COMPARATIVE STUDY OF ADAPTIVE-RATE CDMA TRANSMISSION EMPLOYING JOINT-DETECTION AND INTERFERENCE CANCELLATION RECEIVERS

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Spread Adaptive Quadrature Amplitude Modulation (AQAM) is proposed as a powerful means of exploiting the time variant channel capacity fluctuations of wireless channels and studied in comparison to the Variable Spreading Factor (VSF) method. These two adaptive rate transmission methods are compared in the context of joint detection and interference cancellation assisted Adaptive Code Division Multiple Access (ACDMA) systems. More explicitly, these exploit the time-variant channel quality of mobile channels by switching either the modulation mode (AQAM) or the spreading factor (VSF) on a burst-by-burst basis. The most appropriate modulation mode or spreading factor is chosen based on the instantaneous channel quality estimated. The chosen AQAM mode or spreading factor is communicated to the remote receiver either through explicit signalling or extracted at the receiver using blind detection techniques. The multiuser Joint Detector (JD) and the Successive Interference Cancellation (SIC) receiver are compared in the context of these adaptive schemes with the conclusion that JD outperformed the SIC receiver in the ACDMA schemes, at the cost of increased complexity.

1. INTRODUCTION

Due to the nature of the mobile channel transmission errors typically occur in bursts. A variety of adaptive rate schemes have been proposed in the literature, where the transmission rate is adapted according to the instantaneous channel quality experienced. Abeta *et al* [1] proposed an Adaptive Code Division Multiple Access (ACDMA) scheme, where the transmission rate was modified by varying the channel code rate and the processing gain of the CDMA user. Kim [2] compared the performance of a transmitter power adaptation and information rate adaptation scheme, in order to compensate for the channel quality variations. It was demonstrated using a RAKE receiver that rate adaptation provided the higher average information rate for a given average transmit power and a given BER.

In this contribution Adaptive Quadrature Amplitude Modulation (AQAM) is proposed and compared to Variable Spreading Factor (VSF) transmission. AQAM is an adaptive rate technique whereby the data modulation mode is chosen according to some criterion related to the instantaneous channel quality [6]-[11]. On the other hand, in VSF transmission, the information rate is varied by adapting the spreading factor of the CDMA codes used, while keeping the chip rate constant. The instantaneous channel quality can be estimated at the receiver and the chosen information rate or the corresponding AQAM mode can then be communicated to the transmitter via explicit signalling. This AQAM mode is then used by the transmitter in its next transmission burst. Similarly to the 3rd generation wideband CDMA standard proposals, here we employ a Time Division Duplex (TDD)/CDMA framework [3, 4]. The multiuser receivers used for data detection are joint detection receivers and successive interference cancellation receivers. The performance of these two receivers will be explored in the context of adaptive rate schemes.

The remainder of this contribution is structured as follows. Section 2 describes the proposed joint detection assisted AQAM and VSF ACDMA systems while Section 3 provides an overview of interference cancellation receivers. Our discussions and concluding remarks are summarised in Section 4. Let us now commence our discourse by considering the proposed JD schemes.

2. JOINT DETECTION BASED ACDMA

Multiuser joint detectors (**JD**) [5] constitute a class of multiuser receivers that were developed based on conventional equalization techniques [7]. These receivers utilize the channel impulse response (CIR) estimates and the knowledge of the spreading sequences of all the users in order to reduce the level of multiple access interference (MAI) in the processed signal. In our investigations, we have concluded that the Minimum Mean Square Error Block Decision Feedback Equalization (**MMSE-BDFE**) provided the best performance of all four joint detection schemes studied in [5], while the detection complexity was similar for all four algorithms. Therefore, in our further investigations in this treatise we have used the **MMSE-BDFE**.

2.1. Adaptive Quadrature Amplitude Modulation

Burst-by-burst AQAM [6]-[11] is a technique that attempts to increase the average throughput of the system by switching between modulation modes depending on the state of the channel. When the channel quality is favourable, a

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modulation mode having a high number of constellation points is used to transmit as many bits per symbol as possible, in order to increase the throughput. Conversely, when the channel is hostile, the modulation mode is switched to one using a small number of constellation points, in order to reduce the error probability and to maintain a target BER. Previous research in AQAM schemes for TDMA transmissions have been carried out by Webb and Steele [6], by Sampei, Komaki and Morinaga [8] as well as by Goldsmith and Chua [9]. This work has been extended to wideband channels by Wong *et al* [10], where the received signal also suffers from inter-symbol interference (ISI) in addition to amplitude and phase distortion due to the fading channel.

The implementation of the **JD** algorithm does not require any knowledge of the modulation mode used. It utilizes only the channel impulse response (CIR) estimates and the spreading sequences of all the users. Therefore, the multiuser **JD** is suitable for combining with AQAM, since these arrangements do not have to be reconfigured each time, when the AQAM mode is switched and hence the associated system complexity is independent of the AQAM mode used.

In our work, triple-mode adaptive-rate schemes were compared. For the AQAM scheme, the modulation mode was switched between BPSK, 4-QAM and 16-QAM, allowing the bit rate to vary between the minimum of 1 bit per symbol and the maximum of 4 bits per symbol. By employing spreading codes associated with a spreading factor of $Q = 32$ and a chip rate of 2.167 Mchips/s, the minimum and maximum throughput values were approximately 68 and 271 kbits/s, respectively. The output Signal-to-Interference-plus-Noise Ration (SINR) of the multi-user equaliser was estimated on a burst-by-burst basis - as it was outlined for a single-carrier, single-user AQAM modem in [10] - and it was used as the switching criterion. The conditions used to switch between the two or three AQAM modes were set according to their target Bit Error Rate (BER) requirements as:

$$\text{Mode} = \begin{cases} \text{BPSK} & \text{for } \gamma_o(k) < t_1 \\ \text{4-QAM} & \text{for } t_1 \leqslant \gamma_o(k) < t_2 \\ \text{16-QAM} & t_2 \leqslant \gamma_o(k) \end{cases} \quad (1)$$

where $\gamma_o(k)$ represents the SINR experienced. Our target BER was set to 1% and the switching regime was programmed for maintaining this target BER. Due to the use of varying AQAM modes the performance results are plotted against E_s/N_0 on the horizontal axis, where E_s represents the energy per QAM symbol. The value of E_s/N_0 can be converted to the corresponding E_b/N_0 value by dividing E_s/N_0 with the number of bits in the AQAM symbol. Different sets of AQAM thresholds were investigated, where higher thresholds lowered the BER and throughput, while lower thresholds increased the throughput at the expense of a degraded BER. The set of thresholds that offered the best throughput while maintaining the target BER of 1% was chosen for comparison with the other adaptive schemes.

2.2. Variable Spreading Factor

Another adaptive-rate technique is based on varying the bit-rate by varying the spreading factor on a burst-by-burst basis, while keeping the chip rate constant. Each user in the Variable Spreading Factor (VSF) CDMA system is assigned M number of spreading codes with different lengths, Q. Generally, when the channel is likely to support low-BER transmission, a code with a low spreading factor will be used, in order to increase the throughput. Conversely, when the channel is hostile, a code having a high spreading factor will be used to minimize the number of errors encountered.

Parameter	**Value**
Channel type	COST 207 Bad Urban
Paths in channel	7
Doppler frequency	80 Hz
Spreading sequence	Pseudo-random
Chip rate	2.167 MBaud
Frame burst	FMA 1 Spread burst 1 [12]
Burst duration	577 μs

Table 1: Simulation parameters for AQAM/CDMA systems

For the triple-mode VSF scheme, the transmission rate was varied adaptively by switching between the spreading factors of $Q_1 = 64$, $Q_2 = 32$ and $Q_3 = 16$. In order to provide a fair comparison with the above AQAM scheme, a data modulation mode of 4-QAM is employed. In order to simplify the SINR calculations, the spreading sequence having the highest spreading factor (SF) for each user will always be used in the SINR calculations. In our VSF systems, each user maintains a constant level of transmission power for a certain channel SNR. This is to ensure that the interference experienced by other users remains relatively similar, after compensation for the channel effects at the receiver. The calculation of E_s/N_0 from the channel SNR ensues as $E_s/N_0 = \text{Channel SNR} \times T/T_c = \text{Channel SNR} \times Q$, where $Q = T/T_c$, T is the bit period and T_c is the chip period. Due to the varying value of Q, the value of E_s/N_0 will also vary over the course of transmission.

2.3. Combined AQAM-VSF scheme

In order to amalgamate the benefits of both AQAM and VSF-CDMA, a combined AQAM and VSF adaptive-rate JD-CDMA system was studied by Ue *et al*, who [11] carried out investigations on a combined symbol-rate and modulation-level controlled adaptive modulation system for TDMA/TDD schemes in narrowband channels. In our system, the SINR at the output of the **JD** was estimated as before, for both the AQAM and the VSF systems. Three different transmission modes were chosen for the combined AQAM VSF-CDMA system, which were Mode 1 - BPSK and $Q = 32$; Mode 2 - 4-QAM and $Q = 32$; and finally, Mode 3 - 4-QAM and $Q = 16$. The rules used for switching transmission formats were as follows :

$$\begin{array}{rcl} \gamma_o(k) < t_1 & \Longrightarrow & Q = 32 \text{ and BPSK} \\ t_1 \leqslant \gamma_o(k) < t_2 & \Longrightarrow & Q = 32 \text{ and 4-QAM} \\ t_2 \leqslant \gamma_o(k) & \Longrightarrow & Q = 16 \text{ and 4-QAM} \end{array}$$

The switching thresholds - which were chosen to maintain a target BER of 1% - were set at $t_1 = 8$ dB and $t_2 = 10$ dB.

2.4. Performance comparisons

Table 1 tabulates the simulation parameters used in our investigations. A 7-path Bad Urban COST 207 channel

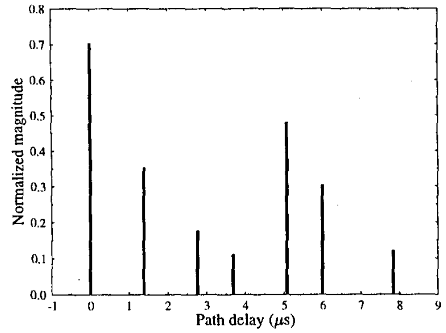


Figure 1: Bad Urban 7-path COST 207 channel used in the simulations [13].

was used and the CIR can be seen in Figure 1. Perfect CIR estimation was assumed, providing an upper-bound performance estimate. For all three adaptive-rate schemes being compared, a BER of 1% was targeted, while achieving the best throughput possible. The minimum and maximum throughput values were 68 and 271 kbits/s, respectively.

The performance results of the three schemes being compared are presented in Figure 2. The AQAM system maintained a fairly constant BER of 1%, while the VSF and combined systems showed a gradual drop in BER, as the average E_s/N_0 increased. The constant BER performance of the AQAM system was due to the use of 16-QAM, which supported a high throughput of 4 bit/symbol, but exhibited a slightly inferior BER performance at low E_s/N_0 values. Considering the BER curves, we can see that the combined scheme outperformed both the triple-mode AQAM scheme and the VSF scheme. The target BER of 1% was achieved and as the transmission power was increased, the BER also gradually decreased. In throughput terms, the combined scheme also outperformed the other two individual schemes. The combined scheme did not employ 16-QAM as the modulation mode, and therefore was capable of maintaining a good BER performance, since the 16-QAM mode is less resilient. Furthermore, in employing spreading codes with the lower SFs of $Q_1 = 32$ and $Q_2 = 16$, a high throughput was obtained without sacrificing the BER performance.

In comparing the implementational complexities of the three systems, let us take the complexity of the highest throughput fixed-rate scheme, i.e. the 4-QAM, $Q = 16$ scheme as a benchmark. The MUD complexity is on the order of $O(KN)^3$ per transmitted burst for the matrix inversion segment of the algorithm, where K represents the number of users and N represents the number of symbols per burst. The complexity of the AQAM system was the same as that of the above benchmarker, since the choice of AQAM mode does not have any effect on the complexity of the JD algorithm. The VSF scheme had the same complexity as the above benchmarker, when $Q_3 = 16$ was used but the complexity decreased by a factor of eight, when $Q_2 = 32$ was used and by a further factor of eight, when $Q_1 = 64$ was invoked. This was because the increase in SF yielded a corresponding decrease in the number of transmitted symbols, N. In the combined AQAM-VSF scheme, the complexity was the same as that of the 4QAM, $Q = 16$ benchmarker, i.e. when the SF of $Q = 16$ was chosen. When the SF switched to $Q = 32$, the complexity also dropped by a factor of eight.

For the VSF scheme and for the combined AQAM-VSF scheme, the configuration of the algorithm had to be altered whenever the spreading code of any of the users was changed, thus increasing the complexity. By contrast, AQAM provided a relatively simple method of adaptively varying the bit rate in order to exploit and accommodate the time-varying nature of the mobile channel without disadvantaging other users. The change in AQAM mode did not affect the operation of the joint detection algorithm, thus there was no complexity penalty. Let us now consider a range of lower-complexity interference cancellation based benchmarkers.

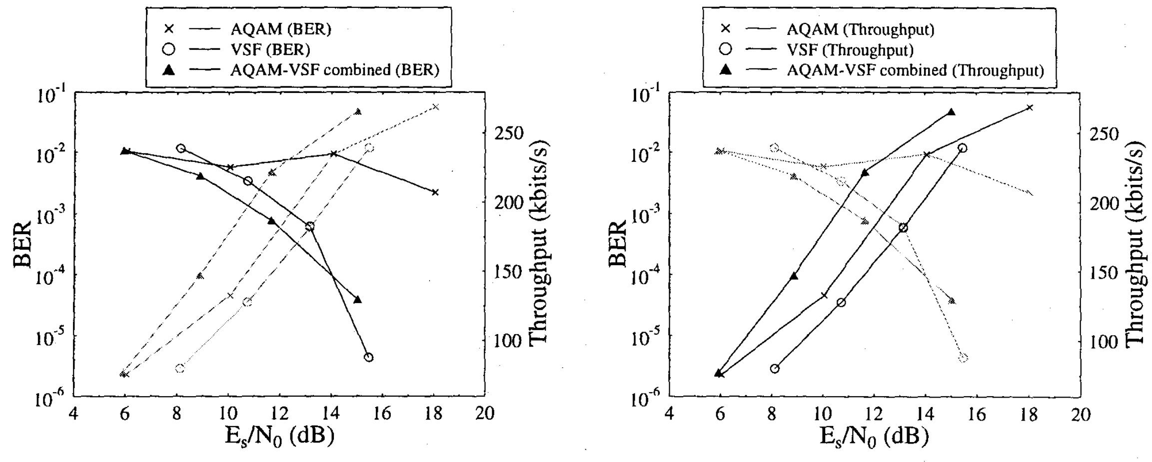
3. INTERFERENCE CANCELLATION

Interference cancellation receivers attempt to remove the MAI by reconstructing the original transmitted signals of one or more users and cancelling the interference imposed by these reconstructed signals on the composite received signal [14, 15]. Successive interference cancellation (**SIC**) [14] receivers rank the users according to received signal quality. Then, the signal of the highest signal-quality user is reconstructed first using the initial data estimates, the CIR and the spreading sequence of that user. This reconstructed signal is subtracted from the composite received signal. The remaining signal is then processed through the matched filter bank or RAKE receiver of the next strongest signal, in order to obtain the data estimates for this user. Employing these data estimates, as well as the CIR and spreading sequence of the user, the transmitted signal is reconstructed and subtracted again from the composite multiuser signal that has already had the strongest user's signal cancelled from it. This is repeated, until the data estimates of all the users have been obtained.

In our forthcoming investigations, the performance of the JD is compared to that of the SIC receiver in the context of our burst-by-burst adaptive CDMA system. In order to generate the initial data estimates for the **SIC** receiver, RAKE correlators were used for each user, where perfect CIR estimation was assumed and maximal ratio combining was employed. The **JD** has a significantly higher complexity, than the **SIC** receiver. As with the adaptive rate JD-CDMA systems, **the criterion used to determine the information rate for the next transmission was chosen to be the SINR at the output of the SIC receiver.** The SINR estimate was derived by modifying the approach followed by Patel and Holtzmann [14] for a multipath channel.

4. VSF COMPARISONS

In this section, the **JD** and the **SIC** receiver will be compared in the context of adaptive variable spreading factor (VSF) schemes. The spreading factor used was varied adaptively, opting for $Q_1 = 64$, $Q_2 = 32$ or $Q_3 = 16$. Since the BER performance of the **SIC** receiver degrades, as the spreading factor decreases, the value of E_s/N_0 was not varied when the spreading factor was switched. Therefore, the transmission power of the signal varied adaptively in order to maintain the constant value of E_s/N_0. This is in contrast to the **VSF/JD-CDMA** schemes, where the



(a) BER comparisons are in bold, throughput comparisons are in grey.

(b) Throughput comparisons are in bold, BER comparisons are in grey.

Figure 2: BER and throughput performance of a **combined AQAM-VSF adaptive-rate JD-CDMA system**. The bit rate was varied adaptively by using both AQAM and a variable spreading factor. The modulation modes were switched between BPSK with $Q = 32$, 4-QAM with $Q = 32$ and 4-QAM with $Q = 16$. The switching thresholds were set at $t_1 = 8$ dB and $t_2 = 10$ dB. Minimum and maximum throughput values were 68 and 270 kbits/s, respectively. Also shown are the performance results for the triple-mode AQAM (BPSK, 4-QAM, 16-QAM) scheme employing $Q = 32$, and the triple-mode VSF scheme utilizing 4-QAM as the modulation mode.

transmission power was kept constant, in order to maintain a constant interference power to all the other users. Figure 3 shows the BER and throughput comparisons for the adaptive VSF schemes using 4QAM both with JD and SIC. The minimum and maximum throughput values were approximately 68 kbits/s and 270 kbits/s, respectively. We compared the **JD** system to two **SIC** systems employing different thresholds. The first SIC system had switching thresholds set to $t_1 = 7$ dB and $t_2 = 10$ dB, while the second one had higher thresholds of $t_1 = 10$ dB and $t_2 = 13$ dB. The switching thresholds of $t_1 = 10$ dB and $t_2 = 13$ dB selected for the **JD** system were chosen for maintaining a target BER of 1%. From Figure 3 we observe that the **SIC** system using the lower switching thresholds achieved a higher overall throughput performance at the expense of an inferior BER performance compared to the **SIC** system invoking the higher thresholds of $t_1 = 10$ dB and $t_2 = 13$ dB. The employment of higher thresholds allowed the **SIC** system to achieve a target BER of 1%. The BER and throughput performance of the **SIC** receiver was inferior in comparison to that of the JD. The **JD** providing a BER of approximately 0.001% and a throughput of 180 kbits/s for an average E_s/N_0 of 13 dB compared to the corresponding throughput value of 135 kbits/s for the same BER and E_s/N_0 values from the more 'aggressive' **SIC** system invoking the lower switching thresholds.

5. CONCLUSION

In conclusion, a range of different complexity adaptive CDMA transceivers were compared, where the minimum and maximum throughput values supported were the same. It was shown that the combined AQAM-VSF scheme outperformed

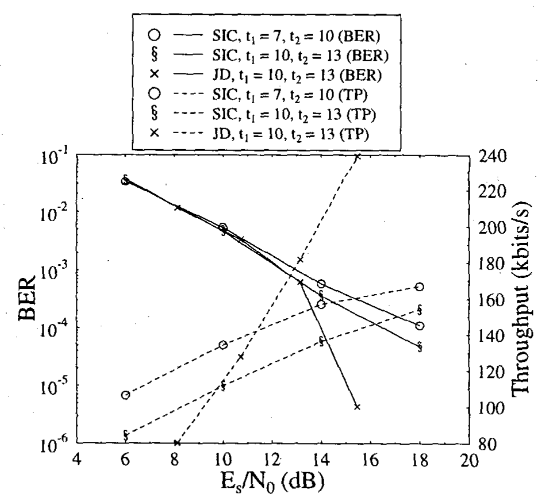


Figure 3: BER and throughput performance comparisons for **triple-mode VSF** schemes with $K = 2$ users, employing **4-QAM** as the data modulation mode. Two different multiuser receivers were compared, namely the **JD** and the **SIC** receiver.

the individual VSF and AQAM schemes. However, it was an advantage of the AQAM system that the complexity of the **JD** remained constant, despite the changes in AQAM mode. By contrast, the complexity of the VSF receiver varied according to the SF used.

As a reduced-complexity design alternative, an adaptive (**SIC**) receiver was also investigated using triple-mode VSF schemes. The employment of variable spreading factors of $Q = 64$, $Q = 32$ and $Q = 16$ enabled the SIC receiver to provide a reasonable BER and throughput performance, which was nonetheless inferior to that of the **JD**. However, the complexity of the **SIC** receiver increases linearly with the number of CDMA users, K, compared to the joint detector, which has a complexity proportional to $O(K^3)$.

It is anticipated that the third-generation systems will be capable of reconfiguring their transceivers on a near-instantaneous basis, which motivated our study. Due to their flexibility, the transceivers will be able to accommodate time-variant channel quality fluctuations due to the various propagation phenomena, such as fast and shadow-fading as well as pathloss, which may change particularly dramatically, when the mobiles roam between indoor and outdoor networks. Upon using the proposed adaptive transceivers seamless roaming of the mobiles is facilitated without powering up - which would inflict increased interference upon other users - or without handovers, which would increase the network's control traffic. Out future work is focused on invoking the proposed transceivers in interactive wireless multimedia systems. Further performance improvements will be sought with the aid of adaptive beam-steering and space time coding.

6. REFERENCES

[1] S.Abeta, S.Sampei, and N. Morinaga, "Channel activation with adaptive coding rate and processing gain control for cellular DS/CDMA systems," in *Proceedings of the IEEE VTC'96*, pp. 1115–1119, 1996.

[2] S.W.Kim, "Adaptive rate and power DS/CDMA communications in fading channels," *IEEE Communications Letters*, vol. 3, pp. 85–87, Apr. 1999.

[3] K.Miya, O.Kato, K.Homma, T.Kitade, M.Hayashi, and T.Ue, "Wideband CDMA systems in TDD-mode operation for IMT-2000," *IEICE Transactions on Communications*, vol. E81-B, pp. 1317–1326, July 1998.

[4] O.Kato, K.Miya, K.Homma, T.Kitade, M.Hayashi, and M.Watanabe, "Experimental performance results of coherent wideband DS-CDMA with TDD scheme," *IEICE Transactions on Communications*, vol. E81-B, pp. 1337–1344, July 1998.

[5] A.Klein, G.K.Kaleh, and P.W.Baier, "Zero forcing and minimum mean square error equalization for multiuser detection in code division multiple access channels," *IEEE Transactions on Vehicular Technology*, vol. 45, pp. 276–287, May 1996.

[6] W.T. Webb and R. Steele, "Variable Rate QAM for mobile radio," *IEEE Transactions on Communications*, vol. 43, pp. 2223 – 2230, July 1995.

[7] L. Hanzo, W.T.Webb, T. Keller, *Single- and Multi-carrier Quadrature Amplitude Modulation : Principles and Applications for Personal Communications, WLANs and Broadcasting*. London: John Wiley and IEEE Press, 2000.

[8] S.Sampei, S.Komaki, and N.Morinaga, "Adaptive modulation/TDMA scheme for large capacity personal multimedia communications systems," *IEICE Transactions on Communications*, vol. E77-B, pp. 1096–1103, September 1994.

[9] A.J.Goldsmith and S.G.Chua, "Variable rate variable power MQAM for fading channels," *IEEE Transactions on Communications*, vol. 45, pp. 1218 – 1230, October 1997.

[10] C.H.Wong and L.Hanzo, "Upper-bound of a wideband burst-by-burst adaptive modem," in *Proceedings of the IEEE VTC'99, Houston, USA, May, 1999*, pp. 1851–1855, 1999.

[11] T.Ue, S.Sampei, and N. Morinaga, "Symbol rate and modulation level controlled adaptive modulation/TDMA/TDD for personal communication systems," in *Proceedings of the IEEE VTC'95*, pp. 306–310, 1995.

[12] T.Ojanperä, A.Klein, and P.-O.Anderson, "FRAMES multiple access for UMTS," *IEE Colloquium (Digest)*, pp. 7/1–7/8, May 1997.

[13] Office for Official Publications of the European Communities, Luxembourg, *COST 207 : Digital land mobile radio communications, final report*, 1989.

[14] P.Patel and J.Holtzman, "Analysis of a simple successive interference cancellation scheme in a DS/CDMA system," *IEEE Journal on Selected Area in Communications*, vol. 12, pp. 796–807, June 1994.

[15] M.K.Varanasi and B.Aazhang, "Multistage detection in asynchronous code-division multiple-access communications," *IEEE Transactions on Communications*, vol. 38, pp. 509–519, Apr. 1990.