Adaptive Error Control for Hybrid (Satellite-Terrestrial) Networks

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Abstract— **Hybrid satellite-terrestrial networks are becoming increasingly popular for asymmetric multimedia services such as file transfer and database services. This paper presents an adaptive error control (AEC) protocol for the hybrid network, in which the transmitter uses a combination of automatic repeat request (ARQ) over terrestrial links and forward error control (FEC) scheme with adaptive code rate over satellite links. Throughput performance shows that the proposed AEC protocol adapts to time-variant satellite channel better than the static hybrid ARQ protocol under different satellite channel conditions.**

I. INTRODUCTION

COMMERCIAL proliferation of telephone and data networks has created a great demand for various multimedia services in terrestrial networks. In the other domain, communication satellites have become the dominant carriers of long distance communications in less than 30 years [6]. These two network infrastructures have been developed as stand-alone systems. The concept of integrating the satellite and terrestrial systems has been introduced recently.

These satellite-terrestrial hybrid networks are becoming increasingly popular due to several advantages. Many multimedia applications, particularly in case of file transfer and database services are asymmetric in nature, i.e., the bandwidth requirements from a sender are different from its counterpart's. Although two-way satellite channels can be used for such asymmetric applications, it is also possible to combine a one-way satellite channel for information flow with a parallel terrestrial channel for control data flow, e.g., retransmission request. This can remarkably reduce the cost of expensive feedback channel and also can be a cost-effective solution if less expensive receive-only terminals are used [3]. Satellites are able to offer high bandwidth services to a large geographical area. However, satellite link is not a perfect communication channel as it has both non-homogeneous and dynamic characteristics. This time-variant channel condition would create bursty errors. With retransmission protocol over relatively reliable terrestrial link, certain degree of throughput performance is expected to be achieved in the satellite channel. In the proposed hybrid network architecture in Figure 1, data packet with forward error control (FEC) is conveyed over satellite links, whereas control packet with automatic repeat request (ARQ) over terrestrial links [3].

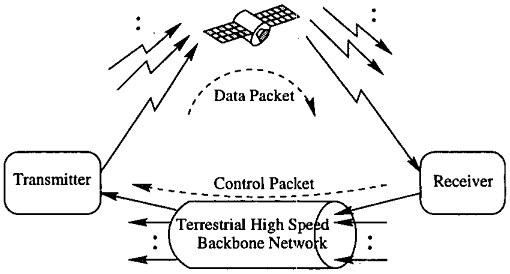

Fig. 1. Proposed Hybrid Network Architecture

Most error control protocols are typically designed with fixed values for link layer parameters such as coding rate and error combating capability for the worst channel condition. This can provide error probability to be below a predefined value. However, throughput performance become smaller than the achievable performance using optimum code parameters. Alternatively, if the required high error protection for the worst channel condition is achieved by using more complex codes, e.g., convolutional code

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with a high memory order, the problem would be the complexity of the decoder. A more efficient approach is to use an adaptive error control scheme that responds to the actual channel error condition by selecting the optimum code rate [8].

In this paper, we propose an adaptive error control (AEC) technique for the hybrid networks. The key ideas of the proposed protocol are the adaptation of the code rate according to the channel conditions and QoS guarantees. Code rate is chosen adaptively based on the estimated channel condition to maximize the throughput performance. Given channel condition, a transmitter decides optimum code rate based on the estimated throughput efficiency.

The paper is organized as follows. Section II describes the channel model for time-variant channels. In section III, proposed adaptive error control protocol is described. Performance evaluation is given in section IV. Then, the paper concludes with section V.

II. CHANNEL MODEL

Satellite link is not a perfect communications channel as it has both non-homogeneous and dynamic characteristics. Imperfections in the satellite channel is due to a number of sources including; the ionosphere, atmospheric gases, ice crystals, cloud cover and rain. These natural phenomena cause a number of impairments to the transmitted signal such as attenuation, depolarization, reflection, refraction, dispersion and delay. Furthermore, the satellite channel is affected by multipath fading. These time-variant channel conditions would cause bursty errors in satellite link of hybrid networks [6].

In this paper, the channel model is assumed to be a frequency non-selective slow fading Rician, which is typical in satellite communication channels [4] [8]. Slow fading causes Rician envelope to be constant during one signal interval, T_s. In this model, we assume no shadowing and coherence detection. Hence, the phase changes of the channel are tracked by the receiver. Accordingly, only the amplitude changes are appeared in the channel model, as in Figure 2.

The sequence from the channel encoder, $\mathbf{x} = (\cdots, x_{i-1}, x_i, x_{i+1}, \cdots)$ is transformed into signal, $s(t) = \mathrm{Re}\{\sqrt{2E_s}\sum_i x_i s_T(t - iT_s)e^{j\omega_0 t}\}$ by M-ary phase shift keying (MPSK) modulator where $s_T(t)$ is the envelope of the transmitted signal with duration T_s and unit energy, ω_0 is the carrier frequency and E_s is the energy per symbol. Then, the received signal, $r(t)$ can be represented by $r(t) = a(t)s(t) + n(t)$ where $n(t)$ is additive white Gaussian noise (AWGN) process. The probability density function of the envelope, Γ of the Rician fading process, $a(t)$ is given by [7]

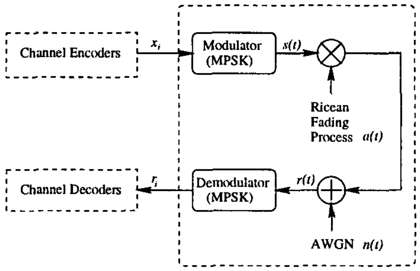

Fig. 2. Rician Channel Model

$$f_\Gamma(\gamma) = \frac{\gamma}{\sigma^2}e^{-(\gamma^2+s^2)/2\sigma^2} I_0(\frac{\gamma s}{\sigma^2}) \tag{1}$$

where the parameter s denotes the peak amplitude of the dominant signal or non-centrality parameter of the distribution and $I_0(\cdot)$ is zero-order modified Bessel function of the first kind and defined as $I_0(x) \triangleq \sum_{k=0}^{\infty}[\frac{1}{k!}(\frac{x}{2})^k]^2$. The Rician distribution is often described in terms of a parameter $\mathcal{K}$ which is defined as the ratio of powers in the direct and diffuse components. It is given by $\mathcal{K}=s^2/2\sigma^2$ or in terms of dB, $\mathcal{K}$ (dB) $= 10\log\,(s^2/2\sigma^2)$ dB. When $\mathcal{K} = 0$, the channel has a Rayleigh envelope and uniformly distributed phase. When $\mathcal{K} = \infty$, the channel is the well-known Gaussian channel. While $0 < K < \infty$, the channel has a Rician envelope and random phase [5].

The bit error probability of binary phase shift keying (BPSK) modulation is given by [7]

$$P_b = \int_0^\infty Q(\sqrt{\frac{2E_b}{N_0}}\gamma) f_\Gamma(\gamma)d\gamma \tag{2}$$

where $Q(x)$ is defined as $Q(x) \triangleq 1/\sqrt{2\pi}\int_x^\infty e^{-y^2/2}dy$, E_b is the energy per bit and N_0 is the one-sided Gaussian noise power spectral density.

The sequence of $\mathbf{r} = (\cdots, r_{i-1}, r_i, r_{i+1}, \cdots)$ is obtained after demodulation, where r_i can be represented by $r_i = \sqrt{E_s/N_0}a_i x_i + n_i$ where a_i and n_i are discrete sample of $a(t)$ and $n(t)$ respectively.

III. ADAPTIVE ERROR CONTROL

Most error control protocols are typically designed with fixed values for link layer parameters such as coding rate and error combating capability for the worst channel condition. These parameters are selected during network design phase. These static protocols may not adapt the dynamically varying channel conditions.

A. Forward Error Control

In the proposed AEC protocol, a transmitter uses a combination of automatic repeat request (ARQ) over terrestrial links and forward error control (FEC) scheme over satellite links. For the FEC portion, we use the Reed-Solomon (RS) codes. The RS code is an efficient block coding scheme for error correction. It is particularly effective at correcting short bursts of errors in a data stream. One advantage of the RS codes is their good distance property. Moreover, the existence of efficient hard-decision decoding algorithms make it possible to implement relatively long codes in many practical applications [7]. The length of the code word is denoted by N and the number of information symbols encoded into a block of N symbols is denoted by K. Hence, the code rate R_c is defined by N/K. The $(N, K, q = 2^k)$ RS codes is guaranteed to correct up to $t = \lfloor (N-K)/2 \rfloor$ errors where $q \geq N+1$.

Assuming bounded distance decoder with error correcting capability, t, the word error probability, P_w, is given by [7]

$$P_w = \sum_{i=t+1}^{N} \binom{N}{i} P_{s,RS}^{i} (1 - P_{s,RS})^{N-i} \tag{3}$$

where the symbol error probability, $P_{s,RS} = 1 - (1 - P_b)^k$. The bit error probability, P_b for BPSK modulation is given in Equation (2).

B. Protocol Description

The AEC protocol utilizes variable code rate depending on the channel conditions. During good channel conditions, more information is sent using higher rate codes. As channel quality becomes worse, lower rate codes are applied. Given channel condition, a transmitter decides optimum code rate based on the estimated throughput efficiency. Throughput performance is the QoS metric for the proposed protocol. The AEC protocol uses both forward and backward channel estimation, i.e., a receiver measures transmission efficiency, which is conveyed back to a transmitter. Then, the transmitter uses this measured efficiency as well as estimated throughput based on the measurement of SNR and parameter $\mathcal{K}$.

B.1 At Receiver

Denote N_e^i *the number of erroneous data packets in bits* and N_r^i *the number of received data packets in bits*, both during measurement period, T_m, for connection i. A receiver provides *feedback packet error ratio for connection* i, η_f^i, to the transmitter through control packet by

$$\eta_f^i \triangleq 1 - \frac{N_e^i}{N_r^i}. \tag{4}$$

Hence, η_f^i indicates the quality of channel at the receiver side.

B.2 At transmitter

Let N_u^j be *the number of user information in bits per data packet* and N_t^j *estimated number of transmitted data packet in bits, both for code* j. Then, estimated throughput at a transmitter side, η_e^j, is defined as

$$\eta_e^j \triangleq \frac{N_u^j}{E(N_t^j)} \tag{5}$$

where $E(N_t^j)$ can be determined by word error probability, P_w. The transmitter computes P_w based on SNR and parameter $\mathcal{K}$ given in Equation (3). Computation of $E(N_t^j)$ can be done as follows:

$$E(N_t^j) = N_u^j + H_u^j + P_w E(N_t^j) \tag{6}$$

where H_u^j is the number of header bits per data packet.

$E(N_t^j)$ can be rewritten as

$$E(N_t^j) = \frac{N_u^j + H_u^j}{1 - P_w} \tag{7}$$

The transmitter estimates *overall throughput efficiency for code* j, η_t^j, based on (1) mathematically calculated efficiency from measurement in the transmitter, η_e^j and (2) measured efficiency, η_f^i, from the feedback channel.

The overall efficiency can be obtained by

$$\eta_t^j = \alpha\, \eta_e^j + (1 - \alpha)\, \eta_f^i \tag{8}$$

where $0 \leq \alpha \leq 1$ is called the *measurement smoothing ratio.* This is evaluated by $\alpha = 0.5 + tan^{-1}(\beta(t - 0.5 \times E(T_r)))/\pi$ where t is time elapsed since control packet received, $E(T_r)$ is mean interarrival time of control packet and β is slope factor.

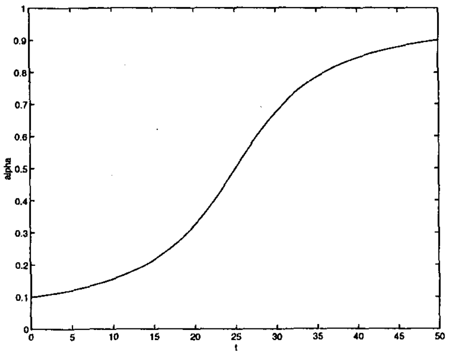

Fig. 3. Choice of α

Whenever a control packet arrives to a transmitter, t is initialized to *zero*. As t increases, α also increases as in Figure 3. This is interpreted as following: when a control packet arrives with current value of η_f^i, η_t^j is approximated by η_f^i. As time passes, i.e., value of η_f^i becomes obsolete, the transmitter gradually reflects more estimated throughput efficiency η_e^j into the total throughput efficiency η_t^j. If no control packets arrives in a long time, the transmitter eventually uses estimated throughput efficiency η_e^j for overall throughput η_t^j.

When there is a data packet to send in a transmitter, the transmitter computes throughput efficiency for each code as in Figure 4 and finds the code with maximum throughput efficiency, $\eta_t^{opt} = \max_{j \in C}\{\eta_t^j\}$ where C is a discrete transmittable code set, $C = \{\text{Code 1, Code 2,}\ldots\text{, Code } N\}$.

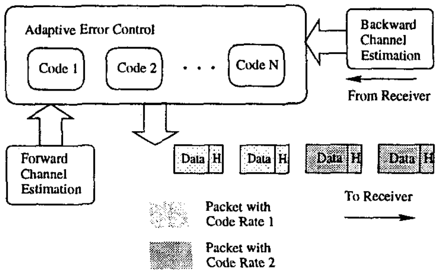

Fig. 4. Illustration of use of Code Rates at Transmitter

IV. Performance Evaluation

The proposed protocol is evaluated using a software emulator which incorporates a satellite channel model described in section II. The channel is modeled by M-state Markov Chain (MC). Each state in the MC represents a frequency non-selective slow Rician fading described in Section II. In this model, we assume only the transitions to adjacent states are allowed where the states are ordered according to decreasing values of bit error probabilities. Adopting state transition matrix from [8], the state diagram is shown in Figure 5.

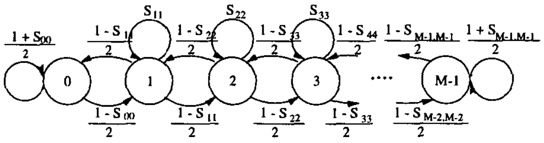

Fig. 5. State Diagram of Channel Model

TABLE I

RS Codes for AEC

N	255				
K	229	179	127	77	25
R_c	0.9	0.7	0.5	0.3	0.1
t	13	38	64	89	115

For the proposed error control schemes, we consider a set of five RS codes as shown in Table I, i.e., $N = 5$. Using these codes, AEC protocol adapts to time-variant channel condition. In all examples, we assume $\beta = 10$.

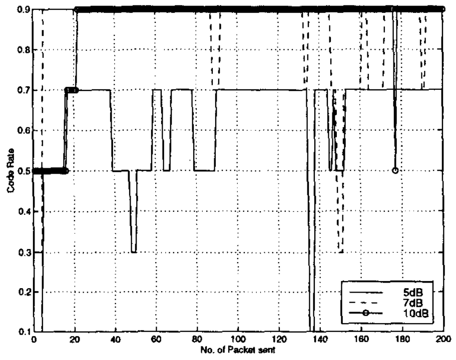

Fig. 6. Illustration of Code Rate Adaptation

Figure 6 shows how the code rate is adapted for each packet sent under different SNR parameters. For this example, the channel model parameters are given in Table II, which are used in satellite mobile channels in [8]. We assume further that the feedback channel is error-free since relatively reliable terrestrial link is used.

Using different channel parameter scenario, we

TABLE II

PARAMETERS FOR EXAMPLE 1

State $= i$	0	1	2
$\mathcal{K}$	0	4	10
S_{ii}	$1 - e^{-6}$	$1 - 5 \times e^{-7}$	$1 - 1.42 \times e^{-7}$
State Probability	0.1	0.2	0.7

TABLE III

PARAMETERS FOR EXAMPLE 2

State $= i$	0	1	2
$\mathcal{K}$	0	4	10
S_{ii}	$1 - e^{-6}$	$1 - e^{-6}$	$1 - 7.5 \times e^{-7}$
State Probability	0.3	0.3	0.4

will show the proposed scheme achieve the better throughput performance.

A. Example 1

The channel parameter and state probability for this experiment is given in Table II. Figure 7 compares the throughput of the AEC protocol with those of static hybrid ARQ protocols. As can be seen, the AEC (solid line) provides the better throughput.

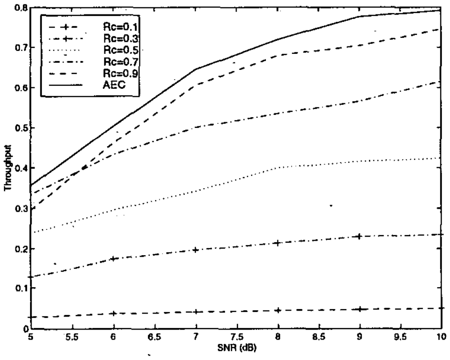

Fig. 7. Throughput vs. SNR(dB)

B. Example 2

In this example, worse channel condition is chosen by changing state probability of both states 0 and 1 to 0.3. The channel parameter and state probability for this experiment is given in Table III. Figure 8 shows the throughput comparison of the AEC protocol with fixed code rate schemes. The AEC (solid line) provides the better throughput. Note that even if the static code rate achieving maximum throughput changes at certain rage of SNR, the throughput of AEC protocol is still higher than the those of static protocols.

V. CONCLUSIONS

This paper presents an adaptive error control (AEC) protocol for the hybrid network, in which the transmitter uses a combination of automatic repeat request (ARQ) over terrestrial links and forward error control (FEC) scheme with adaptive code rate over satellite links. Throughput performance shows that the proposed AEC protocol adapts to time-variant satellite channel better than the static hybrid ARQ protocol under different satellite channel conditions.

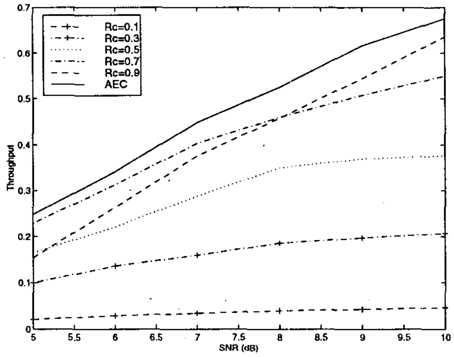

Fig. 8. Throughput vs. SNR(dB)

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