Performance Comparison of FH/MC DS-CDMA with Single- and Multi-carrier DS-CDMA[1]

Lie-Liang Yang, Lajos Hanzo

Dept. of Electronics and Computer Science, University of Southampton, SO17 1BJ, UK.
E-mail: lh@ecs.soton.ac.uk, http://www-mobile.ecs.soton.ac.uk

***Abstract**: In this contribution we review the slow frequency hopping multicarrier direct-sequence code-division multiple-access (SFH/MC DS-CDMA). Then, the system's performance is evaluated and compared to that of the conventional single-carrier (SC) DS-CDMA and MC DS-CDMA, under the assumptions of constant system bandwidth and of constant transmitted signal power. Both random and 'uniform' FH are considered and their advantages as well as disadvantages are investigated. We assume that the system operates in a multipath Nakagami-m fading environment and a maximum ratio combining (MRC) assisted RAKE receiver is used for demodulation.*

Introduction

With the expected substantial increase of Internet users and other new services the provision of high-speed access is an important requirement in the future generations of wireless systems. Consequently, broadband systems having bandwidths significantly wider than that of the 3rd-generation (3G) systems are sought for meeting future requirements. Hence, compatibility with both the emerging Broadband Access Networks (BRAN), which have opted for a multi-carrier, Orthogonal Frequency Division Multiplexing (OFDM) based solution and the existing 2nd- and 3rd-generation CDMA systems is an important consideration. Furthermore, with the deployment of the 3rd generation mobile communication systems, which can provide a wider variety of services with higher QoS than the 2nd generation systems users will migrate from the 2nd generation's band to the 3rd generation's band. Consequently, the bandwidth assigned for wireless mobile communications cannot be evenly and efficiently exploited, unless new multiple access schemes are employed.

A potential candidate multiple access scheme meeting these requirements has been proposed and investigated in [1]-[4]. The multiple-access scheme is constituted by frequency-hopping (FH) based multicarrier DS-CDMA (FH/MC DS-CDMA), where the entire bandwidth of future systems can be divided into a number of sub-bands and each sub-band can be assigned a subcarrier. FH/MC DS-CDMA systems are software re-configurable systems. According to the prevalent service requirements, the set of legitimate subcarriers can be distributed in line with the instantaneous information rate requirements. FH techniques are employed for each user, in order to evenly occupy the whole system bandwidth and to efficiently utilize the available frequency resources. Specifically, slow FH, fast FH or adaptive FH techniques can be utilized depending on the system's design and the state-of-the-art. In FH/MC DS-CDMA systems the sub-bands are not required to be of equal bandwidth. A subcarrier could deliver a narrow-band IS-95 type service or - similarly to the emerging multi-carrier assisted cdma2000 system [5] - it could invoke a number of carriers, while employing a variety of different spreading factors. Hence existing 2nd- and 3rd-generation CDMA systems can be supported using one or more subcarriers, consequently simplifying the frequency resource management and efficiently utilizing the entire bandwidth available. This regime can also remove the rigid spectrum segmentation of existing 'legacy' systems, while ensuring compatibility with future

[1] This work has been carried out in the framework of the IST project IST-1999-12070 TRUST, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues from Siemens AG, France T\'el\'ecom - CNET, Centre Suisse d'Electronique et de Microtechnique S.A., King's College London, Motorola Ltd, Panasonic European Laboratories GmbH, Robert Bosch GmbH, Telefonica Investigation Y Desarrollo S.A. Unipersonal, Toshiba Research Europe Ltd., TTI Norte S.L., University of Bristol, University of Southampton.

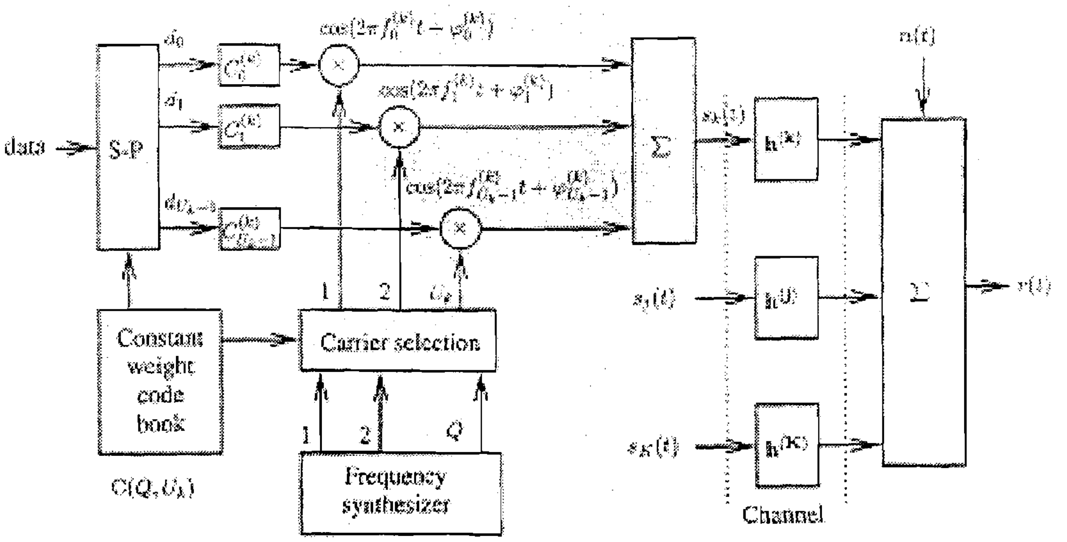

Fig. 1. Transmitter and channel block diagram of the frequency-hopping multicarrier DS-CDMA system.

BRAN and un-licensed systems. Furthermore, a number of sub-channels associated with variable processing gains can be employed, in order to support various services requiring low- to very high-rate transmissions, for example for wireless Internet access.

In this treatise we study a FH/MC DS-CDMA system employing slow FH - resulting in a SFH/MC DS-CDMA system -- and binary modulation. The system operates in a multipath fading environment, and a maximum ratio combining (MRC) assisted RAKE receiver is used. The system's performance is evaluated over the range of Nakagami-m multipath fading channels, which closely model various multipath channels, exhibiting probability density functions (pdf) spanning the range from Rayleigh fading channels to non-fading Gaussian channels by varying a single parameter, namely m, from one to infinity [6][7]. In contrast to [1]-[4], in this paper the performance of the proposed SFH/MC DS-CDMA system is investigated and compared to that of conventional single-carrier DS-CDMA (SC DS-CDMA) systems as well as to conventional MC DS-CDMA systems actively using all the available subcarriers, under the assumption that the receiver of the SFH/MC DS-CDMA scheme has the explicit knowledge of the FH patterns. Two different SFH schemes are considered. The first is a random FH scheme, where each user hops independently according to its FH pattern. By contrast, in the second scheme each user's FH pattern relies on explicit side information, in order that all subcarriers of the system are uniformly occupied and that the multiuser interference is minimized. Hence, in our forthcoming discourse the former FH scheme is referred to random FH, while the latter as uniform FH.

SFH/MC DS-CDMA System

Transmitter Model

The transmitter diagram of the proposed FH/MC DS-CDMA is depicted in Fig. 1. Each subcarrier of the K users in the system is assigned a PN sequence. These PN sequences produce spread, wideband signals. In the figure, $C(Q,U_k)$ represents a constant-weight code of user k with U_k number of `1's and $(Q-U_k)$ number of `0's, hence, the weight of $C(Q,U_k)$ is U_k. This code is read from a so-called constant-weight code book, which represents the frequency-hopping patterns. The constant-weight code $C(Q,U_k)$ plays two different roles. Its first role is that its weight – namely U_k - determines the number of subcarriers invoked, while its second function is that the positions of the U_k number of binary `1's determines the selection of a set of U_k number of subcarrier frequencies from the Q outputs of the frequency synthesizer. High-rate and variable rate transmissions can be implemented by employing a different number of subcarriers in conjuntion with variable spreading factors.

The original bit stream having a bit duration of T_b is first serial-to-parallel (S-P) converted, as seen in the schematic of Fig. 1, yielding U_k parallel streams. Let us denote the bit duration of each parallel stream by T, which represents the symbol duration of the SFH/MC DS-CDMA signals. Then, if the system is designed in order to mitigate the inter-symbol-interference (ISI) in a constant-rate transmission scheme, the symbol duration is extended and becomes $T = U_k T_b$. By contrast, if the design aims to support multiple information rates, a constant bit duration of $T = T_b$ can be employed, and multi-rate transmissions are implemented by employing a different number of subcarriers. Explicitly, Q number of different information rates can be achieved by changing the weight, U_k, of the code $C(Q, U_k)$ from 1 to Q. As seen in Fig. 1, the direct-sequence (DS) spread, transmitted signal of the kth user can be formulated as:

$$s_k(t) = \sum_{u_k=0}^{U_k-1} \sqrt{2P} d_{u_k}^{(k)}(t) c_{u_k}^{(k)}(t) \cos\left(2\pi f_{u_k}^{(k)} t + \varphi_{u_k}^{(k)}\right), \tag{1}$$

where P denotes the transmitted power per carrier, while U_k is the weight of the constant-weight FH code of the kth user. Furthermore, $d_{u_k}^{(k)}(t)$, $c_{u_k}^{(k)}(t)$, $f_{u_k}^{(k)}$ and $\varphi_{u_k}^{(k)}$ denote the kth user's data streams, the DS spreading waveforms, the subcarrier frequencies and the phase angles introduced in the carrier modulation process. Let T_c be the chip duration of the DS spreading waveforms and $N = T_b / T_c$. Then the processing gain of $N_p = T / T_c$ equals to $U_k N$ or N, depending on the choice of the symbol duration, as discussed previously. Furthermore, we assume that the FH interval is T_h, and that the number of data bits, $N_b = T_h / T$, transmitted per hop is a positive integer, which is strictly larger than 1, implying slow FH.

Nakagami Channel Model

We considered a frequency-selective multipath fading Channel [8], whose complex low-pass impulse response for subcarrier u_k of user k is given by:

$$h_{u_k}^{(k)}(t) = \sum_{l_p=0}^{L_p-1} \alpha_{u_k,l_p}^{(k)} \exp\left(j\phi_{u_k,l_p}^{(k)}\right)\delta\left(t - l_p T_c\right), \tag{2}$$

where $l_p T_c$ is the relative delay of the l_p-th path of the u_k th subcarrier of user k with respect to the main path, the phases $\{\phi_{u_k,l_p}^{(k)}\}$ are independent identically distributed (iid) random variables uniformly distributed in the interval $[0, 2\pi)$. The L_p tap weights $\{\alpha_{u_k,l_p}^{(k)}\}$ are independent Nakagami-m random variables with a pdf of [3]:

$$p_{\alpha_{u_k,l_p}^{(k)}}(R) = \frac{2R^{2m-1}}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m \exp\left(-\frac{m}{\Omega} R^2\right), \tag{3}$$

where $\Gamma(\bullet)$ represents the gamma function, and m is the Nakagami-m fading parameter, which is defined as $m = E^2\left[\left(\alpha_{u_k,l_p}^{(k)}\right)^2\right] \Big/ Var\left[\left(\alpha_{u_k,l_p}^{(k)}\right)^2\right]$. Furthermore, $\Omega_{u_k,l_p}^{(k)} = E\left[\left(\alpha_{u_k,l_p}^{(k)}\right)^2\right]$. We assume a negative exponentially decaying multipath intensity profile (MIP) distribution given by $\Omega_{u_k,l_p}^{(k)} = \Omega_{u_k,0}^{(k)} e^{-\eta l_p}, \eta \geq 0$, where $\Omega_{u_k,0}^{(k)}$ is the average signal strength corresponding to the first resolvable path and η is the rate of average power decay.

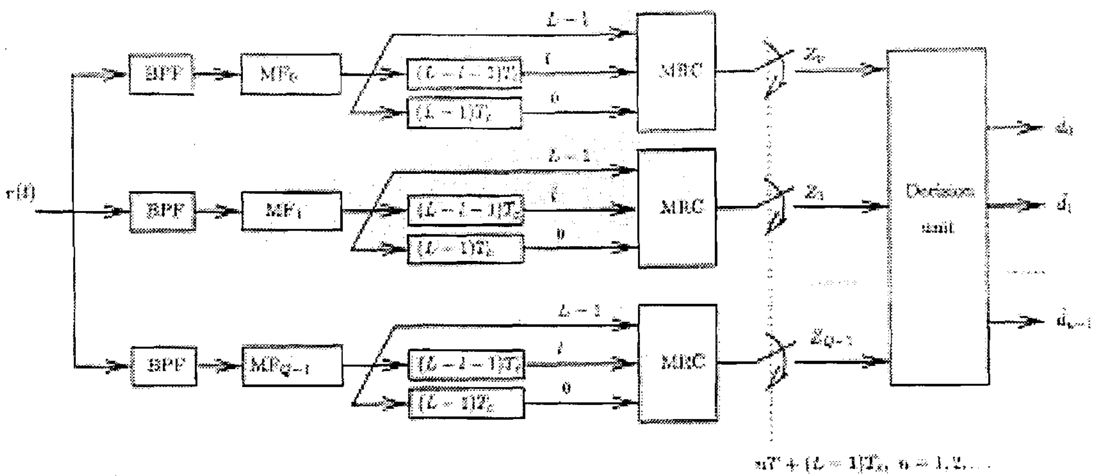

Fig. 2. Receiver block diagram of the frequency-hopping multicarrier DS-CDMA systems.

Receiver Model

The conventional matched filter based maximum ratio combining (MRC) assisted RAKE receiver is considered, as shown in Fig. 2 [4]. In Fig. 2 L number of diversity branches are used by the receiver. Upon exploiting the knowledge of the FH patterns, detection can be implemented by demodulating only the U_k active subcarriers, or alternatively, all Q subcarriers can be always demodulated, while only U_k MRC outputs are selected according to the FH patterns used for detection.

Frequency-Hopping Schemes

Random FH Scheme - In our proposed SFH/MC DS-CDMA system using random FH, the subcarriers associated with each transmission of the *k*th user, where $k = 1,2,...,K$, are determined by the pre-assigned FH patterns constituting a group of constant-weight codewords. The active subcarriers are switched from a group of frequencies to another without the knowledge of the FH patterns of the other users. The advantage of the proposed SFH/MC DS-CDMA system using random FH is that -- similarly to hybrid DS/FH CDMA systems -- it can combine the best features of DS and FH spread spectrum modulation schemes, while avoiding many of their individual shortcomings. However, the number of users activating each subcarrier is a random variable ranging from zero to K for the SFH/MC DS-CDMA system using the random FH scheme. Hence, in this context multiuser detection algorithms associated with a variable number of active users must be investigated, if multiuser detection has to be invoked.

Uniform FH Scheme - For the SFH/MC DS-CDMA system using uniform FH, we assume that the FH patterns of all users are determined jointly under the control of the base station (BS), in order that each subcarrier is activated by a similar number of users. For the down-link (base-to-mobile) uniform FH can be readily implemented, since the BS has the knowledge of the FH patterns of all users. However, for implementing up-link (mobile-to-base) transmissions, the FH patterns must be signalled by the BS to each mobile station (MS), in order to be able to implement uniform FH. The advantage of the SFH/MC DS-CDMA system using uniform FH is that the number of users activating each subcarrier is nearly constant, and this constant is lower than the number of active users, K of the system. Another advantage using the uniform FH scheme is that upon employing a multiuser detector, the complexity of the SFH/MC DS-CDMA system is significantly lower, than that of the corresponding conventional SC DS-CDMA system or that of the conventional MC DS-CDMA system, provided that each user activates a fraction of the subcarriers for transmission. The disadvantage of the SFH/MC DS-CDMA system using uniform FH is however that the side information in the context of the FH patterns has to be explicitly signalled to the mobiles, which, to some extent, decreases the system's capacity. All in all, random FH can be employed for the up-link, in order to benefit from both the FH and DS spreading schemes, while uniform FH can be employed for the down-link, in order achieve low complexity for the multiuser detectors of the MS.

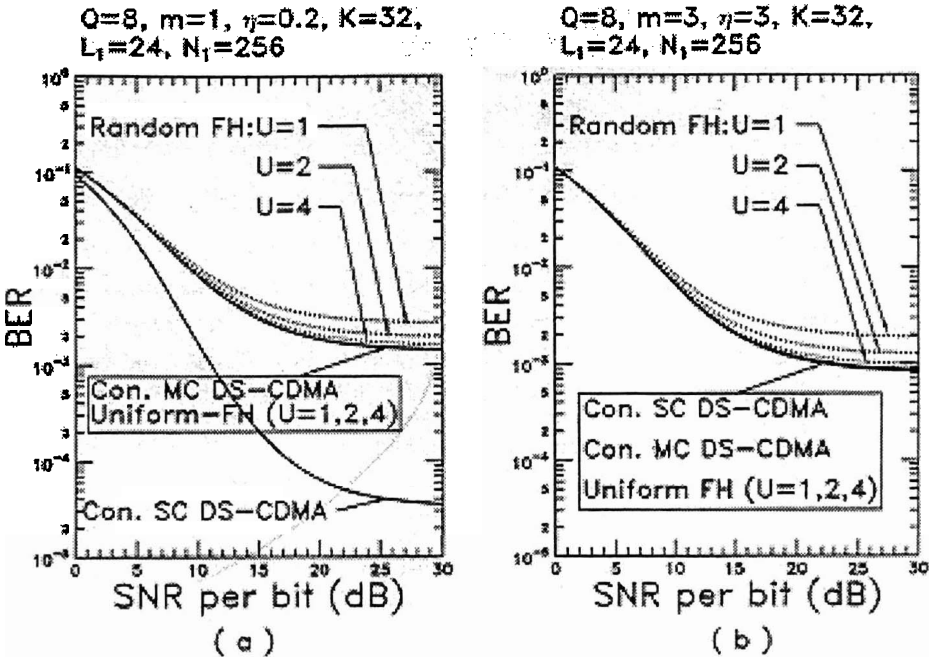

Fig. 3. BER versus SNR per bit performance comparison among the SFH/MC DS-CDMA, conventional SC DS-CDMA and conventional MC DS-CDMA systems over multipath fading channels.

Numerical Results and Discussion

In this section, the average BER performance is evaluated as a function of the average received signal-to-noise ratio (SNR) per bit. In Fig. 3(a) and Fig. 3(b) we compare the BER performance of the SFH/MC DS-CDMA systems using both random FH and uniform FH with that of the conventional SC DS-CDMA system as well as that of the conventional MC DS-CDMA system. The curves in both figures were plotted against the average SNR per bit under the assumption that the number of resolvable paths and the spreading gain of the corresponding SC DS-CDMA system was $L_1 = 24$ and $N_1 = 256$, respectively. We assumed that the number of subcarriers in both the SFH/MC DS-CDMA system and in the conventional MC DS-CDMA system was Q=8. Hence, the number of resolvable paths associated with each subcarrier signal was about $L_p \approx L_1 / Q = 3$. In Fig. 3(a) we used m=1 and $\eta = 0.2$, while in Fig. 3(b) we assumed m=3 and $\eta = 3$. The results of Fig. 3(a) show that under the assumption of dispersive multipath Rayleigh fading ($m = 1$), the conventional SC DS-CDMA system achieves the best BER performance, since it has a significantly higher diversity order of $L_1 = 24$, than the SFH/MC DS-CDMA and the conventional MC DS-CDMA systems, which exhibit a diversity order of $L_p = 3$. The conventional MC DS-CDMA system has the same BER performance as that of the SFH/MC DS-CDMA system using the uniform FH scheme, and their BER performance is better than that of the SFH/MC DS-CDMA system using the random FH scheme. For a given SNR per bit value the BER performance of the SFH/MC DS-CDMA system using the uniform FH scheme remains a constant, irrespective of the number of subcarriers activated. However, for the SFH/MC DS-CDMA system using the random FH scheme, the BER slightly decreases upon increasing the number of active subcarriers. The results of Fig. 3(b) indicate that if the communication environment becomes better and a low-dispersion fading channel is assumed, the conventional SC DS-CDMA, the conventional MC DS-CDMA and the proposed SFH/MC DS-CDMA using the uniform FH scheme achieve almost the same BER. However, for the SFH/MC DS-CDMA system using random FH, the BER decreases upon increasing the number of active subcarriers, as it was observed also in Fig. 3(a).

The BER performance of the constant-weight code based multi-rate SFH/MC DS-CDMA systems using random FH schemes is shown in Fig. 4 over multipath Nakagami-*m* fading channels having different fading parameters of *m*. In Fig. 4, a single-rate (1-rate) is supported by employing a weight-1 constant-weight code C(8,1), while a dual-rate (2-rate) system is supported by the constant-weight codes C(8,1) and C(8,2). Similarly, a triple-rate (3-rate) system is created by C(8,1), C(8,2) and C(8,4), and a quadruple-rate (4-rate) system is generated by the codes C(8,1), C(8,2), C(8,3) and C(8,4). Let R_b be the information rate provided by a single subcarrier. Since the symbol duration of the multi-rate SFH/MC DS-CDMA system was assumed to be a constant, i.e., $T = T_b$, the information rates supported by C(8,1), C(8,2), C(8,4) and C(8,8) hence are R_b, $2R_b$, $4R_b$ and $8R_b$, respectively. From the results of Fig. 4 we observe that for a given fading parameter *m*, the system performance degrades, as the number of information rates supported increases. Taking $m = 3$ as an example, the transmitted energy per bit must be increased by about 0.8dB, in order that the system can support the information rates of R_b and $2R_b$, instead of the information rate of R_b (diamond), while maintaining a BER of 10^{-6}. Similarly, a further 1.1dB or 4dB transmitted energy per bit must be invested, in order to upgrade the system from a dual-rate to triple-rate or from triple-rate to quadruple-rate, respectively.

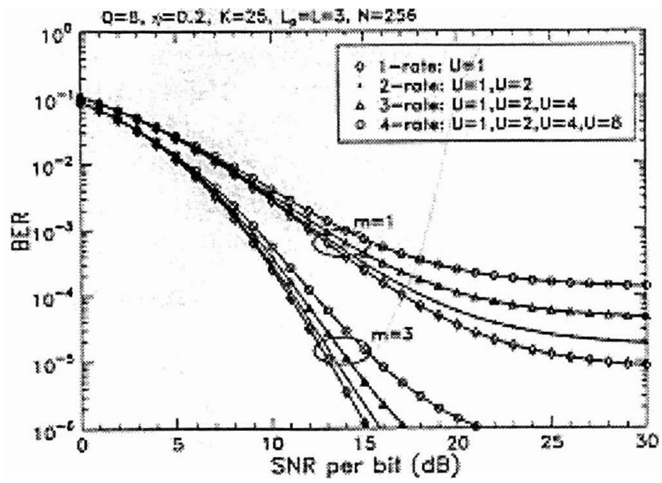

Fig. 4. BER versus SNR per bit performance for the constant-weight code based multi-rate SFH/MC DS-CDMA system over multipath fading channels upon varying the number of different information rates provided.

References

[1] L.-L. Yang and L. Hanzo, ``Slow-frequency-hopping multicarrier {DS-CDMA}," in *International Symposium on Wireless Personal Multimedia Communications* (WPMC'99)}, (Amsterdam, The Netherlands), pp.224-229, Sept. 21-23 1999.

[2] L.-L. Yang and L. Hanzo, ``Blind soft-detection assisted frequency-hopping multicarrier DS-CDMA," in *Proc. of IEEE GLOBECOM'99*, pp. 842-846, Rio de Janeiro, Brazil, 5-9 of Dec., 1999.

[3] L.-L. Yang and L. Hanzo, ``Blind joint soft-detection assisted slow frequency-hopping multicarrier DS-CDMA," To appear in *IEEE Transactions on Communications*, 2000, (http://www-mobile.ecs.soton.ac.uk/lly).

[4] L.-L. Yang and L. Hanzo, ``Slow Frequency-Hopping Multicarrier DS-CDMA over Nakagami Multipath Fading Channels," submitted to *IEEE Journal on Selected Areas in Communications* (Revised), March, 1999, (http://www-mobile.ecs.soton.ac.uk/lly).

[5] *TIA/EIA Interim Standard: Physical Layler Standard for cdma2000 Standards for Spread Spectrum Systems*, TIA/EIA/IS-2002.2-A, Mar. 2000.

[6] N. Nakagami, ``The *m*-distribution, a general formula for intensity distribution of rapid fading," in *Statistical Methods in Radio Wave Propagation*, W. G. Hoffman, ed. Oxford, England:Pergamon, 1960.

[7] L. L. Yang and C. S. Li, ``DS-CDMA performance of random orthogonal codes over Nakagami multipath fading channels," in *Proc. 4th IEEE ISSSTA'96*, pp. 68-72, Mainz, Germany, 22-25, Sept. 1996.

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