PAPER

A Hybrid-ARQ Protocol with Adaptive Rate Error Control

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SUMMARY This paper presents an adaptive rate error control scheme for digital communication over time-varying channels. The cyclic code with majority-logic decoding is used in a cascaded way as an inner code to create a simple and powerful hybrid-ARQ error control scheme. Inner code is used only for error correction and the outer code is used for both error correction and error detection. When an error is detected, retransmission is required. The unsuccessful packets are not discarded as with conventional schemes, but are combined with their retransmitted copies. Approximations for the throughput efficiency and the undetectable error probability are given. A high reliability coupled with a simple high-speed implementation makes it suitable for high data rate error control over both stationary and non-stationary channels. Adaptive error control scheme becomes the best solution for time-varying channels when the optimum code is selected according to the actual channel conditions to enhance the system performance. The main feature of this system is that the basic structure of the encoder and decoder need not be modified while the error-correction capability of the code increases. Results of a comparative analysis show that the proposed scheme outperforms other similar ARQ protocols.

key words: *information theory and coding theory, communication theory, hybrid-ARQ error control codes, error correction codes, adaptive rate error control, selective-repeat ARQ*

1. Introduction

Error control techniques can generally be classified either as forward-error-correction (FEC) or as automatic-repeat-request (ARQ) [1]. The positive attributes of both FEC and ARQ techniques can be obtained by combining the techniques within a single hybrid-ARQ protocol [1]. One of the most popular hybrid approaches involves the encoding of transmitted data blocks for both error detection and correction. In many ARQ schemes, the received blocks which are detected to be in error are usually discarded. However, an error-detected block still contains an appreciable amount of information. Therefore, several ARQ schemes using parity retransmissions were proposed [2]–[6], which take advantage of the residual information in the error-detected blocks.

Majority-logic techniques are used in the decoding of both block and convolutional codes to provide a modest amount of coding gain. The implementation simplicity of the majority-logic techniques is the primary benefit attained through the use of these techniques, and thus allows for the operation of these decoders at very high data rates.

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Kousa and Rahman [2] proposed a scheme, in which two linear block codes, denoted by C_0 and C_1 are used in a concatenated code. The inner code C_1 is an (N, K) systematic Hamming code which is designed to correct $t = 1$ error in a block, and the inner code is used in a cascaded way of the same code. The outer code is an (n, k) binary BCH code, which is designed for error detection only.

In this paper, we modify the coding scheme proposed by Kousa and Rahman by that the outer (n, k) BCH code is used to correct errors and simultaneously to detect errors. The inner code is an (N, K) systematic binary cyclic code with majority-logic decoding which can be decoded by a much simpler algorithm [1] compared to other codes, and hence a high decoding speed can be obtained. The proposed system retains the simplicity of the original decoder, but provides a significant improvement in error protection through the incorporation of cascaded coding and hybrid-ARQ techniques. In the next section the scheme of the hybrid-ARQ protocol with adaptive rate error control is introduced. Section 3 concentrates on the error probability analysis. The throughput analysis is given in Sect. 4. The results and performance comparisons are presented in Sect. 5.

2. Cascaded Majority-Logic Decoding of Cyclic Codes

The proposed scheme is shown in Fig. 1. The outer code is a high-rate (n, k) BCH code used for both error correction and error detection at the first transmission, and only for error detection after the first transmission. The inner code is an (N, K) systematic cyclic code used in a cascaded way of the same code and for error correction only.

The k information bits are first encoded by the outer encoder into n bits. The block of n bits is then divided into groups of K bits . Each group of K bits is encoded into N bits by an (N, K) cyclic encoder. The total number of bits at this stage is $(n/K)N$. This stage is referred to as the first level of cascading. The $(n/K)N$ available bits can be divided into groups of K bits again and each group is encoded into N bits again by same

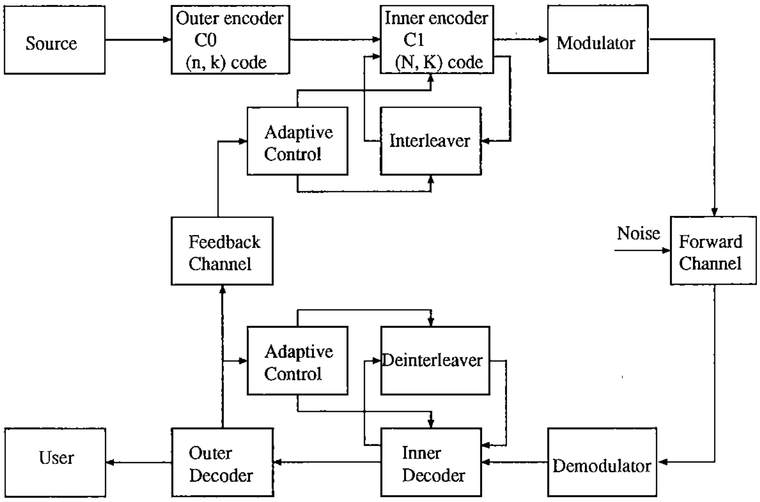

Fig. 1 A communication system using a hybrid-ARQ scheme with adaptive rate error control.

encoder as in first level of cascading. This stage is referred to be second level of cascading. At the end of this stage, there should be $(n/K^2)N^2 = n(N/K)^2$ bits. Any level of cascading can be reached by repeating this process. If the initial sequence (n bits) is of length K^m or any integer multiple of K^m, where m is the maximum intended level of cascading, we can obtain an integer number of sub-blocks after each division by K at any stage. For m-level cascading we get $n(N/K)^m$ bits.

When the receiver receives a sequence of bits which are known to have been encoded to the m-th level, the receiver divides the received sequence into blocks of N bits, and computes the syndrome of each block to perform error correction, then the receiver discards the check bits leaving the K information bits. The remaining bits correspond to the $(m-1)$-th level of cascading. There are $n(N/K)^{m-1}$ bits at this stage. These $n(N/K)^{m-1}$ bits are divided into blocks of N bits again, and each block is decoded by receiver and check bits are discarded. This process is repeated until the receiver decodes the original n information bits. If the selection of K bits for a sub-block is done carefully at each stage, any further cascading leads to a higher error-correction capability of the system.

To guarantee the correct decoding of the cascading code, the perfect interleaving is absolutely needed. The process of perfect interleaving is equivalent to randomizing the errors after any level of decoding process. At the transmitter side, to perform a second level of encoding, each K information bit should be chosen from K different blocks of the first level of coding. Similarly to perform a third level of encoding, each K information bit should be chosen from K different blocks of the first and the second level of encoding. This process is the perfect interleaving. When the cascaded encoding process is organized by such suitable interleaving, the bit errors in each block after de-interleaving are guaranteed to be statistically independent, because each decoded bit comes from a different block. An example of the perfect interleaving is shown in Fig. 2, where two level of encoding a $(7, 4)$ systematic Hamming code are used for simplicity.

For the first transmission, only the outer code C_0 is used. The outer code is a high rate (n, k) BCH code which is used to correct t errors and simultaneously to detect many other errors. The receiver does both decoding and error detection for c_0, where c_0 is a codeword of C_0. If the decoder decides that c_0 has an error pattern of weight no greater than t, then the decoder corrects the errors and no retransmission is required. If c_0 is detected to contain an uncorrectable error pattern, then a retransmission is requested, and the erroneous word is saved in a buffer. The retransmission consists of parity-check bit sub-blocks, which is based on the original message and the cyclic code at the first level of encoding. When this super-block of parity-check bits is received, it is used to correct the errors in the erroneous word stored in the received buffer, and the decoded block is checked for errors by the outer code decoder(only for detecting errors). If it is not a codeword of C_0, then an error condition is detected. The receiver stores the first-level parity-check bits also and requests a second retransmission.

The second retransmission consists of another super-block of parity-check bit sub-blocks based on the original message, the first-level check bits which are already stored at the transmitter, and the same error-correcting code. Appropriate interleaving before encoding and de-interleaving after decoding are assumed. When this block of second-level check bits is received, it is again used to correct the erroneous message stored at the receiver. This process is repeated if necessary un-

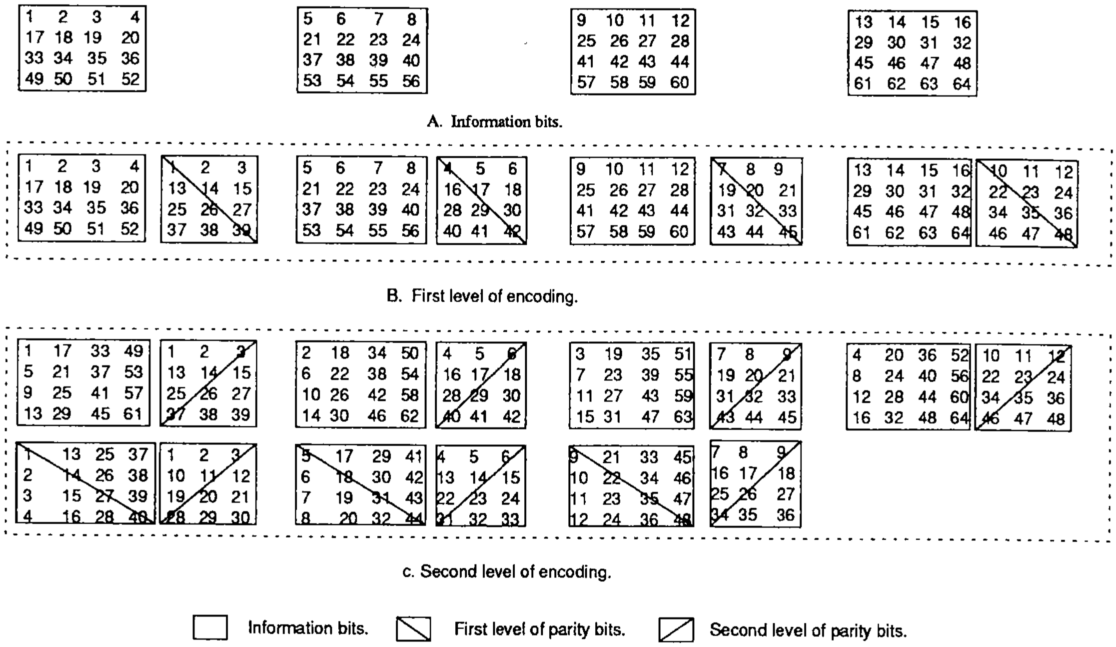

Fig. 2 Interleaving and encoding for two levels of cascading of the (7, 4) systematic Hamming code.

til the m-th level parity-check bits are transmitted. If a negative acknowledgement (NACK) is still sent back, the next transmission should be the initial information sequence again. The receiver will automatically replace the old information bits by the new ones and try to decode the message with the help of all parity checks already available. If an NACK is again received, the next transmission is the same as the first retransmission, containing the first level of parity checks, and so on. The sequence of transmissions in this procedure for successive NACK's will be $I, P_1, P_2, \ldots, P_m, I, P_1, \ldots$, where I is the original n-bit message and P_i is the i-th level parity sub-block. After the $(2m)$-th retransmission, the whole set will have been renewed. With the reception of parity bits at the i-th level ($i = 1, 2, \ldots, m$), the decoder is required to rearrange the information sequence and the parity bits up to the $(i-1)$-th level in order to be consistent with the interleaving operation by the encoder.

3. Performance Analysis

The channel is assumed to be a binary symmetric channel (BSC) with transition probability ε. For the first transmission, only outer code is used for error correction and error detection. Thus we have the following relation

$$P(D_c^0) + P(D_{ud}^0) = P(D_a^0) \tag{1}$$

and

$$P(D_a^0) + P(D_d^0) = 1, \tag{2}$$

where $P(D_c^0)$ is the probability that the received decoded n-bit word is error free at first transmission, $P(D_{ud}^0)$ is the probability of an undetected error for the outer error-detection (n, k) BCH code C_0 in the received decoded n-bit word error pattern at first transmission, $P(D_a^0)$ is the probability that the received decoded n-bit word is accepted by the receiver at the first transmission, and $P(D_d^0)$ is the probability that the outer code detects errors at the first transmission. $P(D_{ud}^0)$ is given by [7], [8]

$$P(D_{ud}^0) = \sum_{w=d_0}^{n} A_w \sum_{i=0}^{t_0} \sum_{j=0}^{\min(t_0-i, n-w)} \binom{w}{i} \times \binom{n-w}{j} \varepsilon^{w-i+j} (1-\varepsilon)^{n-w+i-j} \tag{3}$$

where A_w, $w = d_0, d_1, \cdots, n$, is the number of codewords in C_0 of weight w. In most interesting cases, $P(D_{ud}^0) \ll P(D_c^0)$, and hence

$$P(D_a^0) \doteq P(D_c^0) \tag{4}$$

and

$$P(D_d^i) \leqq 1 - P(D_c^i) \tag{5}$$

where i is the ith retransmission and $i = 0$ is first transmission.

For the outer code with error correcting ability t_0, we have

$$P(D_c^0) = \sum_{i=0}^{t_0} \binom{n}{i} \varepsilon^i (1-\varepsilon)^{n-1}. \tag{6}$$

After the first transmission, the outer code is used only for error detection. The probability of undetected error is then

$$P(D_{ud}^{i}) = \sum_{w=d_0}^{n} A_w \varepsilon^{w}(1-\varepsilon)^{n-w}. \quad (7)$$

From Refs. [7] and [8], we can find that the $P(D_{ud}^{0})$ and $P(D_{ud}^{i})$ are negligibly small if 40 parity check bits of the outer code are used for error correction and error detection, and thus the outer code can be considered to be a perfectly error detected-code. In the following, the performance of the inner code is analyzed. For an (N, K) cyclic code with minimum distance d_{min} and error correction ability t, the bit error rate after decoding is given by

$$\varepsilon' \leqq \frac{1}{N}\sum_{i=t+1}^{N}\binom{N}{i}\varepsilon^{i}(1-\varepsilon)^{N-i}. \quad (8)$$

Figure 3 shows upper bound of ε' versus ε for $(15, 7)$, $(15, 9)$, $(64, 37)$, and $(64, 49)$ systematic codes with $t = 2$, 1, 4, and 1, respectively.

Similarly, the decoded bit error probability with two levels of decoding is given by

$$\varepsilon'' \leqq \frac{1}{N}\sum_{i=t+1}^{N}\binom{N}{i}(\varepsilon')^{i}(1-\varepsilon')^{N-i}. \quad (9)$$

Thus, Eq. (8) can be used recursively, by replacing ε with the bit error probability after decoding from the previous level.

If an (N, K) cyclic code with the error correcting ability t is employed for inner coding, the probability of correct decoding is

$$p(D_c^1) \leqq \sum_{i=0}^{t}\binom{N}{i}\varepsilon^{i}(1-\varepsilon)^{N-i} \quad (10)$$

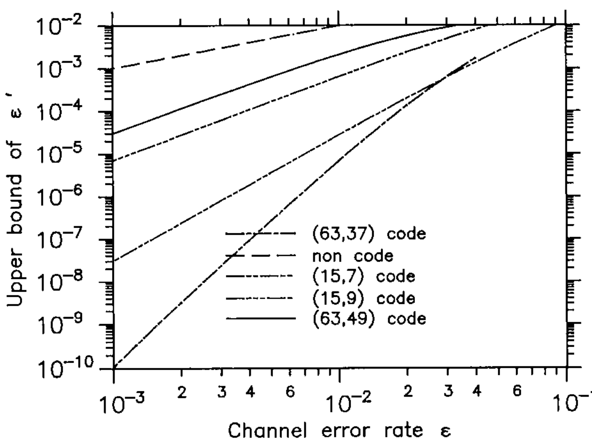

Fig. 3 Upper bound of the decoded bit error rate versus channel bit error rate.

where $p(D_c^i)$ is the probability of correct decoding of a sub-block for the cascading level i. For the two levels of cascading, the bit error rate at the receiver after the first decoding step will reduce to ε'. Due to interleaving, we obtain N such independent bits. The probability of correct decoding of a block after the second decoding step is then given as

$$p(D_c^2) \leqq \sum_{i=0}^{t}\binom{N}{i}(\varepsilon')^{i}(1-\varepsilon')^{N-i}. \quad (11)$$

This technique can be applied to any level of cascading under the condition of perfect interleaving.

The previous discussion takes one block of N bits into consideration. In principle, for any level of cascading, we should have n/K blocks of N bits to be decoded just before the final step of decoding.

Let $P(D_c^i)$ denote the probability of correct decoding of the super-block (the block of n/K sub-block), for the encoding level i ($i = 1$ and 2). Thus we get

$$P(D_c^i) = [p(D_c^i)]^{n/K}, \quad (12)$$

if a perfect interleaving as mentioned in Sect. 2 is made.

4. Throughput Analysis

We assume that the forward channel is a random error channel with bit error rate ε, and the feedback channel is error-free. Since selective repeat (SR) ARQ is the most efficient ARQ scheme, we consider the throughput of the system in the SR mode. we first consider the situation of infinite m. In order to calculate the throughput, we determine the average number of bits needed to be transmitted before k information bits are successfully accepted by the receiver. If we denote this number by T_r, then the throughput η is given by

$$\eta = \frac{k}{T_r}. \quad (13)$$

We can write

$$\begin{aligned} T_r = &[a(0)]P(D_c^0) + [a(0)+a(1)]P(D_d^0, D_c^1) \\ &+ [a(0)+a(1)+a(2)]P(D_d^0, D_d^1, D_c^2) \\ &+ [a(0)+a(1)+a(2)+a(3)] \\ &\times P(D_d^0, D_d^1, D_d^2, D_c^3) + \cdots \end{aligned} \quad (14)$$

where $a(i)$ denotes the number of bits in i-th transmission.

The expression for T_r given in Eq. (14) is a general expression for the average number of bits to be transmitted in a hybrid-ARQ system. Applying Eq. (5) to Eq. (14), we get

$$\begin{aligned} T_r = &a(0) + a(1)P(D_d^0) + a(2)P(D_d^0, D_d^1) + \cdots \\ &+ a(i)P(D_d^0, D_d^1, \cdots, D_d^{i-1}) + \cdots. \end{aligned} \quad (15)$$

T_r is therefore lower and upper bounded by

$$a(0)+\sum_{n=1}^{\infty}a(n)\prod_{j=1}^{n}P(D_d^{j-1})\leqq T_r\leqq a(0)+\sum_{n=1}^{\infty}a(n)P(D_d^{n-1}). \quad (16)$$

We use $T=T_r/a(0)$ to express the average number of transmission in the hybrid-ARQ system. Then

$$1+\sum_{n=1}^{\infty}\frac{a(n)}{a(0)}\prod_{j=1}^{n}P(D_d^{j-1})\leqq T\leqq 1+\sum_{n=1}^{\infty}\frac{a(n)}{a(0)}P(D_d^{n-1}). \quad (17)$$

Next, we consider the situation of only m parity retransmissions being used. For the left side of Eq. (17), we get

$$T\geqq 1+\sum_{n=1}^{m}\frac{a(n)}{a(0)}\prod_{j=1}^{n}P(D_d^{j-1})+\sum_{j=1}^{m+1}P(D_d^{j-1})\times[1+\sum_{n=1}^{m}\frac{a(n)}{a(0)}P^n(D_d^m)\frac{1}{1-P^{m+1}(D_d^m)}]. \quad (18)$$

For the right side of (17), we get

$$T\leqq 1+\sum_{n=1}^{m}\frac{a(n)}{a(0)}P(D_d^{n-1})+P(D_d^m)\times[1+\sum_{n=1}^{m}\frac{a(n)}{a(0)}\frac{P^n(D_d^m)}{1-P^{m+1}(D_d^m)}]. \quad (19)$$

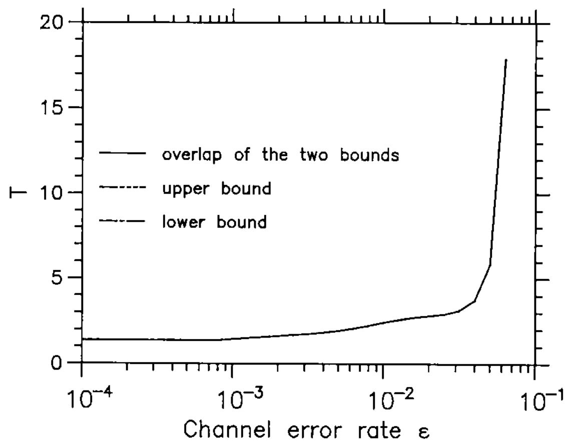

Fig. 4 Upper and lower bounds on the average number of transmissions.

Clearly, since $P(D_d^n)$ decreases exponentially as n increases, Both summations in Eqs. (18) and (19) converge. Evaluation of T, using the approximation of $P(D_d^n)$ by the lower bound given by Eq. (5) has shown that the two bounds on T agree at high and moderate signal-to-noise ratios, and differ slightly at low signal-to-noise ratios. However, the difference is relatively small as shown in Fig. 4 where the two bounds are overlapped with each other. As a consequence of the tightness of the two bounds Eqs. (18) and (19), the average number of transmissions T for a given data packet can thus be approximated by the upper bound.

The expression of the throughput efficiency η for the selective-repeat ARQ protocol, defined as the average number of accepted information bits per transmitted channel symbol, is given by

$$\eta=k/T_r=k/a(0)T. \quad (20)$$

5. Results and Performance Comparisons

Here we examine the throughput over the BSC of the adaptive hybrid-ARQ scheme for the inner codes with $(15,7), (15,9), (63,37)$, and $(63,49)$ systematic cyclic codes and the majority-logic decoding with cascading level $m=2$. Outer codes is selected as follows [2]. For (15,7) code, the outer code can be selected as (1029,983) code by adding 6 check bits to the (1023,983) BCH code. For (15,9) code, by deleting 51 bits of the (1023,983) BCH code we can get the shortened (972,932) BCH code. For (63,37) code, the outer code is selected as (4107,4047) by adding 12 check bits to the (4095,4047) BCH code. For (63,49) code, by deleting 1694 bits of the (4095,4047) BCH code we get the shortened (2401,2353) BCH code. Obviously, the performance of the extended and shortened BCH codes is better than that of the original BCH codes.

The throughput for the outer code with $t=0$ is shown in Fig. 5. From this figure we find that at a low

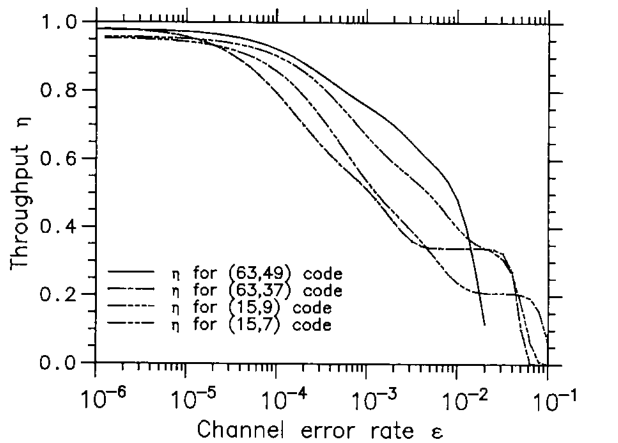

Fig. 5 Throughput rate of an adaptive rate hybrid-ARQ scheme for outer codes with error correction ability $t=0$.

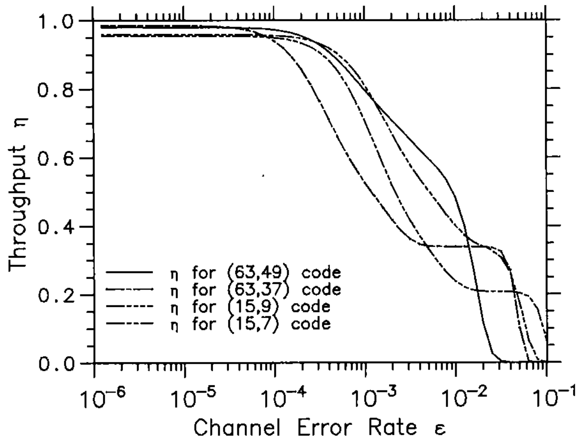

Fig. 6 Throughput rate of an adaptive rate hybrid-ARQ scheme for outer codes with error correction ability $t = 1$.

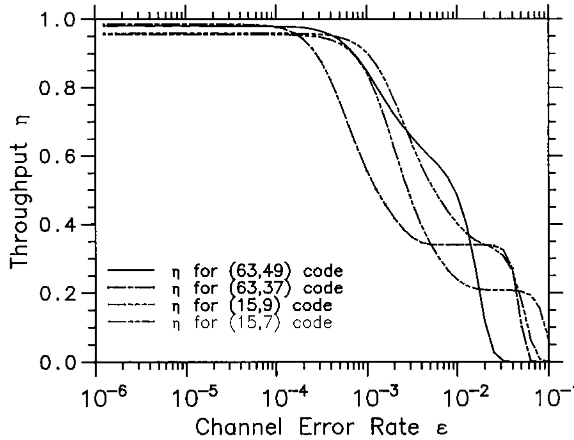

Fig. 7 Throughput rate of an adaptive rate hybrid-ARQ scheme for outer codes with error correction ability $t = 2$.

channel error rate the throughput mainly depends on the outer code rate. At a medium channel error rate the throughput mainly depends on inner code rate, and at a high channel error rate the throughput mainly depends on the error correction ability. So in the low error probability case the throughput is almost the same for the four schemes with different inner code rate. In the medium level error probability, the schemes with higher rate inner code have higher throughput rate, and at the higher level error probability, the schemes with higher error correction ability inner code have the higher throughput rate.

Figure 6 and Fig. 7 show the throughput rate for the outer code with $t = 1$ and 2, respectively. It is clear that the throughput rate increases as the error correction ability of the outer code increases. The error correction ability of the outer code greatly improves the throughput of the system. The throughput rates of our scheme with the $(15, 9)$ cyclic inner code and the outer code having error correction ability $t = 2$ and $m = 2$ is plotted in Fig. 8 as "Our scheme A". The

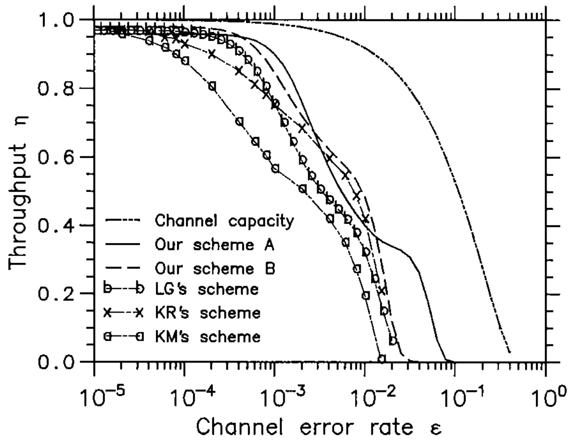

Fig. 8 Comparison of the throughput rate for the different schemes.

throughput rates of our scheme with the $(63, 49)$ cyclic inner code and the outer code having error correction ability $t = 2$ and $m = 2$ represented by "Our scheme B" is also plotted in the figure. In order to examine the performance of the proposed scheme, we have compared it with other schemes. Lin and Guu proposed a scheme [5], in which inner code is a $(8, 4)$ extended Hamming code and outer code is a $(1024, 993)$ extended BCH code. The result of Lin and Guu's scheme is indicated by "LG" in Fig. 8. In the same figure the result of Krishna and Morgera's scheme [6] (KM) is also plotted. The results of the Kousa and Rahman's scheme [2] represented by "KR" with the $(15, 11)$ Hamming code as the inner code and outer code having error correcting ability $t = 0$ and $m = 2$ are also shown in the same figure. For reference, the channel capacity limit C for the BSC [11] as an upper bound is given in the same figure. Results showed that under lower level of error probability, the throughput rate of our schemes are similar to that of other schemes. For ε larger than 10^{-4} our scheme B is better than all conventional schemes. Our scheme A has noticeably better performance for ε from 10^{-4} to 3×10^{-3} and from 10^{-2} to 10^{-1} than all conventional schemes, although it has a little lower throughput than our scheme B and the KR's scheme for ε from 3×10^{-3} to 10^{-2}. The advantages of our scheme are: The outer code is used for error detection and simultaneously for error correction, and hence enhances the throughput rate. The cyclic code and the majority-logic decoding are used that can simplify the decoding procedure so that the scheme can be used for high data rate transmission. The upper and lower bounds of the throughput rate are given which simplifies the analysis.

6. Conclusion

We have proposed a hybrid-ARQ protocol with adaptive rate error control and code combining. Since the channel rate is fixed in most transmission schemes due to modulation and channel filter requirements, changing the code rate means a change of information rate and thus a buffer for the incoming information stream is required. For the proposed system, the rate of the first transmission is fixed to k/n, the outer code rate. After first retransmission the rate drops to $(k/n)K/N$. The second retransmission reduces the rate to $(k/n)(K/N)^2$, and so on. With cyclic codes, we have proposed an efficient hybrid ARQ strategy which combines the benefits of the majority-logic decoding and the code-combining ARQ strategy. The performance of the concatenated adaptive coding scheme for error probability and the system throughput of the concatenated coding scheme were analyzed. The performance of several specific code examples was compared. Results indicate that a high throughput and a very low error probability can be achieved by using these schemes. The proposed scheme is found to have a relatively good throughput under poor and moderate channel conditions ($\varepsilon \geq 10^{-5}$). Therefore, the concatenated coding scheme is suitable for applications involving high speed transmission, such as satellite communication systems and file transfer systems.

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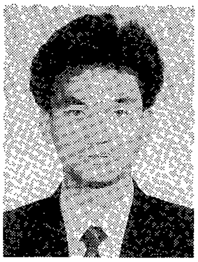

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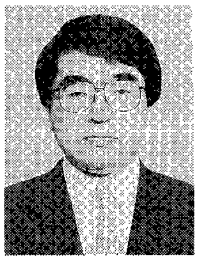

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