Integrated error control and power control for DS-CDMA multimedia wireless communications

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Abstract: The paper studies a packetised direct sequence code division multiple access (DS-CDMA) wireless network for providing multimedia services to mobile users. A strategy for integrating transmission error control with power control is presented and evaluated for the reverse link transmission where orthogonal signalling and noncoherent demodulation are necessary. For delay insensitive traffic requiring a very low bit error rate (BER), convolutional coding and an automatic retransmission request (ARQ) protocol are used to guarantee the transmission accuracy. By using the modified Viterbi decoder for decoding error detection, power control based on the received E_b/I_0 (the ratio of signal energy per bit to interference-and-noise density) is employed to minimise the total received power at the base station, resulting in a maximal frequency spectrum efficiency. Numerical results are presented to evaluate the optimal received E_b/I_0 value, the system radio frequency spectrum efficiency, and the optimal packet length, given the required BER and the traffic type. It is shown that the spectrum efficiency can be significantly increased by using an ARQ protocol with integrated optimal power control and convolutional coding for delay insensitive traffic.

1 Introduction

Research and development of wireless personal communication networks (PCNs) is increasingly gaining momentum within the telecommunications industry. Initial services offered by PCNs are limited to voice and low-rate data applications. Future development of PCNs envisions applications for mobile users that extend to a broad range of multimedia services. As a packet-switching technique, asynchronous transfer mode (ATM) is the leading transport mechanism for broadband networks capable of providing constant, variable, and available bit rate services for multimedia traffic. An extended network consisting of a wireless subnetwork to support local mobile users and a wired ATM network as the backbone for interconnection allows users to have completely tetherless and mobile access to the network for multimedia services. Therefore, it is expected that wireless networks will be interconnected in the near future with wired broadband networks using ATM technology. One of the challenges in internetworking the wireless and wired networks is to guarantee quality of service (QoS) requirements while taking account of the radio frequency spectrum limitations and radio propagation impairments.

Power control on the reverse link is a key issue in satisfying transmission accuracy requirement and achieving high capacity for wireless systems using direct sequence code division multiple access (DS-CDMA). Significant research efforts have been devoted to the subject [1]. For voice only DS-CDMA systems, power is controlled to achieve equal received power from all the mobile users in each cell. In a multimedia environment, various traffic types require different QoS such as different transmission accuracy. As a result, the concept of power control for voice only DS-CDMA systems cannot be directly applied to multimedia wireless communications. More recently, power control algorithms for multimedia CDMA systems have been proposed to satisfy various bit error rate (BER) requirements [2, 3]. Power control has also been studied as part of the optimisation problem for system resource allocation [4–6]. In previous work on power control for multimedia communications, emphasis was placed either on the power control techniques to achieve a given required signal energy per bit to interference-and-noise density (E_b/I_0) ratio at the receiver for each traffic type, or on optimal system resource management (including transmission rate and transmitted power allocation, base station assignment) under the assumption that the required E_b/I_0 is given. To the best of our knowledge, no work is available in the open literature on defining the optimal received E_b/I_0 value given the required transmission accuracy and the user traffic type.

On the other hand, to mitigate the impairments of wireless fading channels on digital transmission, convolutional coding for voice [7] and BCH (Bose–Chaudhuri–Hocquenghem) coding for low-rate video [3] without retransmission have been proposed, and BCH coding with retransmission has been applied to data transmission to guarantee a low BER [3]. Automatic retransmission request (ARQ) protocols have been studied for higher transmission accuracy based on CRC (cyclic redundancy check) [8] and on the modified Viterbi decoding algorithm [9, 10]. Previous work on convolutional coding with ARQ mainly targets coherent channels and is not suitable for a realistic reverse link of wireless CDMA systems. Over the reverse link, the transmission of a pilot signal from each mobile for coherent pseudorandom noise (PN) code synchronisation and coherent detection is not well justified due to extra

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interference to other users and the transmitted power needed. Hence, orthogonal signalling and noncoherent demodulation are necessary.

In this paper, we consider a packetised DS-CDMA wireless network capable of providing multimedia services in a protocol compatible with ATM. In particular, we study the transmission error control and power control for noncoherent reverse link transmission where convolutional coding with ARQ and without ARQ is used for error sensitive traffic and delay sensitive traffic, respectively. A strategy for integrating the transmission error control techniques with power control is presented, which maximises the frequency spectrum efficiency and, at the same time, guarantees various QoS requirements. Using a different approach from those of previous work on power control for multimedia communications, our focus is to define the optimum received E_b/I_0 value based on required transmission BER and the traffic type. The upper bound on BER performance for the error sensitive traffic is derived and numerical results are presented to evaluate (i) the optimal received E_b/I_0 at base stations given a required BER value, (ii) the system radio frequency spectrum efficiency versus the BER requirement, and (iii) the optimal packet length to maximise the frequency spectrum efficiency. It is shown that the spectrum efficiency can be significantly increased when using an ARQ protocol integrated with the power control and convolutional coding for delay insensitive traffic.

2 Integrated error control and power control

A packetised DS-CDMA system model is considered which supports voice, data and video traffic in a protocol compatible with ATM. The system operates in a frequency-division duplex mode. In the forward link, each base station transmits a distinct pilot signal for a mobile to choose its home base station and to determine its initial transmitted power. Each mobile terminal uses the pilot signal for its PN code synchronisation and coherent detection. In the reverse link, connection admission control is needed to provide satisfactory QoS to mobile users transmitting different types of traffic [11]. The reverse link consists of an admission control channel and a number of data transmission channels. During the admission process, a mobile user uses the admission channel to inform the base station of its traffic type, required transmission BER, transmission rate, transmission delay, etc. Based on these parameters, the base station determines whether the system has enough resource to admit the mobile terminal. Once admitted, the mobile terminal transmitted fixed length packets over the assigned channel(s). With packetisation of user source information and parallel transmission over multiple data channels, the system can provide services for both constant bit rate and variable bit rate types of traffic. Since any burstiness in interference level causes substantial degradation in transmission quality over the duration of the burst, transmission is unsynchronised among users to give a distribution of interference closer to uniform than that with synchronised transmission, resulting in better statistical multiplexing.

To provide multimedia services, the wireless network should accommodate both delay sensitive traffic (such as voice and video) and error sensitive traffic (such as file transfer) with guaranteed QoS. Usually, the transmission accuracy required for voice communications is BER (p_b) $\leq 10^{-3}$ and for low-rate video (in applications such as video conferencing) is $p_b \leq 10^{-4}$ or 10^{-5}. On the other hand, error sensitive traffic may require a very low BER (e.g. $p_b \leq 10^{-9}$). With DS-CMDA, the approaches to achieving various BER values include both error control and power control. Delay sensitive users with more stringent BER requirements can be accommodated by increasing their transmitted power so as to increase their received E_b/I_0 values, resulting in a lower BER. However, the consequence is an increase in the interference seen by all other users in the wireless network, which will increase the BER for all other users or reduce the capacity of the system. Since DS-CDMA is interference limited, the system resources (in terms of the frequency spectrum and the interference density level to others) used by a mobile is generally proportional to the transmission rate and the received power level from the mobile. Consequently, a larger received power from a mobile means that the mobile occupies a larger portion of the system capacity. With a constant transmission rate, the lower BER value that a mobile requires, the more system resources it needs. As a result, a very low BER value cannot be achieved simply by increasing the transmitted power of mobile terminals, especially taking into account hostile wireless propagation environments. In other words, power control itself may not be efficient in utilising the limited radio frequency spectrum. Transmission error control techniques should be used in combination with power control. Channel coding can reduce the required E_b/I_0 when the required BER is low, which can then increase the overall frequency spectrum efficiency of the network. Coding is worthwhile if the increase in spectrum efficiency outweighs the cost of adding redundant coding bits to each packet. Here, we consider convolutional codes with rate $r = b/n$ and constraint length K. Low rate codes should be used which, when combined with spread spectrum modulation, can achieve maximum theoretical performance [12]. For delay sensitive traffic with moderate transmission accuracy requirements, power control and convolutional coding are used to support real-time services and to guarantee satisfactory BER values. Based on the convolutional code used and the required BER value for real-time traffic from a mobile user, the required E_b/I_0 can be determined. The base station compares the measured E_b/I_0 value with the target one, and then informs the mobile terminal whether to increase, decrease, or keep the same transmitted power level. No automatic retransmission request (ARQ) protocol is used for the delay sensitive traffic due to its strict transmission delay requirement.

For error sensitive data traffic, real-time delivery is generally not a requirement which is different from voice and video traffic. Therefore, in addition to convolutional encoding, an ARQ protocol can be used to achieve a very low BER value. To implement an ARQ protocol for packets with convolutional encoding, the decoder should be able to detect decoding errors. The error detection can be implemented by using CRC codes at the end of each information packet or by using the modified Viterbi decoder [9]. With the modified Viterbi decoding algorithm, a retransmission request is generated according to the following strategy. If the difference in the metrics of the survivor and the next best path is less than some prespecified value A (≥ 0), the survivor is labelled with an X. The X label remains on that path as long as it continues to be a survivor. If, at any level of the trellis, all the survivors are labelled with an X, a retransmission is requested, that is, when all survivors are considered unreliable a retransmission request is issued. This error detection is different from using CRC error detection after Viterbi decoding. The modified Viterbi decoder is preferred for the system model because of the following advantages: (i) no redundant bits are needed for each information packet for the purpose of error detection;

(ii) the system does not need to have the CRC encoder and decoder and, therefore, can avoid the processing delay due to CRC error detection; and (iii) by selecting different values of the decoding parameter A, the probability of transmission error and the probability of retransmission can be controlled. Advantage (iii) facilitates the integration of transmission error control with power control to achieve the maximum frequency spectrum efficiency. In general, increasing the decoding threshold A value will reduce the transmission error, at the expense of an increased retransmission probability. Given a multiple access interference (due to other users in the system) and background noise density level, there is a one-to-one relation between the required received E_b/I_0 and the required received power. Let $\tilde{P}$ denote the average received power required to achieve a BER of value $\tilde{p}_b$ which is larger than the required BER (p_b). The probability of bit error $\tilde{p}_b$ is to be further reduced to p_b by retransmission. $\tilde{p}_b$ is determined as follows. The relation between $\tilde{p}_b$ and $\tilde{P}$ depends on channel fading statistics, convolutional encoder structure, decoder parameter A, diversity reception order, multiple access interference due to other users in the system and additive white Gaussian (background) noise. Let P denote the statistical average of the received power which takes the retransmission into consideration, then the value of P needed to achieve a required BER p_b is

$$P = \frac{\tilde{P}}{1 - p_R} \tag{1}$$

where p_R is the probability of the packet retransmission, and is a function of $\tilde{P}$, A, and packet length. In general, p_R is very small, resulting in the value of P only slightly larger than $\tilde{P}$. On the other hand, $\tilde{P}$ can be much smaller than the received power required to achieve p_b without retransmission, depending on the values of p_b and $\tilde{p}_b$. As a result, the received power P with retransmission is smaller than the required received power without retransmission, which is verified by the numerical results given in Section 4. Our strategy for optimal power control is to determine the received power level $\tilde{P}$ (and hence the E_b/I_0 value) in such a way that the total received power P is minimised. In other words, based on channel coding scheme used and the required BER (p_b), $\tilde{p}_b$ is determined which results in a minimal P, and power control is to achieve the target E_b/I_0 value corresponding to $\tilde{p}_b$ for the channel coding scheme used. In this way, error control is integrated with power control to achieve the required BER and a minimal interference level that the mobile introduces to all other users, leading to a maximum utilisation of the radio frequency spectrum. The target received E_b/I_0 value can be determined at the base station in the connection admission process based on the QoS requirements of the mobile terminal. For each delay insensitive traffic source, the base station compares the calculated optimal E_b/I_0 value with the measured one. Based on the comparison, a power control command is then generated for the mobile. In the case that the cell has extra capacity available, delay insensitive traffic sources may transmit more power than the target values as long as the BER requirements for all traffic sources can be guaranteed. Thus, the frequency spectrum efficiency can be maximised in a way similar to introducing the ABR service in a wired ATM network.

In summary, the integrated error control with optimal power control maximises the utilisation of the system radio frequency spectrum and, at the same time, guarantees various QoS requirements of mobile users. Considering different priorities of multimedia traffic, the strategy can be implemented by:

Step 1: allocating the minimum received E_b/I_0 to each delay sensitive traffic source for its required BER value without retransmission. Some connections with lower priorities have to be dropped (i.e. the transmitted power from the mobiles is reduced to zero) if no enough resource is available to guarantee the QoS requirements of all delay sensitive sources;

Step 2: allocating the remaining resource to delay insensitive sources where the received E_b/I_0 for each source is determined such that the total received power P with retransmission is minimised. Some connections with lower priorities may have to be suspended (i.e. the transmitted power from the mobiles is reduced to zero) if no enough resource is available. Some suspended connections may be resumed if there is extra resource remaining;

Step 3: allowing delay insensitive sources to have their received E_b/I_0 larger than the corresponding optimal one if there exists an extra resource after all the suspended connections are resumed.

Here the resource is referred to the capacity for the received signal power from mobile terminals in each cell, given that the BER requirements of the mobile terminals can be satisfied. Details of implementing the power control to achieve a target E_b/I_0 in a slowly fading environment can be found in [3], where a power control algorithm combining closed loop power control with channel estimation is proposed and evaluated to give the best performance for the packetised multimedia traffic (including voice, data and low-rate video). The numerical results on the optimal E_b/I_0 value are presented in Section 4 based on the upper bounds of BER and retransmission probability derived in the next Section.

3 Transmission performance analysis

In the following, we derive the upper bounds of BER and retransmission probability for the reverse link transmission which uses a convolutional code, an ARQ protocol, the modified Viterbi decoder, and M-ary orthogonal modulation with noncoherent detection. For convolutionally encoded binary phase shift keying (BPSK) over an unfaded additive white Gaussian noise (AWGN) channel with coherent demodulation and the modified Viterbi decoding algorithm, it can be derived that the probability of first retransmission request at any decoding level and the probability of bit error are bounded respectively by

$$p_r \le \sum_{k=d_f}^{\infty} \alpha_k p_{rk} \tag{2}$$

$$p_b \le \frac{1}{b} \sum_{k=d_f}^{\infty} \beta_k p_{bk} \tag{3}$$

where α_k is the number of code words of weight k, β_k is the total number of nonzero information bits on all weight k paths, d_f is the free distance of the convolutional code, and [9]

$$p_{rk} = Q\left(\frac{-A}{2\sqrt{2kE/I_0}} + \sqrt{\frac{2kE}{I_0}}\right)$$

$$p_{bk} = Q\left(\frac{A}{2\sqrt{2kE/I_0}} + \sqrt{\frac{2kE}{I_0}}\right)$$

with $Q(x) \triangleq \int_x^\infty e^{-y^2/2}dy/\sqrt{2\pi}$. The Chernoff bounds on p_{rk}

and p_{bk} are

$$p_{rk} \le \exp\left(+\frac{A}{2}\right)\exp\left(-\frac{kE_b}{I_0}\right)$$

and

$$p_{bk} \le \exp\left(-\frac{A}{2}\right)\exp\left(-\frac{kE_b}{I_0}\right)$$

respectively. As a result, the upper bounds of p_r and p_b are

$$\begin{aligned} p_r &\le \exp(A/2)\sum_{k=d_f}^{\infty}\alpha_k \exp(-kE_b/I_0) \\ &= \exp(A/2)T(D,I)\big|_{D=\exp(-E_b/I_0),I=1} \end{aligned} \quad (4)$$

$$\begin{aligned} p_b &\le \frac{1}{b}\exp(-A/2)\sum_{k=d_f}^{\infty}\beta_k \exp(-kE_b/I_0) \\ &= \frac{1}{b}\exp(-A/2)\left.\frac{\partial T(D,I)}{\partial I}\right|_{D=\exp(-E_b/I_0),I=1} \end{aligned} \quad (5)$$

where $T(D, I)$ is the generating function of the code. The corresponding upper bound on the probability of packet retransmission is

$$p_R = 1 - (1 - p_r)^N \quad (6)$$

where N is the number of information bits in each packet.

Over the reverse link, M-ary orthogonal modulation is used for the noncoherent detection at the base station receivers, which can be implemented by using BPSK combined with Hadamard–Walsh orthogonal sequences [13]. The information data sequence is convolutionally encoded, Hadamard–Walsh encoded, interleaved, and modulated by a PN code sequence. The receiver consists of a noncoherent demodulator, a de-interleaver, and a modified Viterbi decoder with threshold A. For real-time traffic, the decoding threshold A is set at zero and there is no retransmission request, which corresponds to using a conventional Viterbi decoder; for non-real-time traffic, the threshold A (≥ 0) depends on the BER requirement. The bounds of p_r and p_b (eqns. 4 and 5) can be extended to the case of the noncoherent detection in the reverse link with Rayleigh fading. Under the assumption of perfect interleaving and the multiple access interference due to other users in the network having a Gaussian distribution, the required excess energy of the noncoherent modulation in a Rayleigh fading channel over coherent BPSK in an unfaded AWGN channel can be obtained. Eqns. 4 and 5 can then be extended to the case of noncoherent modulation over a Rayleigh fading channel by taking account of the required excess E_b/I_0.

The frequency spectrum efficiency of the reverse link is defined as the ratio of the maximum information bit rate from all the mobiles in each cell to the total frequency bandwidth of the wireless link, given that all the required BER values from all mobile users are the same and can be guaranteed. In general, the frequency spectrum efficiency decreases as the required BER value reduces. The spectrum efficiency can be directly transformed to the cell capacity, i.e. the maximum number of mobile users that each cell can accommodate given that the BER requirement can be guaranteed. Under the assumptions of (i) negligible background noise (i.e. the interference-and-noise spectral density I_0 resulting mainly from multiple access interference), (ii) accurate power control, and (iii) perfect statistical multiplexing, it can be derived that the system frequency spectrum efficiency for a single-cell network is

$$\gamma = (1 - p_R)\left[\frac{N - (K-1)}{N}\right]\left[\frac{1}{(E_b/I_0)_r} + \frac{1}{G}\right] \quad (7)$$

where G is the processing gain of the DS-CDMA system, and $(E_b/I_0)_r$ denotes the target E_b/I_0 value to achieve a probability of bit error $\tilde{p}_b$ which results in the satisfactory BER with retransmission probability p_R. In eqn. 7, $[1/(E_b/I_0)_r + 1/G]$ represents the single-cell spectrum efficiency [7] under the assumptions, while the factor $(1 - p_R)$ is to take into account the efficiency loss due to retransmission, and the factor $(N - (K - 1))/N$ is to take into account that a $(K - 1)$ bit tail of all zeros needs to be added to each packet for the decoding path to converge at the receiver decoder. Using packetised transmission, a header is added to each data segment to form a packet. If the header is viewed as an overhead, then the corresponding spectrum efficiency is

$$\gamma^* = (1 - p_R)\left[\frac{N - (K-1) - N_h}{N}\right]\left[\frac{1}{(E_b/I_0)_r} + \frac{1}{G}\right] \quad (8)$$

where N_h is the length of the packet header in bits. Eqns. 7 and 8 can be extended to the case of a multiple-cell network by using the interference correction factor to take into account the interference from mobiles in all other cells. It should be mentioned that different implementation procedures of the power control will result in different power control errors which, together with nonperfection in the statistical multiplexing, will reduce the frequency spectrum efficiency. The numerical results presented in the next Section are obtained based on the assumption of accurate power control and perfect statistical multiplexing, which demonstrate the benchmarking performance of the integrated error control and power control strategy.

4 Numerical results and discussion

Table 1 lists the convolutional codes under consideration. The codes have the maximum free distance for the corresponding constraint length and code rate [14, 15]. Therefore, these codes give the best transmission performance asymptotically with coherent detection. For the reverse link with noncoherent detection, these codes also have the best BER upper bounds asymptotically over an L-path Rayleigh fading channel.

Table 1: Convolutional codes used in the analysis

Code number	Code rate r	Constraint length K	Generators in octal		
1	1/2	7	171	133	
2	1/2	9	753	561	
3	1/3	7	175	145	133
4	1/3	9	711	663	557

Figs. 1 and 2 show the upper bound of the BER performance for the codes with noncoherent demodulation using orthogonal signals ($M = 64$) with the decoding parameter $A = 0$ over one-path ($L = 1$) and two-path equal-strength ($L = 2$) Rayleigh fading channels respectively. It is observed that the transmission performance improves as the code constraint length K increases and/or the code rate r decreases, as expected. The BER performance improvement is achieved at the cost of the transmission overhead and the complexity of the encoder and decoder. As L is increased from 1 to 2, the BER performance is also improved because diversity reception is an

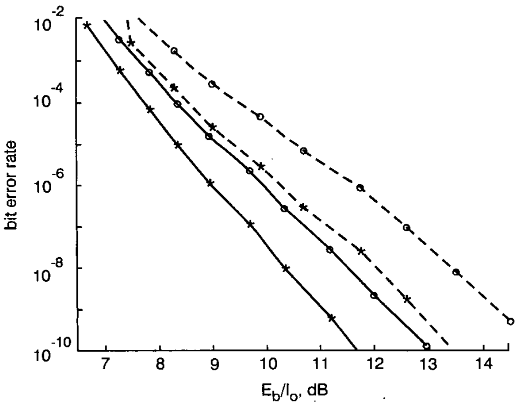

Fig. 1 *BER performance over a one-path Rayleigh fading channel*
--O-- $K = 7, r = 1/2$
—O— $K = 7, r = 1/3$
--*-- $K = 9, r = 1/2$
—*— $K = 9, r = 1/3$
$L = 1, A = 0$

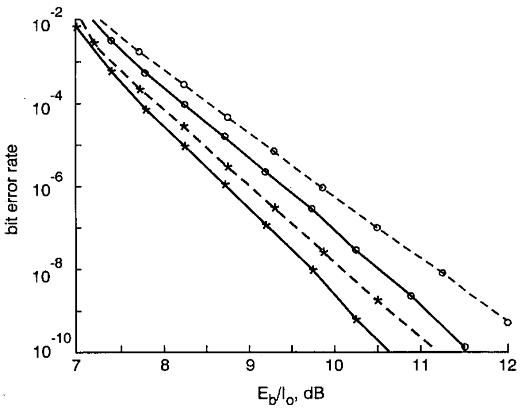

Fig. 2 *BER performance over a two-path equal-strength Rayleigh fading channel*
--O-- $K = 7, r = 1/2$
—O— $K = 7, r = 1/3$
--*-- $K = 9, r = 1/2$
—*— $K = 9, r = 1/3$
$L = 2, A = 0$

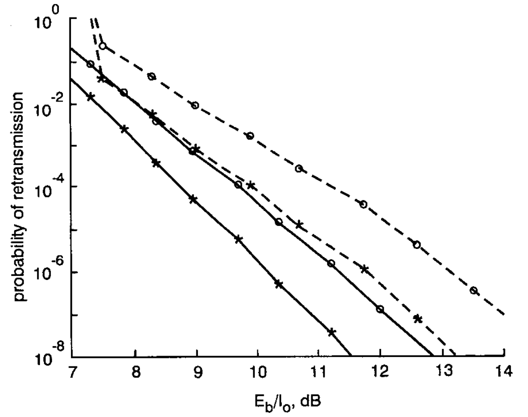

Fig. 3 *Probability of retransmission over a one-path Rayleigh fading channel*
--O-- $K = 7, r = 1/2$
—O— $K = 7, r = 1/3$
--*-- $K = 9, r = 1/2$
—*— $K = 9, r = 1/3$
$L = 1, A = 10$

efficient approach to mitigating the effect of channel fading. Figs. 3 and 4 give the upper bound of the retransmission probability (p_r) for the codes with the decoding parameter $A = 10$ over one-path ($L = 1$) and two-path equal-strength ($L = 2$) Rayleigh fading channels respectively. As the value of E_b/I_0 increases, probability of bit error decreases, so does the probability of retransmission. For the same E_b/I_0 value, the probability of retransmission decreases as the L value increases from 1 to 2 due to reduced effect of channel fading on degrading transmission performance. Among the codes under consideration, code 4 has the best performance and code 1 has the worst in terms of requiring the minimum E_b/I_0 for the same transmission error and retransmission probability.

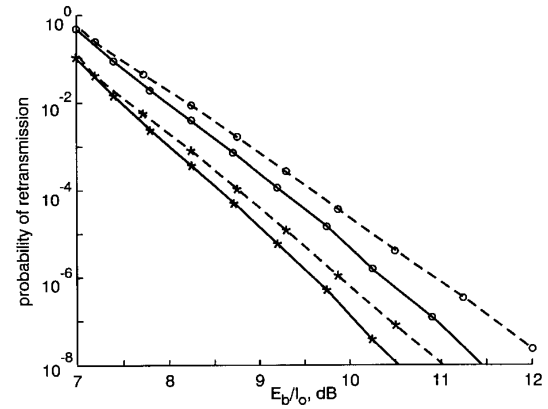

Fig. 4 *Probability of retransmission over a two-path equal-strength Rayleigh fading channel*
--O-- $K = 7, r = 1/2$
—O— $K = 7, r = 1/3$
--*-- $K = 9, r = 1/2$
—*— $K = 9, r = 1/3$
$L = 2, A = 10$

Table 2: Required E_b/I_0 (dB) and frequency bandwidth efficiency (bit/s/Hz) over a one-path Rayleigh fading channel without ARQ

	Code 1		Code 2		Code 3		Code 4	
BER	E_b/I_0	γ	E_b/I_0	γ	E_b/I_0	γ	E_b/I_0	γ
10^{-3}	8.5	0.1454	7.9	0.1684	7.7	0.1758	7.1	0.1980
10^{-4}	9.5	0.1182	8.6	0.1430	8.4	0.1512	7.8	0.1722
10^{-5}	10.6	0.0944	9.4	0.1202	9.2	0.1275	8.4	0.1503
10^{-6}	11.8	0.0736	10.3	0.1002	10.0	0.1074	9.0	0.1326
10^{-7}	12.6	0.0618	11.1	0.0838	10.8	0.0906	9.7	0.1128
10^{-8}	13.4	0.0532	12.0	0.0694	11.6	0.0765	10.4	0.0981
10^{-9}	14.2	0.0452	12.9	0.0584	12.3	0.0657	11.0	0.0855

Table 3: Required E_b/I_0 (dB) and frequency bandwidth efficiency (bit/s/Hz) over a two-path equal-strength Rayleigh fading channel without ARQ

	Code 1		Code 2		Code 3		Code 4	
BER	E_b/I_0	γ	E_b/I_0	γ	E_b/I_0	γ	E_b/I_0	γ
10^{-3}	7.9	0.1666	7.4	0.1860	7.8	0.1704	7.4	0.1869
10^{-4}	8.6	0.1452	8.0	0.1648	8.4	0.1512	7.9	0.1680
10^{-5}	9.2	0.1254	8.5	0.1476	8.9	0.1356	8.4	0.1503
10^{-6}	9.9	0.1092	9.0	0.1216	9.4	0.1203	8.7	0.1392
10^{-7}	10.5	0.0954	9.5	0.1168	10.0	0.1062	9.2	0.1254
10^{-8}	11.2	0.0824	10.1	0.1046	10.5	0.0966	9.8	0.1116
10^{-9}	11.8	0.0736	10.7	0.0910	11.0	0.0867	10.2	0.1023

Tables 2 and 3 give the required E_b/I_0 value and frequency spectrum efficiency γ for the codes to provide required BER performance over one-path and two-path equal-strength Rayleigh fading channels respectively, where retransmission is not allowed (using a conventional Viterbi decoder for real-time traffic). The length of each packet is 50 bytes, with a 2-byte header and 48-byte information. It is observed that: (i) To provide higher transmission accuracy, the required E_b/I_0 value increases, which results in a reduced frequency spectrum efficiency; (ii) In terms of the spectrum efficiency, the rate 1/3 codes perform better than the rate 1/2 codes and, for the same code rate, codes with a larger constraint length perform better; (iii) As L increases from 1 to 2, the spectrum efficiency of all the codes increases, due to the suppressed channel fading impairments. Tables 4 and 5 give the required E_b/I_0 value, the optimal decoding parameter A value, and the frequency spectrum efficiency for the codes where retransmission is allowed (using the modified Viterbi decoder for nonreal-time traffic). The packet length is equal to 50 bytes. It is observed that:

(i) The optimal decoding threshold A value increases as the required BER value decreases. With ARQ, a smaller BER value should be achieved by both requiring a higher E_b/I_0 value and having a larger A value (i.e. larger probability of retransmission), so that the total transmitted power (taking retransmission into account) is minimal.

(ii) For a large BER value such as 10^{-3}, using ARQ does not increase the spectrum efficiency due to a large probability of retransmission. However, as the required BER value reduces, allowing retransmission reduces the required E_b/I_0 value and hence increases the spectrum efficiency, at the expense of increased transmission delay due to retransmission.

(iii) The improvement of the spectrum efficiency by using ARQ increases as the required BER value decreases. At a BER of 10^{-9}, the efficiency is increased by 40% to 60% for $L = 1$ and 27% to 40% for $L = 2$. ARQ is particularly effective when the transmitted signal experiences deep channel fading.

(iv) Using ARQ, the spectrum efficiency is significantly increased for the rate 1/2 codes but only slightly increased for the rate 1/3 codes, when L is increased from 1 to 2. In fact, for a BER larger than or equal to 10^{-5}, the diversity reception reduces the spectrum efficiency when the rate 1/3 codes are used. This can be explained as follows. The bit energy E_b is defined as the received signal energy per bit from both diversity paths when $L = 2$. With noncoherent demodulation, there exists a noncoherent combining loss during the process that signals from the two paths are combined. The loss decreases as the E_b/I_0 increases or the BER decreases [16]. For a large BER value, the noncoherent combining loss is larger than the gain due to diversity, resulting in no performance improvement or even worse performance. It should be mentioned that the comparison is based on the same total received signal energy per bit. In reality, with the same transmitted signal power and the same channel condition, diversity reception with $L = 2$ can achieve 3dB larger received signal bit energy than that with $L = 1$. As a result, the diversity reception achieves better performance even at a large BER. It is expected that as the value of L increases such as $L = 4$ or $L = 8$, the required E_b/I_0 value will decrease correspondingly with or without ARQ, as more diversity paths improve transmission accuracy. In the case of having ARQ, the optimal value of the threshold A also decreases as L increases.

Fig. 5 shows the spectrum efficiency γ^* as a function of the packet length N with a two-byte header for code 2 over one-path and two-path equal-strength Rayleigh fading channels respectively. When N has a small value (up to 100 bytes), increasing the N value achieves a better spectrum efficiency, primarily due to the reduced overhead of the two-byte header. As the N value further increases, the spectrum efficiency gradually reduces because of the significantly increased retransmission probability. With the assumption of perfect interleaving, the variation pattern of the spectrum efficiency versus packet length does not

Table 4: Required E_b/I_0 (dB), optimal A value and frequency bandwidth efficiency (bit/s/Hz) over a onepath Rayleigh fading channel with ARQ

	Code 1			Code 2			Code 3			Code 4		
BER	E_b/I_0	A	γ	E_b/I_0	A	γ	E_b/I_0	A	γ	E_b/I_0	A	γ
10^{-3}	8.5	0.0	0.1382	7.6	0.0	0.1716	7.5	0.0	0.1611	7.3	0.2	0.1848
10^{-4}	9.1	2.0	0.1234	8.0	2.2	0.1550	8.1	1.2	0.1539	7.6	2.2	0.1719
10^{-5}	9.6	4.2	0.1102	8.5	4.4	0.1400	8.5	3.4	0.1410	7.9	4.4	0.1602
10^{-6}	10.1	6.4	0.0986	9.0	6.4	0.1266	8.9	5.8	0.1293	8.3	6.4	0.1494
10^{-7}	10.6	8.6	0.0880	9.4	8.6	0.1144	9.3	8.0	0.1185	8.6	8.6	0.1392
10^{-8}	11.2	10.8	0.0790	9.9	10.8	0.1036	9.7	10.4	0.1089	8.9	10.8	0.1296
10^{-9}	11.7	13.0	0.0708	10.3	13.0	0.0938	10.1	12.6	0.0999	9.2	12.8	0.1209

Table 5: Required E_b/I_0 (dB), optimal A value and frequency bandwidth efficiency (bit/s/Hz) over a two-path equal-strength Rayleigh fading channel with ARQ

	Code 1			Code 2			Code 3			Code 4		
BER	E_b/I_0	A	γ	E_b/I_0	A	γ	E_b/I_0	A	γ	E_b/I_0	A	γ
10^{-3}	7.9	0.0	0.1564	7.4	0.0	0.1768	7.8	0.0	0.1545	7.4	0.0	0.1746
10^{-4}	8.3	1.6	0.1472	7.7	1.4	0.1682	8.2	0.8	0.1530	7.7	1.2	0.1686
10^{-5}	8.7	3.8	0.1368	8.0	3.6	0.1580	8.5	3.2	0.1437	8.0	3.4	0.1599
10^{-6}	9.0	6.0	0.1274	8.3	6.0	0.1486	8.8	5.4	0.1353	8.2	5.6	0.1518
10^{-7}	9.3	8.2	0.1186	8.6	8.2	0.1396	9.0	7.8	0.1275	8.5	7.6	0.1443
10^{-8}	9.7	10.6	0.1102	8.9	10.4	0.1314	9.3	10.0	0.1200	8.7	9.8	0.1371
10^{-9}	10.0	12.8	0.1028	9.1	12.6	0.1236	9.6	12.4	0.1131	8.9	12.0	0.1302

change much as L increases from 1 to 2 and/or the BER value increases from 10^{-9} to 10^{-5}. A packet with 48-byte to 96-byte payload is a good choice for the code over the Rayleigh fading channel.

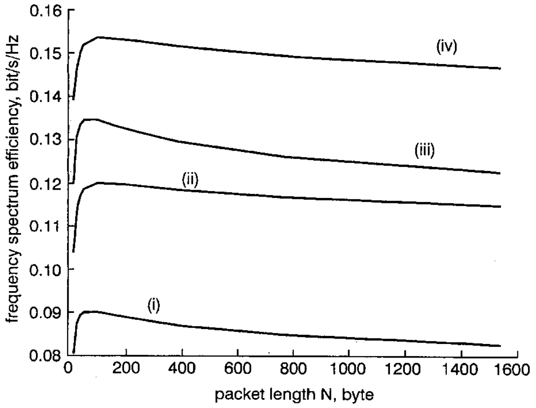

Fig. 5 *Frequency spectrum efficiency γ^* against packet length N*
(i) $L = 1$, BER = 10^{-9}
(ii) $L = 2$, BER = 10^{-9}
(iii) $L = 1$, BER = 10^{-5}
(iv) $L = 2$, BER = 10^{-5}

The above numerical results are obtained under the assumption of accurate power control which removes the effect of slow fading such as lognormal shadowing. In reality, imperfect power control may result in a lognormal distribution of local (averaged over a short time period) received E_b/I_0 [13]. The imperfect power control will degrade the transmission accuracy. As a result, the received E_b/I_0 should be increased correspondingly to achieve the target BER. On the other hand, if ARQ is allowed, then the required increase of the E_b/I_0 value (or the received power) is not significant, due to the fact that the slow fading is correlative and ARQ is particularly effective to combat bursty errors.

5 Conclusions

Error control and power control issues have been investigated for noncoherent reverse link transmission of the packetised DS-CDMA wireless network. The proposed integrated error control and power control strategy can simultaneously guaranteel QoS requirements of various traffic types and maximise the frequency spectrum efficiency. The upper bounds of BER and retransmission probability for the orthogonal signalling with noncoherent demodulation are derived. Numerical results are presented to demonstrate the effects of diversity reception, BER requirement, transmission delay requirement (real-time or nonreal-time services), and packet length on the frequency spectrum efficiency. It is shown that, by using an ARQ protocol with optimal power control and convolutional coding for delay insensitive traffic, the spectrum efficiency can be significantly increased (up to 60%).

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