 대한 반동기 상관 검파의 zero 반송파 주파수 오프셋 환경에서의 이론적 성능. 분할 반동기 상관 검파기의 비트오율(사각형: 0%의 반송파 주파수 오프셋, 십자가: 50% 반송파 주파수 오프셋)이 2Tb 단위의 반동기 상관 검파기의 비트오율(투명원:50%의 반송파 주파수 오프셋)보다 뛰어남을 보인다.

Fig. 4. BER performances of proposed detection methods of the DSSS-FSK signal. Solid line is the theoretical result of coherent detection of non-DSSS FSK and DSSS-FSK signals with zero carrier frequency offset. Dotted line is the theoretical result of semi-coherent correlation detection of non-DSSS FSK and DSSS-FSK signals. Note 2Tc-based segmented correlation detection (rectangle for 0% carrier frequency offset and cross for 50% carrier frequency offset) gives much better BER performance than the semi-coherent correlation detection of 2Tb period (open circle for 50% carrier frequency offset).

where

$$C_{ij} = \sum_{k=0}^{10} \left[\left(\int_{k*2T_b/11}^{(k+1)*2T_b/11} s(t) \cdot \cos(\omega_c t + \phi_{ij}(t)) dt \right)^2 + \left(\int_{k*2T_b/11}^{(k+1)*2T_b/11} s(t) \cdot \sin(\omega_c t + \phi_{ij}(t)) dt \right)^2 \right] \quad (6)$$

Ⅳ. Numerical Results

Fig. 4 shows the BER performances of proposed detection methods for the DSSS-FSK signal in AWGN channel. The coherent correlation detection of the DSSS-FSK signal has the same performance as the non-DSSS FSK signals as it should do. Same is true for the semi-coherent correlation detection methods for the zero carrier frequency offset. In Fig. 4, it is shown that when there is 50% carrier frequency offset over data rate, the segmented semi-coherent correlation detection has better BER performance than the semi-coherent correlation detection of $2T_b$ period.

Ⅴ. Conclusion

In this paper, the DSSS-FSK modulation has been proposed for the low power and low cost transceivers. The DSSS-FSK modulation makes it possible to use a simple direct modulation with PLL, and DCR.

It has also been proposed optimum coherent and semi-coherent correlation detection methods for the DSSS-FSK signal. It has been shown that the BER performances of the coherent detection and the semi-coherent correlation detection methods of the DSSS-FSK signal are identical to those of the non-DSSS FSK signals. Simulation result has shown that the segmented semi-coherent correlation detection has better BER performance than the semi-coherent correlation detection of $2T_b$ period at large carrier frequency offset.

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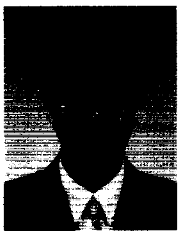

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