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Analysis of the Chip Waveforms for LPI Communication

Jun-Ho Maing[1] · Heung-Gyoon Ryu[1] · Dae-Il Lee[2]

Abstract

DAM(Delay-And-Multiplier) intercept receiver usually detects the symbol rate of the transmitted DS spread spectrum signal for the feature extraction. It is important for secure communication to reduce the normalized output signal-to-noise ratio that is generated at the DAM intercept receiver as a measure of detectability. In this paper, several kinds of chip waveforms are novelly analyzed for LPI(Low-Probability of Intercept) communication against DAM intercept receiver. Consequently, it is shown that the rectangular chip waveform shows the best LPI performance in the bandwidth of $2/T_c$, $4/T_c$, and $6/T_c$. Except the rectangular waveform, kaiser chip waveform show better LPI performance than the other waveforms in the bandwidth of $4/T_c$ and $6/T_c$.

Key words : LPI(Low-Probability of Intercept), Symbol Rate Line, Chip Waveform and DAM(Delay-And-Multiplier) Receiver.

Ⅰ. Introduction

Unlike the commercial communication, there may be an intentional interception of the information in the secure communication. For this reason, the DS- SS (direct sequence spread spectrum) communication methods against this interception have been widely investigated[1]~[5]. Chip waveform used in DS-SS system is very important factor to the LPI communication. There are several interception methods. First one is the radiometer to identify transmission signal detection by analyzing the signal energy. Second one is the DAM (Delay-And-Multiplier) to detect the symbol rate. Third one is the frequency doubler to detect the carrier frequency[1]. In [2], it was shown that the LPI performance could be improved by Nyquist pulse shaping of the baseband signal since the magnitude of the symbol rate line is reduced at the output of the DAM receiver. In [3], it was shown that the LPI performance is degraded under the multi-path environment. In [4], the LPI performance was analyzed in the condition that the input signals of the DAM receiver were BPSK/ OQPSK-modulated signal. The results of the paper show that the LPI performance for BPSK is identical to QPSK and inferior to OQPSK.

In this paper, we consider the DAM as the feature detector to extract the symbol rate of a digitally modulated signal[5]. The analyses of LPI performance for several waveforms - rectangular, half-sine, TDRC (Time Domain Raised Cosine), Blackman, Kiser, and SFSK - are novelly presented when the intercept receiver has the DAM structure. LPI performances of each chip waveform are compared in the three different bandwidths($2/T_c$, $4/T_c$, $6/T_c$,). For the fair comparison, the transmitted power of each waveform is set to be same within the assigned bandwidth.

Ⅱ. Detector Model and Signal Analysis

A block diagram of a simplified delay and multiply receiver is shown in Fig. 1. This receiver consists of pre-filter(BPF) with the bandwidth W, delay device, multiplier, and post-filter(BPF) that has sharp bandwidth to detect the symbol rate line. The pre-filter is assumed to have an ideal rectangular band-pass transfer function with cutoff frequencies $f_s \pm W/2$. The post-filter is called a complex correlator that serves as a narrow band-pass filter centered about the wanted rate line.

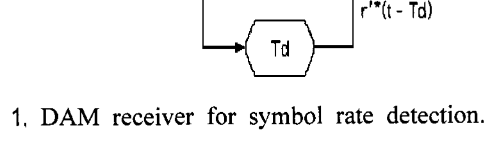

Fig. 1. DAM receiver for symbol rate detection.

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[1] Dept. of Electronic Engineering and Research Institute of Computer, Information & Communication, Chungbuk National University.
[2] Satellite System Department, 4th Development Center, Agency for Defense Development.

The total observation time is T. The delay time is T_d. The DAM receiver tries to find the optimum value of W and T_d to maximize the symbol rate line output.

The measure of detectability is the signal-to-noise ratio(SNR_o) of the symbol rate line at the output of the post-filter. BPSK-modulated signal is assumed to use as an input signal of the DAM receiver.

$$r(t) = s(t) + n(t)\,. \tag{1}$$

$$s(t) = A\sum_{k=-\infty}^{\infty} a_k p(t-kT_s)\,. \tag{2}$$

In eq. (2), $\{a_k\}$ is an independent symbol sequence that takes on value of ± 1. $p(t)$ is a pulse function with unit energy. A is amplitude of the signal and T_S is the symbol period.

$$r'(t) = s'(t) + n'(t) = A\sum_{k=-\infty}^{\infty} a_k p'(t-kT_s) + n'(t)\,. \tag{3}$$

$$y(t) = r'(t)r'^{*}(t-T_d)\,. \tag{4}$$

The post-filter operates as a narrow band-pass filter with bandwidth $B=1/T_s$ centered at the symbol rate[4]. Thus, the power spectrum of the DAM output is denoted by $S_y(f)$ which can be written as

$$S_y(f) = S_s(f) + S_{s\times s}(f) + S_{s\times n}(f) + S_{n\times n}(f) \tag{5}$$

where $S_s(f)$ consists of the discrete spectral line, $S_{s\times s}(f)$ is the signal self-noise spectrum, $S_{s\times n}$ is the signal-times-noise spectrum, and $S_{s\times n}(f)$ is the noise-times-noise spectrum.

The rate line at the symbol rate can be sought by passing $y(t)$ through a band-pass filter centered at $f_s=1/T_s$. Let the equivalent noise bandwidth of the post-filter, B, which should be narrow enough so that the various noise spectra in eq. (5) can be assumed constant in the vicinity of the rate line. Then, the output signal-to-noise ratio is defined as

$$SNR_o = \frac{S_s(f_s)}{B[S_{s\times s}(f_s) + S_{s\times n}(f_s) + S_{n\times n}(f_s)]}\,\cdot \tag{6}$$

The input signal-to-noise ratio and the normalized parameters are defined as follows.

$$\frac{A^2T_s}{N_o} = \frac{E_s}{N_o},\; B_n = BT_s,\; W_n = WT_s,\; T_{dn} = T_d/T_c\,. \tag{7}$$

By using the eq. (7), eq. (6) can be rewritten as (8)

$$SNR_o = \left(\frac{E_s}{N_o}\right)^2 \frac{k_s}{B_n\left[k_{nn} + \left(\frac{E_s}{N_o}\right)k_{sn} + \left(\frac{E_s}{N_o}\right)^2 k_{ss}\right]} \tag{8}$$

where k_s, K_{ss}, K_{sn}, and K_{nn} are normalized power spectrum coefficients, B_n is the normalized post-filter bandwidth which is multiplied by the symbol duration. Since the main interest in this DAM receiver is k_s component and input signal-to-noise ratio is very small, the self-noise(K_{ss}) and signal-times-noise(K_{sn}) can be ignored.

$$SNR_o = \left(\frac{E_s}{N_o}\right)^2 \frac{k_s}{B_n[k_{nn}]}\,. \tag{9}$$

where $$k_s(f) = \sum_{n=-\infty}^{\infty}\left|Q\left(\frac{n}{T_s};T_d\right)\right|^2 \cdot \delta\left(f-\frac{n}{T_s}\right), \tag{10}$$

$$k_{nn}(f) = \frac{WT_s}{2f_s^2}\left(1-\frac{|f|}{2W}\right)\cdot\left\{1+\sin c\left[4WT_d\left(1-\frac{|f|}{2W}\right)\right]\right\}, \tag{11}$$

$$|Q(f;T_d)|^2 = \left|\int_{-\infty}^{\infty} P(f+\lambda)\cdot P^*(\lambda)\cdot e^{-j2\pi\lambda T_d}\,d\lambda\right|^2. \tag{12}$$

Ⅲ. Chip Waveforms

The considered waveforms are 6 kinds of chip waveform. First of all, it is assumed that total transmitted power over entire frequency band is identical for each waveform. Next, the normalization factor will be used for each analysis bandwidth.

A. Rectangular

$$p(t) = 1, \qquad 0 \le t \le 1\,. \tag{13}$$

B. Half-sine

$$p(t) = \sqrt{2}\sin\left(\frac{\pi t}{T_c}\right),\quad T_c : Chip\ duration\,. \tag{14}$$

C. TDRC(Time-Domain Raised Cosine)

$$p(t) = \sqrt{\frac{2}{3}\left[1-\cos\left(\frac{2\pi t}{T_c}\right)\right]}\,. \tag{15}$$

D. Blackman

$$p(t) = 1.8119\left[0.42 - 0.5\cos\left(\frac{2\pi t}{T_c}\right) + 0.08\cos\left(\frac{4\pi t}{T_c}\right)\right]. \tag{16}$$

E. Kaiser

$$p(t) = \frac{2.1137 I_0\left(\beta\pi\sqrt{1-\left(\frac{t-T_c/2}{T_c}\right)^2}\right)}{I_0(\beta\pi)},\; \beta = 20\,. \tag{17}$$

F. SFSK(Sinusoidal FSK)

$$p(t)=\sqrt{2}\sin\left(\frac{\pi t}{T_c}-\frac{1}{4}\sin\left(\frac{4\pi t}{T_c}\right)\right). \tag{18}$$

The responses of time and frequency domain are shown in Fig. 2 and 3. Since the frequency domain responses of each waveform are different, the frequency bandwidth including the same power is also different. Therefore, the normalized factors are used for the fair comparison that the transmitted power is the same within a given bandwidth. This is because the received power at DAM interceptor should be same for each waveform.

Ⅳ. Numerical Results and Discussion

In this section, the LPI performance for various waveforms is analyzed in terms of the normalized output SNR in DAM receiver. The optimum value of T_{dn} is 0.5 for rectangular waveform when BPSK modulation scheme is used [2].

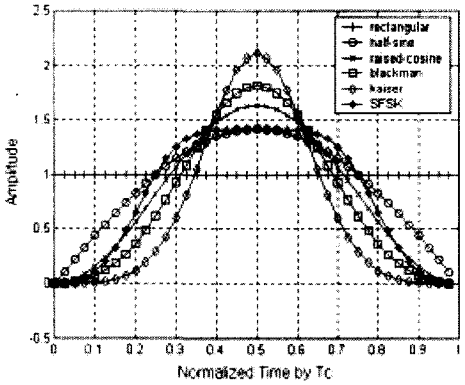

Fig. 2. Chip waveforms in time domain.

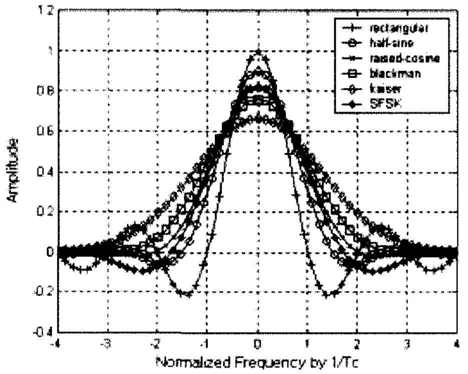

Fig. 3. Chip waveforms in frequency domain.

A. For $2/T_c$ Bandwidth

The LPI performance analysis for $2/T_c$ bandwidth is shown in Fig. 4. On the whole, rectangular waveform shows better LPI performance than the other ones.

B. For $4/T_c$ Bandwidth

Fig. 5 shows the LPI performance analysis for $4/T_c$ bandwidth. In terms of DAM receiver optimization, W_n for rectangular has the interval of about(from W_n =0.772 to W_n=2.0) within 1[dB] compared with the normalized maximum output SNR value. For the others, however, the interval is about(from W_n=0.8186 to W_n=1.1590). Namely, it is more difficult for the other waveforms to optimize the pre-filter bandwidth than that of rectangular. Furthermore, Kaiser chip waveform shows better LPI performance than the other waveforms except the rectangular waveform.

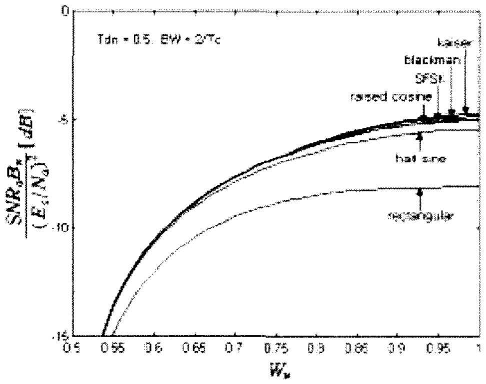

Fig. 4. W_n versus normalized output SNR for $2/T_c$ bandwidth.

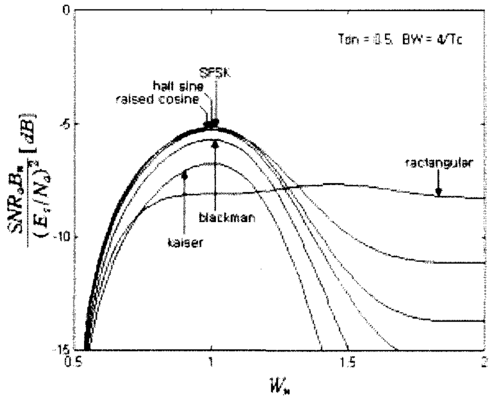

Fig. 5. W_n versus normalized output SNR for $4/T_c$ bandwidth.

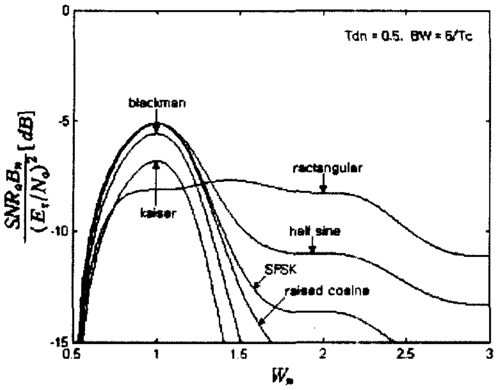

Fig. 6. W_n versus normalized output SNR for $6/T_c$ bandwidth.

Table 1. Maximum normalized output SNR in the bandwidth of $4/T_c$ and $6/T_c$.

	Maximun $\frac{SNR_oB_n}{(E/N_0)^2}$ [dB]					
Bandwidth	Rectangular	Half-sine	TDRC	Blackman	Kaiser	SFSK
$2/T_c$	- 8.13	- 5.53	- 5.1	- 4.9	- 4.8	- 5.05
$4/T_c$	- 7.65	- 5.27	- 5.27	- 5.71	- 6.17	- 5.13
$6/T_c$	- 7.65	- 5.01	- 5.01	- 5.44	- 6.81	- 5.05

C. For $6/T_c$ Bandwidth

Fig. 6 shows the LPI performance analysis for $6/T_c$ bandwidth. In terms of DAM receiver optimization, W_n for rectangular has the interval of about(from W_n= 0.772 to W_n=2.297) within 1[dB] compared with the normalized maximum output SNR. For the others, however, the interval is about(from W_n=0.8186 to W_n= 1.1589). Namely, it is easier for rectangular to optimize the pre-filter bandwidth than other waveforms. Furthermore, Kaiser shows the best LPI performance.

V. Conclusions

In this paper, the LPI performance of several chip waveforms is analyzed. DAM receiver is considered which is generally used for chip rate detection. Since the PSD of each waveform is different, the analysis is made by setting the three cases of bandwidth as $2/T_c$, $4/T_c$ and $6/T_c$. Also, it is assumed that the transmitting power within useful bandwidth is same for fair comparison. Consequently, it is shown that the rectangular chip waveform shows the best LPI performance in the bandwidth of $2/T_c$, $4/T_c$ and $6/T_c$. And except rectangular waveform, kaiser chip waveform show better LPI performance than the other waveforms in the bandwidth of $4/T_c$ and $6/T_c$.

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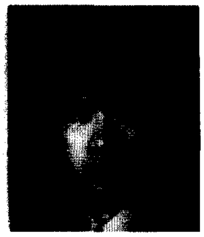
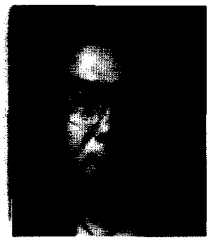
Jun-Ho Maing



was born in Seoul, Republic of Korea, 1977. He received the B.S. degrees in electronic engineering from Chungbuk National University in 2003. He is currently working toward M.S. degree at the Department of Electronic Engineering, Chungbuk National University, Republic of Korea. Her research interests include digital communication system, spread spectrum technique and digital signal processing for communication.

Heung-Gyoon Ryu



was born in Seoul, Republic of Korea, 1959. He received the B.S. and M.S. and Ph.D. degrees in electronic engineering from Seoul National University in 1982, 1984 and 1989. Since 1988, he has been with Chungbuk National University, Korea, where he is currently Professor of Department of Electrical, Electronic and Computer Engineering and Chief of RICIC(research institute of computer, information communication center) in Chungbuk National University. His main research interests are digital communication systems, communication circuit design, spread spectrum system and communication signal processing. Since 1999, he has worked as reviewer of the IEEE transaction paper. He was a winner of '2002 ACADEMY AWARD' from the Korea Electromagnetic Engineering Society, Korea.

Dae-Il Lee

was born in Seoul, Republic of Korea, 1972. He received the B.S. and M.S. degrees in electronics engineering from University of Seoul in 1995 and 1997. Since 1997, he has been working for Agency for Defense Development. His main research interests are digital communication systems, communication circuit design, spread spectrum system and communication signal processing.