An Effective Go-Back-N ARQ Scheme for Variable-Error-Rate Channels

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***Abstract*— In nonstationary channels, error rates vary considerably. This letter proposes an effective go-back-N ARQ scheme which estimates the channel state in a simple manner, and adaptively switches its operation mode in a channel where error rates vary slowly. It provides higher throughput than other comparable ARQ schemes under a wide variety of error rate conditions.**

I. Introduction

ARQ (AUTOMATIC-REPEAT-REQUEST) techniques, including stop-and-wait, go-back-N, and selective repeat, are widely used for error control in data communication systems. Particularly, the go-back-N ARQ scheme is very popular because it provides higher throughput compared to stop-and-wait ARQ, and its implementation is simpler than selective repeat ARQ since it does not require buffering and resequencing at the receiver end [1].

The operation procedure and throughput efficiency of the basic go-back-N scheme is well known. One disadvantage of this scheme is that its throughput decreases quickly when the error probability increases, especially when the roundtrip delay is large, because of the repeated retransmissions of the N blocks (assuming that the roundtrip delay is equivalent to the $N - 1$ block transmission duration). Sastry modified the basic go-back-N scheme by transmitting the erred block continuously until an ACK (positive acknowledgment) is received [2] which improves the efficiency when the block error probability, P_e, is larger than 0.5. Moeneclaey and Bruneel proposed an ARQ scheme [3] which further improves the basid go-back-N efficiency when $P_e > 0.5$.

Most studies of ARQ schemes are conducted under the assumption of a fairly constant level of channel noise, i.e., a stationary channel. For example, the approaches given in [2] and [3] result in better performance than the basic go-back-N scheme only if the channel stays in a very noisy state. This letter proposes a go-back-N scheme for nonstationary channels where the error rate changes (P_e varies from as low as approaching zero to as high as 0.5 or above, possibly in a wireless communication environment). In this scheme, the transmitter estimates the channel state (low/high error rate) in a simple manner and adaptively changes its operation mode. It provides higher throughput than other comparable schemes under a wide range of error rate conditions.

The idea of dynamically changing the ARQ algorithm was previously considered in the technical literature [4]–[8], and several schemes were proposed for nonstationary channel applications. The approach taken in [4] and [6] requires the knowledge of the instantaneous block error probability which is difficult to estimate. In [5] and [8], hybrid ARQ schemes are used resulting in increased implementation complexity. The scheme proposed in this letter differs from others in its simplicity in both channel state estimation and ARQ operation.

Paper approved by N. Shacham, the Editor for Networks of the IEEE Communications Society. Manuscript received December 16, 1991; revised July 5, 1993.

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IEEE Log Number 9406244.

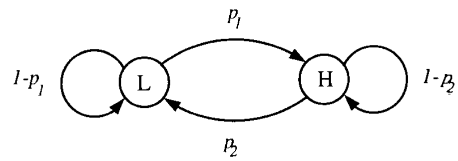

Fig. 1. Channel state model.

II. Channel States and ARQ Operation Modes

The forward channel (from the transmitter to the receiver) is considered to have two states, L state (low error rate) and H state (high error rate), as shown in Fig. 1. The channel transits from state L to state H with a probability of p_1 and from H to L with a probability of p_2.

Corresponding to the two channel states, there are two operation modes in the proposed go-back-N ARQ scheme. If the channel is in state L, the transmitter follows the basic go-back-N procedure (the basic go-back-N mode) and the system throughput is known as [2], [3]

$$S_1 = \frac{1 - P_e}{1 + (N - 1)P_e}. \quad (1)$$

In this operation mode, the transmitter goes back N blocks upon reception of an NAK (negative acknowledgment). If a total of α ($\alpha \geq 2$) contiguous NAK's are received for the same data block, the transmitter would consider that the channel is transiting from L state to H state. The transition probability is $p_1 = P_e^\alpha$ since the block errors of the first transmission and the succeeding retransmissions of the concerned data block are mutually independent.

In channel state H, the transmitter functions in an n-copy transmission mode [4], [6], which operates like the basic go-back-N scheme except for sending n copies of a data block in each transmission and, if necessary, each retransmission. The throughput of an n-copy transmission ARQ scheme is given in [4] and [6]

$$S_2 = \frac{1 - P_e^n}{n + (N - 1)P_e^n}. \quad (2)$$

The receiver sends an acknowledgment for each copy of the data block received. If the transmitter receives β ACK's ($2 \leq \beta \leq N$) continuously, the transmitter would consider that the channel is transiting from H state to L state. The transition probability is therefore $p_2 = (1 - P_e)^\beta$.

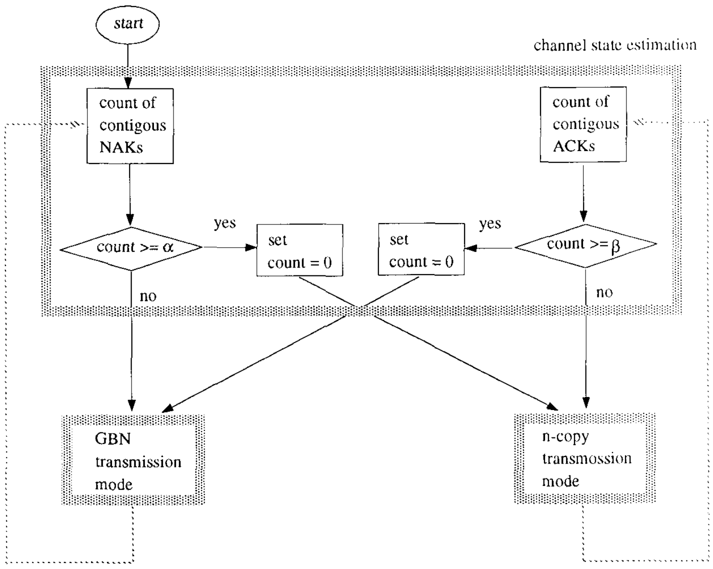

Fig. 2. Proposed ARQ scheme, transition between two operation modes.

Note that the channel state model (with parameters p_1 and p_2) shown in Fig. 1 does not define a channel environment. Instead, it is used by the transmitter to estimate the current channel state. Basically, the channel under consideration in this letter is disturbed by random noise (which results in independent errors) although the error probability may vary considerably from time to time. The variation is relatively slow compared to the roundtrip delay duration so that the transmitter can estimate the channel state based on the received acknowledgment (ACK/NAK). For simplicity, we first assume that there is a noiseless feedback channel, i.e., no errors occur in the acknowledgment messages. The effect of a noisy feedback channel will be considered in Section IV.

With the change of channel states (L/H), the proposed go-back-N ARQ scheme switches its operation modes (basic go-back-N and n-copy transmission). The decision of mode switching is made based on the received acknowledgments. The knowledge of the current channel error rate is therefore not required. The operation mode switching is characterized by a transition matrix

$$T = \begin{bmatrix} 1-p_1 & p_1 \\ p_2 & 1-p_2 \end{bmatrix}. \tag{3}$$

The flow chart shown in Fig. 2 summarizes the proposed ARQ scheme. There are three elements: the go-back-N transmission block and the n-copy transmission block as defined in [2], [3], and a channel state estimation block. The dashed line in the flow chart indicates that the transmitter obtains ACK/NAK messages through a feedback channel.

It is noted that a major element of the proposed scheme is a simple channel state estimator, based on counting contiguous ACK's/NAK's. Other known channel estimation techniques include signal power measurements [9] and pilot tone transmissions [10]. In the approach with signal power measurements, an analog absolute measure of the signal strength is made. The measurements need to be accurate over a wide dynamic signal range, which adds estimation complexity [9]. The pilot tone approach, which is often used to assist signal demodulation, can be applied for channel estimation. The pilot tone provides an explicit amplitude/phase reference relating to channel states, which also requires relatively complex signal processing [10]. The method proposed in this letter estimates the channel states without measuring the received signal power or other parameters.

III. Throughput Analysis

The proposed go-back-N scheme operates in one of the two ARQ modes and adaptively switches between them. The throughput of the proposed scheme is therefore an average of the throughput values of the two ARQ operation modes, i.e.,

$$S = S_1 P_L + S_2 P_H \tag{4}$$

where P_L is the probability that the channel is in L state and the system operates in the basic go-back-N mode and P_H corresponds to the H state and n-copy mode. Using (3), P_L is found as

$$P_L = P_L(1-p_1) + (1-P_L)p_2 \tag{5}$$

which gives $P_L = p_2/(p_1+p_2)$. Similarly, we have $P_H = p_1/(p_1+p_2)$.

Using (1), (2), and (4), it is easy to show that $S > S_1$ when $P_e > (n-1)/N$. That is to say, the proposed go-back-N scheme outperforms the basic go-back-N scheme when the block error probability is larger than $(n-1)/N$. Note that the basic go-back-N scheme is outperformed by Sastry's modification [2] and Moeneclaey and Bruneel's scheme [3] only when $P_e > 0.5$.

The throughput versus block error rate performance of the proposed go-back-N ARQ scheme ($\alpha = \beta = 2$ and $n = 2$) is

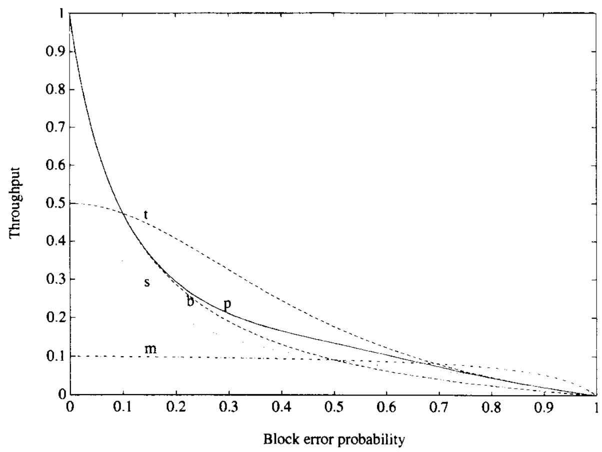

Fig. 3. Throughput versus block error probability. ($\alpha = \beta = 2$, $n = 2$, $N = 10$; t: two-copy transmission, p: proposed scheme, b: basic go-back-N, s: Sastry's modification, m: Moeneclaey and Bruneel's scheme).

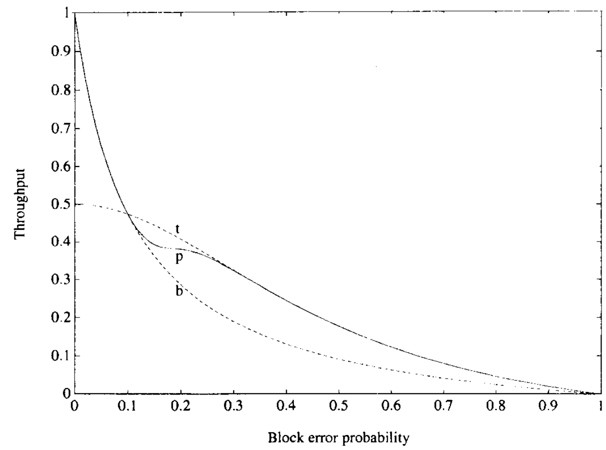

Fig. 4. Throughput versus block error probability, design parameter modified ($\alpha = 2$, $\beta = 20$, $n = 2$, $N = 10$; t: two-copy transmission, p: proposed scheme, b: basic go-back-N).

shown in Fig. 3. The performance curves of several comparable ARQ schemes are also shown in the same figure, which include 2-copy transmission (n-copy transmission with $n = 2$), basic go-back-N, Sastry's modification, and Moeneclaey and Bruneel's scheme. It is analytically shown that the proposed scheme outperforms basic go-back-N for $P_e > (n-1)/N$, and Fig. 3 indicates that, when $P_e < (n-1)/N$ (N is assumed to be 10 in the figure), the two schemes provide approximately the same performance. It is observed in Fig. 3 that, when the block error probability varies from 0 to about 0.67, the proposed scheme offers higher or similar throughput compared to other schemes except for the 2-copy case. A disadvantage of the 2-copy approach is that, compared to the proposed scheme, its throughput is very low under low error rate conditions.

Fig. 3 indicates that the two-copy transmission approach outperforms the proposed go-back-N scheme under a wide range of error rate conditions. It is therefore desirable to design the proposed go-back-N scheme such that it approaches the performance of two-copy transmission in this wide range. As defined in Section II, there are three design parameters in the proposed scheme—α, β, and n—in which α and β are related to the channel state estimation model. In Fig. 3, we assume $\alpha = \beta = 2$. If α remains to be 2 and β is chosen to be 20, i.e., the channel is considered to be transitting from state H to state L upon reception of 20 consecutive ACK's (higher probability of remaining in state H which corresponds to the 2-copy transmission mode), the proposed go-back-N scheme results in a throughput curve as shown in Fig. 4. The performance of the proposed scheme not only approaches that of basic go-back-N for low error rates, but also approaches that of 2-copy transmission under high error rate conditions. Comparing Figs. 4 and 3, it is concluded that the proposed go-back-N ARQ scheme offers much better performance than other comparable schemes under a wide range of error rate conditions.

The effects of the ARQ design parameters are further examined in Fig. 5(a)–(c). It is observed in Fig. 5(a) that the ARQ throughput is increased with an increase of β (see curves with $\beta = 2$, 10, and 20). However, an excessive increase of β results in lower throughput under lower error rate conditions (see the curve with $\beta = 30$). A larger value of α relates to a higher probability of being in state L (with basic go-back-N operations) and, as shown in Fig. 5(b), yields lower throughput within the error rate range in which the ARQ operation mode switches. The effect of n is shown in Fig. 5(c). Although a larger value of n results in improved throughput performance when the error rate is very high, a substantial throughput reduction is observed under other error rate conditions.

IV. Considerations of a Noisy Feedback Channel

This section examines the effect of a noisy feedback channel. This is an important issue since acknowledgment messages transmitted through the feedback channel determine the ARQ operation mode of the proposed scheme. We assume that feedback channel errors can only make an ACK or NAK indistinguishable. It cannot convert an ACK to NAK or vice versa [11]. That is to say, an error in an acknowledgment message can always be detected. Such an assumption is reasonable since the undetectable error probability of a massage can be made very small [5] through coding. Let us denote the error probability of an acknowledgment message as P_f and assume that a transmitter will handle an erred ACK/NAK message as an NAK.

The (forward) channel state model shown in Fig. 1 is still valid in the case with a noisy feedback channel and so are (4) and the expressions of P_L and P_H. However, the state transition probabilities p_1 and p_2 changed due to feedback channel errors. A transmitter receives an ACK if and only if both forward (data block) and feedback (acknowledgment message) transmissions are successful. Otherwise, an NAK or an indistinguishable ACK/NAK message is received. Thus we have $p_2 = [(1-P_e)(1-P_f)]^\beta$ and $p_1 = [1-(1-P_e)(1-P_f)]^\alpha$. Following the derivations in [5] and [6], we find throughput expressions

$$S_1 = \frac{(1-P_e)(1-P_f)}{1+(N-1)[1-(1-P_e)(1-P_f)]} \tag{6}$$

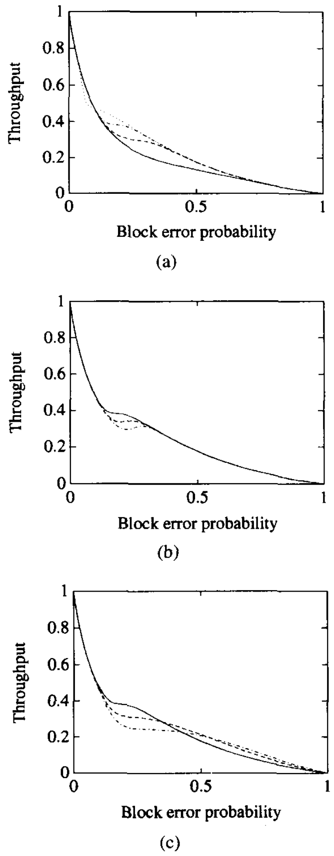

Fig. 5. Throughput versus block error probability, effects of the design parameters on the proposed ARQ scheme ($N = 10$). (a) $\alpha = 2$, $n = 2$; solid: $\beta = 2$, dashed: $\beta = 10$, dash-dot: $\beta = 20$, dotted: $\beta = 100$. (b) $\beta = 20$, $n = 2$; solid: $\alpha = 2$, dashed: $\alpha = 3$, dash-dot: $\alpha = 4$. (c) $\alpha = 2$, $\beta = 20$; solid: $n = 2$, dashed: $n = 3$, dash-dot: $n = 4$.

and

$$S_2 = \frac{1 - [1 - (1 - P_e)(1 - P_f)]^n}{n + (N - 1)[1 - (1 - P_e)(1 - P_f)]^n} \tag{7}$$

for basic go-back-N and n-copy transmission ARQ, respectively, in a noisy feedback channel.

Combining (4), (6), and (7), we could evaluate the proposed ARQ scheme under a noisy feedback channel. It is observed, in Fig. 6, that the throughput efficiency decreases with an increase of the ACK/NAK error probability. However, the throughput reduction is significant only when the ACK/NAK error rate is very high (for example, $P_f = 0.1$ in the figure). Note that, compared to the forward channel block error probability, the ACK/NAK error rate is much lower since an acknowledgment message is much shorter than a message block (forward channel).

V. Conclusions

As discussed in [6], the knowledge of block error probabilities is required in order to optimize an ARQ scheme. This letter proposes an effective go-back-N ARQ scheme which simply

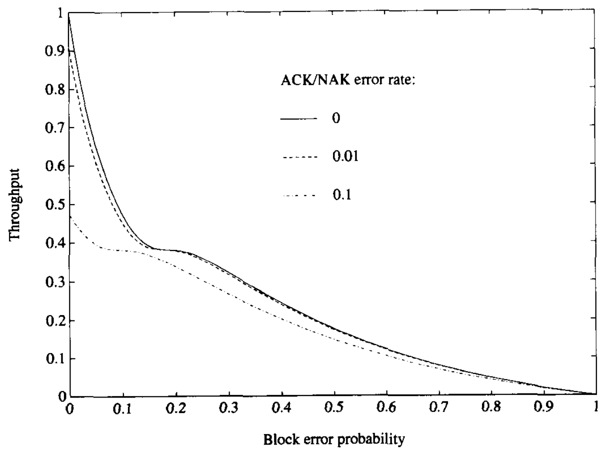

Fig. 6. Throughput versus block error probability, effects of a noisy feedback channel on the proposed ARQ scheme ($\alpha = 2$, $\beta = 20$, $n = 2$, $N = 10$).

estimates the channel state based on the acknowledgment messages received and adaptively switches its ARQ operation mode. It offers higher throughput than other comparable schemes under a wide range of error rate conditions. This is particularly applicable to nonstationary channels where error rates vary considerably. The proposed ARQ scheme can be generalized to consider more channel states. For example, using a three-state channel model (low, high, and very high error rate states), the ARQ scheme could consist of three operation modes, i.e., basic go-back-N, n-copy transmission, and, finally, Moeneclaey and Bruneel's approach [3].

Acknowledgment

The author wishes to thank the reviewers for their valuable comments.

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