Correlative Encoded Frequency Shift Keying (CEFSK) Modulation Technique

Kee-Hoon Lee and Jong-Soo Seo

Abstract: **A new power and bandwidth efficient modem technique-Correlative Encoded FSK (CEFSK) is proposed. CEFSK has a spectral efficiency comparable to Gaussian filtered FSK (GFSK), and it achieves 0.7dB E_b/N_0 improvement at bit error rate (BER) of 1×10^{-4} over GFSK in an additive white Gaussian noise (AWGN) channel and 3.0dB improvement in a Rayleigh fading channel**

Index Terms: **CEFSK, GFSK, modem technique.**

Table 1. Current digital mobile and cellular systems.

Standard	Modulation scheme
GSM	GMSK $BT = 0.3,\ h = 0.5$
CT2	GFSK $BT = 0.3,\ h = 0.28–0.35$
Bluetooth, DECT	GMSK $BT = 0.5,\ h = 0.5$
"Proposed"	CEFSK $A = 0.7–1.0,\ h = 0.28–0.35$

I. INTRODUCTION

Minimum Shift Keying (MSK) is a form of FSK, with modulation index $h = 0.5$ yielding the minimum frequency separation for orthogonal signaling over a signaling interval of T [1]. Premodulation filtering is employed to improve the bandwidth efficiency of the modulated carrier. Murota and Hirade proposed the use of a premodulation Gaussian low pass filter (GLPF) to shape the spectrum of MSK signal, that is, to generate Gaussian filtered MSK (GMSK) signal [2]. In Gaussian prefiltered FSK systems (GFSK), the modulation index h can be chosen in a wide range, for example $0.1 \leq h \leq 1.0$, in several wireless applications. GMSK is a family of GFSK, where h is preset to 0.5, and the GLPFs are characterized by 3dB bandwidth (B) of the filter and bit-duration (T) product BT. A smaller BT leads to more compact spectrum at the expense of more ISI. Hence, the choice of BT is a compromise between spectrum efficiency and BER performance. GSM employs GMSK, where BT is 0.3 and h is 0.5. Bluetooth employs GFSK, where BT is 0.5 and h is 0.28–0.35 [3]. Some of current digital mobile and cellular systems are summarized in comparison with CEFSK in Table 1. Motivated by BER performance improvement without increasing hardware complexity, we propose a new modem technique that has reduced ISI as well as spectral characteristics comparable to GFSK.

II. CORRELATIVE ENCODER

Correlations and/or smooth phase transitions between modulating signals give compact transmit power spectrum [2], [4]. A correlative encoded (CE) baseband signal can be generated by superposing double interval impulse responses of premodulation LPF [4]. An impulse response of correlative encoder is determined to generate signals free of ISI and timing jitter, and also to result in continuous and smooth phase transitions of the modulated carrier. The baseband CE signal of CEFSK is expressed as

$$y(t) = \sum_k \left[a_k s(t - kT) + a_{k+1} s(t - (k+1)T)\right], \quad (1)$$

where $a_k,\ a_{k+1} = \{\pm 1\}$ and $s(t)$ is an impulse response of the CE signal processor defined as

$$s(t) = \frac{(1 + \cos \pi t/2)}{2} - \frac{(1 - A)(1 - \cos \pi t/2)}{2}. \quad (2)$$

$-T \leq t \leq T$, $T (= 1/f_b)$ is the data bit duration and 'A' is an amplitude parameter of the CE signal which is a constant within $[0.5,\ 1.5]$ that controls the modulating pulse shape and transmit power spectrum. To obtain a signal free of ISI and timing jitter, the impulse response of the correlative encoder must meet the following conditions:

$$s(t) = s(-t), \quad (3)$$

$$s(T) = s(-T) = 0,\ 0 \leq t \leq T. \quad (4)$$

An alternative way of generating the above signal is using a PROM look-up table as defined in Table 2. An increase of 'A' leads to more compact spectrum but at the same time more ISI. Note that, regardless of the value of 'A', ISI introduced by the CE signal processor is limited within the corresponding bit interval [4]. Whereas in GFSK, GLPF introduced ISI extends to adjacent bits [5]. In Fig. 1, the impulse responses of a CE signal processor are compared to that of a GLPF with $BT = 0.5$.

III. CEFSK TRANSMITTER

A transmitted CEFSK signal can be written as [2]

$$p(t) = \mathrm{Re}\left\{ \sqrt{\frac{2E}{T}} \exp\left\{ j2\pi \left\{ f_c t + h \int_{-\infty}^{t} y(\tau) d\tau \right\} \right\} \right\}, \quad (5)$$

where E is the energy per symbol, T is the data bit duration, f_c is the carrier frequency, and $y(t)$ is the output of correlative encoder. For the purpose of comparison, we take $A = 0.8$

Manuscript received March 22, 2003; approved for publication by Shigeaki Ogose, Division II Editor, August 19, 2003.

The authors are with the Department of Electrical & Electronic Engineering, Yonsei University, Seoul, Korea, email: {powerlee, jsseo}@yonsei.ac.kr.

This paper was supported by University IT Research Center Project.

1229-2370/04/$10.00 © 2004 KICS

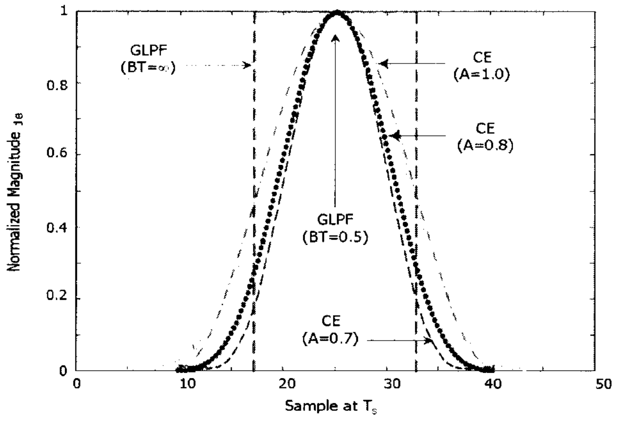


Fig. 1. Impulse responses of CE signal processor and GLPF.

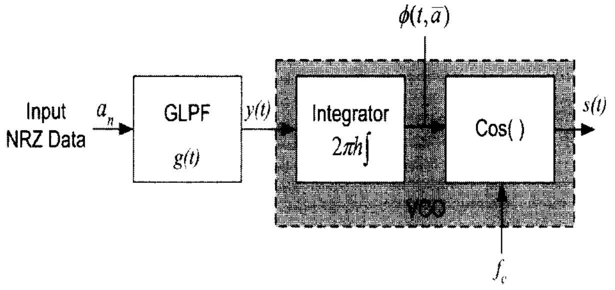


Fig. 2. Block diagram of CEFSK transmitter.

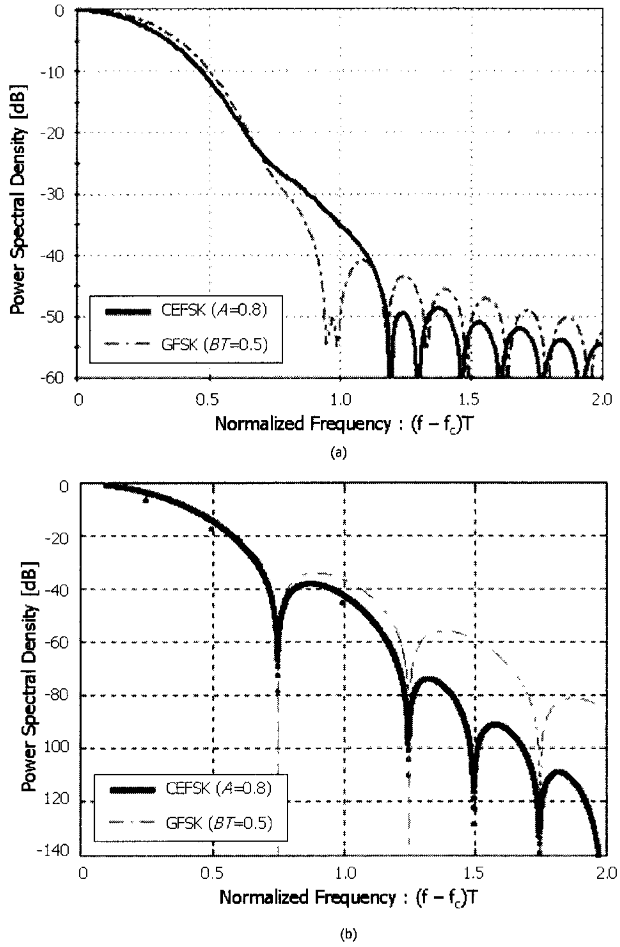


Fig. 3. (a) Simulated power spectra of GFSK and CEFSK for h=0.35.(b) Analytical power spectra of GFSK and CEFSK.

Table 2. Look-up table to generate CE baseband signal.

NRZ input data		CE output signal
a_k	a_{k+1}	$y(t)$
-1	-1	$y_1 = -A - (1 - A)\cos(2\pi t/T)$
-1	-1	$y_2 = -\cos(\pi t/T)$
1	-1	$y_3 = \cos(\pi t/T)$
1	1	$y_4 = A + (1 - A)\cos(2\pi t/T)$

for CEFSK, which provides the best BER performance [4], while obtaining a spectral efficiency comparable to GFSK with $BT = 0.5$. The block diagram of a CEFSK transmitter is shown in Fig. 2. In both CEFSK and GFSK, the lower value of h improves its spectral efficiency at the cost of higher BER degradation. Both CEFSK and GFSK are based on MSK and they are developed to improve the spectral properties of MSK. Thus, the normalized power spectral density (PSD) of the equivalent baseband signal of CEFSK is given by

$$\begin{aligned} C(f) &= H_{CE}(f)\cdot H_M(f) \\ &= \left\{\left(\frac{T}{1-4f^2T^2}+\frac{(A-1)T}{1-f^2T^2}\right)\frac{\sin 2\pi fT}{2\pi fT}\right\} \\ &\quad\times\left\{\frac{16}{\pi^2}\left[\frac{\cos 2\pi fT}{1-16f^2T^2}\right]\right\}, \qquad (6)\end{aligned}$$

where $H_{CE}(f)$ and $H_M(f)$ are the transfer function of the CE signal processor [4] and the normalized PSD of MSK, respectively. Fig. 3 shows the simulated and the analytical power spectra of CEFSK in comparison with those of GFSK. It can be seen that CEFSK with $A = 0.8$ has a spectral efficiency comparable to GFSK with $BT = 0.5$.

IV. CEFSK RECEIVER

The received CEFSK signal r(t) can be written as

$$\begin{aligned} r(t) &= m(t)c(t) + n(t) \\ &= \sqrt{\frac{2E}{T}}C(t)e^{j(\phi(t,\bar{a})+\phi_c(t))} + N(t)e^{j\phi_n(t)}, \qquad (7)\end{aligned}$$

where $c(t)$=$C(t)e^{j\phi_c(t)}$ is the channel transfer function, $n(t)$= $N(t)e^{j\phi_n(t)}$ is the AWGN, and $m(t) = \sqrt{2E/T}e^{j\phi(t,\bar{a})}$ is the equivalent complex envelop of the transmitted signal [3]. Among the various signal detection techniques, we assume 1-bit differential detection (1DD) employed at the receiver, the complex input signal is multiplied by its complex conjugate which is delayed by a bit-duration. The resulting signal is

$$r_1(t) = \cos(\phi_i - \phi_{i-1}) + \sin(\phi_i - \phi_{i-1}), \qquad (8)$$

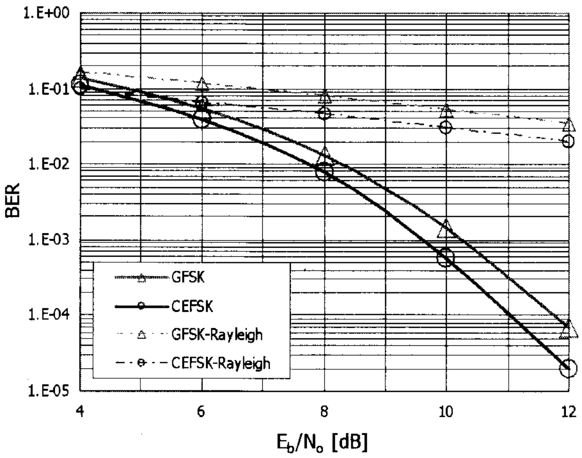


Fig. 4. BER performance of CEFSK (A=0.8) and GFSK (BT=0.5).

where $\phi_i - \phi_{i-1} (= \Delta\Phi)$ represents the variation of the phase in a bit-duration. The threshold detector then decides that a "1" is sent if $\Delta\Phi$ is greater than or equal to zero, and a "-1" otherwise. For CEFSK with $A = 0.8$ and GFSK with $BT = 0.5$, the calculated values of $\Delta\Phi$ corresponding to consecutive input data patterns have been tabulated in Table 3. For instance, when the input data pattern $(a_{k-1},\ a_k,\ a_{k+1})$ is $(1,\ -1,\ 1)$, the values of $\Delta\Phi$ are 39.8° and 34.2° for CEFSK ($A = 0.8$) and GFSK ($BT = 0.5$), respectively. This increment of $\Delta\Phi$ improves the BER performance.

V. BER PERFORMANCE

Based on the above discussion, the average error probability of 1-bit differential detected signal is given by [5]

$$P_b = \frac{1}{2}\overline{\Pr\{\sin\Delta\Phi(T) < 0 \mid a(t), \text{“1” sent}\}} + \frac{1}{2}\overline{\Pr\{\sin\Delta\Phi(T) > 0 \mid a(t), \text{“}-1\text{” sent}\}}, \qquad (9)$$

In (9), $a(t)$ and the overbar denote the effective transmitted signal waveform and statistical averaging over all equally likely input data sequences, respectively.

BER performance of CEFSK as well as GFSK is evaluated by using SPW (Signal Processing Work System). The demodulated signal is passed through a GLPF. For CEFSK and GFSK, the optimum BT product of the receive GLPF is 1.1, and the GLPF is assumed to be phase equalized [5]. Fig. 4 illustrates the BER performance of CEFSK and GFSK. It is noticed that CEFSK outperforms GFSK by 0.7dB in an AWGN channel and 3.0dB in a Rayleigh fading channel at BER of 1×10^{-4}.

VI. CONCLUSIONS

A new power and bandwidth efficient modem technique-CEFSK is proposed. CEFSK has a spectral efficiency comparable to GFSK, and outperforms GFSK by 0.7dB at BER of 1×10^{-4} in an AWGN channel and 3.0dB in a Rayleigh fading channel.

Table 3. Differential phase angles $\Delta\Phi$ of 1DD corresponding to NRZ input data.

NRZ input data			**$\Delta\Phi$ (in degrees)**	
a_{k-1}	a_k	a_{k+1}	**CEFSK(A=0.8)**	**GFSK(BT=0.5)**
1	1	1	54.2	63.0
1	1	−1	47.0	48.6
−1	1	1	47.0	48.6
−1	1	−1	39.8	34.2
1	−1	1	−39.8	−34.2
1	−1	−1	−47.0	−48.6
1	−1	1	−47.0	−48.6
−1	−1	−1	−54.2	−63.0

REFERENCES

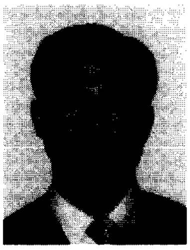
[1] J. G. Proakis, *Digital Communications*, 3rd ed., New York, McGraw-Hill, 1995.

[2] K. Murota and K. Hirade, "GMSK modulation for digital mobile radio telephony," *IEEE Trans. Commun.*, vol. COM-29, pp. 1044–1050, July 1981.

[3] C. H. Park *et al.*, "Channel estimation and DC-offset compensation schemes for frequency-hopped Bluetooth networks," *IEEE Commun. Lett.*, vol. 5, no. 1, pp. 4–6, Jan. 2001.

[4] J.-S. Seo and K. Feher, "SQAM - a new superposed QAM modem technique," *IEEE Trans. Commun.*, vol. COM-33, pp. 296–300, Mar. 1985.

[5] M. K. Simon and C. C. Wang, "Differential detection of Gaussian MSK in a mobile radio environment," *IEEE Trans. Veh. Technol.*, vol. VT-33, pp. 307–320, Nov. 1984.



Kee-Hoon Lee received the B.S. degree from the ROK Air Force (ROKAF) Academy, Cheong-ju, Korea, in 1987 and the M.S. degree from University of Dayton, USA, in 1996. Since joining the ROKAF in 1987, he has been working as an Inf. & Commun. officer. From 1999, he is working toward his Ph.D. degree in the department of electrical and electronics engineering, Yonsei University. His current research interests are the areas of digital modems, satellite communication systems, and standard time & frequency dissemination systems.

Jong-Soo Seo received the B.S. degree in electronics engineering from Yonsei University, Seoul, Korea, in 1975, and the M.S. and the Ph.D. degrees in electrical engineering from University of Ottawa, Canada in 1983 and 1988, respectively. He worked in IDC and CAL, Canada for digital satellite and broadcasting systems for 6 years. Since 1995 he has been a professor at the School of electrical and electronics engineering, Yonsei University, Seoul, Korea. Since Nov. 2001, he has been a director of the Center for Advanced Broadcasting Technology. His current research interests include digital transmission and broadcasting technologies.