Rate-Adaptive Error Control for Multimedia Multicast Services in Satellite-Terrestrial Hybrid Networks

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Abstract— This paper presents a rate-adaptive error control (RAEC) protocol for multimedia multicast services in satellite-terrestrial hybrid networks. The proposed scheme considers user fairness to multicast group and adapts code rate according to the channel conditions. In order to provide fairness perceived by user application, a packet is transmitted via satellite, while the retransmission of the packet is carried out over either terrestrial links or satellite link based on the number of negative acknowledgments of the packet. For code rate adaptation, a code is chosen adaptively based on the estimated channel condition. In the RAEC protocol, transmitter uses a combination of forward and backward channel estimation. Throughput performance shows that the proposed RAEC protocol outperforms the static hybrid ARQ protocol under different channel conditions.

I. Introduction

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

These satellite-terrestrial hybrid networks (in short, we call hybrid networks) are becoming increasingly popular for multimedia multicast services due to several advantages. Many multimedia applications, particularly in case of file transfer, video multicast, and database services are asymmetric in nature, i.e., the bandwidth requirement from a receiver is much less than that from its counterpart. 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. This can remarkably reduce the cost of expensive satellite feedback channel. Furthermore, satellites are able to offer efficient bandwidth services to a large geographical area and easy to add new users to the system by simply installing the stations. Hence, the satellite network is an excellent infrastructure for multicast services. Possible applications in the hybrid networks are:

- Data transfer to large user populations,
- Continuous sensor data feed to large user populations,
- Group tele-conferencing,
- Dissemination of video and/or audio streams to large user populations,
- Distance learning, and
- Distributed interactive simulation.

However, satellite link is characterized as a time-varying communication channel since it has both non-homogeneous and dynamic characteristics. This time-varying channel condition would create bursty errors. As in all communication systems, an adequate error control scheme is required for multicast services in these hybrid networks.

Error control schemes for unicast services have been extensively studied and developed. However, relatively few schemes for multicast have appeared in literature [2], [3], [6], [7], [8]. Typical problem in a multicast error control protocol is user fairness, i.e., if a receiver suffers a relatively high error probability, the throughputs of all other receivers are limited to the throughput of the poor receiver.

In this paper, we propose a rate-adaptive error control (RAEC) technique for multimedia multicast services in the hybrid network. The proposed protocol provides user fairness to receivers and adapts the code rate according to the channel conditions. For the user fairness, a packet is transmitted via satellite, while the retransmission of the packet is carried out over either terrestrial links or satellite link based on the number of negative acknowledgments of the packet. If the majority of the receivers gets erroneous packet, retransmission is sent over satellite link; otherwise, it is sent over terrestrial link. For code rate adaptation, a code is chosen adaptively based on the estimated channel condition in order to maximize the throughput. In the RAEC protocol, transmitter uses a combination of forward and backward channel estimation.

The paper is organized as follows. Section II presents the throughput comparison between the hybrid network configuration and pure-satellite network configuration. Section III describes a channel model for time-varying satellite channels. In section IV, proposed rate-adaptive error control protocol is described. Performance evaluation is given in section V. Then, the paper concludes with sec-

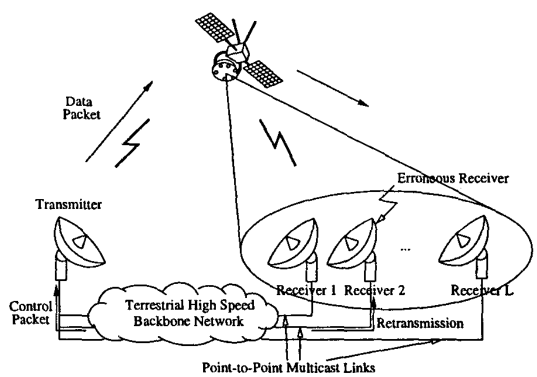

Fig. 1. Satellite-Terrestrial Hybrid Network Architecture

tion VI.

II. Throughput Comparison

In this section, we analyze the throughput performance of multicast services in two network configurations: pure-satellite network, and hybrid network configuration shown in Fig. 1. Consider a pure-satellite multicast network in which retransmission as well as transmission of a packet take place through the satellite link. If only one receiver gets an erroneous packet and requests a retransmission, then other good receivers are forced to receive redundant (futile) packets. This can breach the fairness of all other users in the multicast group. If the ARQ scheme takes secondary route such as terrestrial link, the retransmission could be sent only to the receiver with an erroneous packet. This basic idea is proposed in [3] which supplements a satellite multicast system with a set of point-to-point terrestrial links between the transmitter and each receiver.

However, it may not be efficient to retransmit the packet through the terrestrial link to each receiver, if the majority of the receivers suffer high error rate. It is because the retransmission traffic may cause congestion in the terrestrial network, generating more errors. Instead, in our scheme, a packet is transmitted via sallite link, while retransmission of the packet is done through either satellite or terrestrial link, based on the number of negative acknowledgments. If the number of negative acknowledgments is larger than the half of the number of receivers, retransmission is sent over satellite link; otherwise, it is sent over terrestrial link.

In order to compare the performance of both configurations, we choose throughput as a performance metric. Throughputs η_s and η_h are defined as the fraction of information bits to the total number of bits in each packet transmitted to receivers, for pure-satellite and hybrid network configuration, respectively. To analyze multicast networks, we make the following assumptions:

1. There are L receivers, and each receiver has equal priority.
2. The packet error probability over satellite and terrestrial link is P_s and P_t, respectively. The error statistics at each receiver is independent and identically distributed.
3. There are l user information bits and h header bits per packet.
4. All acknowledgments are delivered error-free.
5. The propagation delays of acknowledgment from the receivers to the transmitter are identical.
6. The transmitter can distinguish which receiver sends its acknowledgment. Thus, the transmitter is informed of the number of negative acknowledgments.

For the pure-satellite network configuration, the expected number of transmitted bits to L receivers, $N^s(L)$ is given by

$$N^s(L) = \sum_{i=0}^{L}\{(l+h)L + N^s(i)\}\binom{L}{i}P_s^i(1-P_s)^{L-i} \quad (1)$$

Throughput for pure-satellite configuration, η_s is given by

$$\eta_s = \frac{l+h}{N^s(L)} \quad (2)$$

In the hybrid network configuration, each packet is initially transmitted via satellite link. However, retransmission is sent either through terrestrial or satellite link based on the number of negative acknowledgment the transmitter received. If the number of negative acknowledgments is less than $\lfloor L/2 \rfloor$, retransmission is sent through terrestrial link. Otherwise, retransmission is delivered via satellite link. Therefore, the expected number of transmitted bits to L receivers, $N^h(L)$ is given by

$$N^h(L) = \sum_{i=0}^{L}\{(l+h)L + N_r^h(i)\}\binom{L}{i}P_s^i(1-P_s)^{L-i} \quad (3)$$

where expected number of transmitted bits to i receivers given that error occurs, $N_E^h(i)$ is obtained by

$$N_E^h(i) = \begin{cases} \frac{i(l+h)}{1-P_t}, & \text{for } 1 \le i \le \lfloor L/2 \rfloor \\ \frac{i(l+h)+\sum_{j=1}^{i-1} N_E^h(j)\binom{i}{j}P_s^j(1-P_s)^{i-j}}{1-P_s^i}, & o.w. \end{cases} \quad (4)$$

Throughput for hybrid network configuration, η_h is given by

$$\eta_h = \frac{l+h}{N^h(L)} \quad (5)$$

Let η_{rel} denote the relative throughput by $\eta_{rel} \triangleq \eta_s/\eta_h$. Then, Fig. 2 shows the relative throughput efficiency versus the number of receivers with varying bit error rate in the satellite link. The throughput of pure-satellite network configuration is poor than the hybrid network configuration. Also, as the number of receiver increases, the throughput of pure-satellite network substantially decreases. From the throughput comparison, hybrid network with our scheme can be more suitable for multimedia multicast services.

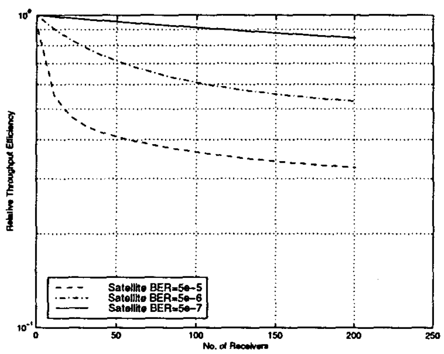

Fig. 2. Relative Throughput vs. Number of Receivers ($P_t = 10^{-7}$, $l = 2000$, and $h = 40$)

III. Channel Model

In this paper, the channel model is assumed to be a frequency non-selective slow fading Rician, which is typical in satellite communication channels [9]. 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.

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 [5]:

$$f_\Gamma(\gamma) = \frac{\gamma}{\sigma^2} e^{-(\gamma^2+s^2)/2\sigma^2} I_0(\frac{\gamma s}{\sigma^2}) \tag{6}$$

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. 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.

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.

IV. Rate-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. This can provide error probability to be below a pre-defined value. However, throughput performance become smaller than the achievable performance using optimum code parameters. 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 [9].

Our proposed RAEC 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. The RAEC 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 feedback efficiency as well as estimated throughput based on the measurement of SNR and Rician parameter $\mathcal{K}$.

A. Receiver Procedure

Let $N_e(i)$ denote the number of erroneous bits in i-th data packet and $N_r(i)$ the number of bits in i-th data packet, both during measurement period, T_m. A receiver provides feedback packet transmission efficiency for i-th packet, $\eta_f(i)$, to the transmitter through control packet by

$$\eta_f(i) \triangleq 1 - \frac{N_e(i)}{N_r(i)} \tag{7}$$

Hence, $\eta_f(i)$ indicates the quality of channel at the receiver side.

B. Transmitter Procedure

Let $N_u(i)$ be the number of user information bits in i-th data packet and $H_u^j(i)$ is the number of header bits including redundancy in i-th data packet encoded with code j. Then, the estimated throughput of the i-th data packet at a transmitter side,

$\eta_e^j(i)$, is given by

$$\eta_e^j(i) = \frac{N_u(i)}{N_u(i) + H_u^j(i)} \cdot (1 - P_w) \tag{8}$$

where P_w is word error probability. If we assume Reed-Solomon (RS) code, P_w, is given by [5]

$$P_w = \sum_{i=t+1}^{N} \binom{N}{i} P_s^i (1 - P_s)^{N-i} \tag{9}$$

where N is code word length, t is error correcting capability, and P_s is symbol error probability.

C. Code Selection

The transmitter estimates the overall throughput efficiency for code j at the instant of transmitting k-th packet, $\eta_t^j(k)$, based on (1) efficiency evaluated at the transmitter (forward channel estimation), and (2) measured efficiency from the feedback channel (backward channel estimation).

The overall efficiency $\eta_t^j(k)$ is obtained by

$$\eta_t^j(k) = \alpha\ \eta_e^j(k)\ +\ (1\ -\ \alpha)\ \eta_f(\mathcal{R}(k)) \tag{10}$$

where $0 \leq \alpha \leq 1$ is called the measurement smoothing ratio, and $\mathcal{R}(k)$ is the identifier of the last packet acknowledged at the time of the transmission of the k-th packet, e.g., $\mathcal{R}(k) = i$ as shown in Fig. 3.

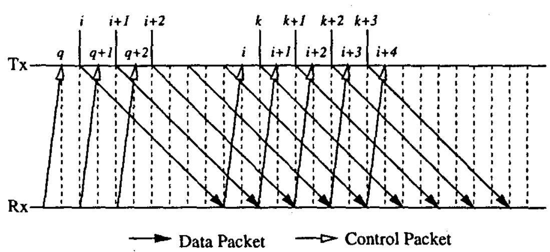

Fig. 3. Choice of α

Since the backward channel estimation becomes obsolete as time passes, the transmitter gradually reflects more forward channel estimation into the overall throughput efficiency, i.e., α is an increasing function of the time. However, in reality, it is difficult to choose the slope of α. To solve this problem, we use the mean square error (MSE) estimator.

Let ε_i denote the forecast error of the i-th packet, i.e., $\varepsilon_i = \eta_t^j(i) - \eta_f(i)$. Note that ε_i is based on η_e and η_f of the i-th packet as well as η_f of the $\mathcal{R}(i)$-th packet which is the most recent acknowledgment identifier at the instant of the transmission of the i-th packet. If there are n packets taken into consideration and the $(i-1)$-th acknowledgment is available at the transmitter, then the MSE, $\epsilon_n(i)$, is given by

$$\epsilon_n(i) \quad = \quad \frac{\sum_{l=i-n}^{i-1} \varepsilon_l^2}{n} \tag{11}$$

We obtain α which minimizes $\epsilon_n(i)$ given by

$$\begin{aligned} \alpha &= \arg\max_\alpha \epsilon_n(i) \\ &= \frac{\sum_{l=i-n}^{l=i-1} (\eta_e^j(l) - \eta_f(\mathcal{R}(l)))(\eta_f^l + \eta_f(\mathcal{R}(l)))}{\sum_{l=i-n}^{l=i-1} (\eta_e^j(l) - \eta_f(\mathcal{R}(l)))^2} \end{aligned} \tag{12}$$

When there is a data packet to be sent in a transmitter, the transmitter computes throughput efficiency for each code based on the Eq. (10) and finds the code with maximum throughput efficiency, $\eta_t^{max}(k) = \max_{j \in C}\{\eta_t^j(k)\}$ where C is a discrete transmittable code set, C = {Code 1, Code 2,..., Code N}.

V. Performance Evaluation

The proposed protocol is evaluated using a software emulator which incorporates a satellite channel model described in section III. Most real wireless channels are time-varying. Experimental results show that the channel parameters are stationary over a short time interval [9]. The channel is modeled as stationary in these time intervals. A non-stationary channel can thus be represented by M stationary channel models. The simplest forms of this model are Gilbert [4] model with only two binary symmetric channel states.

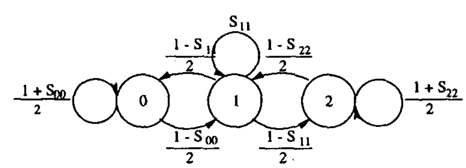

Fig. 4. State Diagram of Channel Model

In this paper, the channel is modeled by 3-state Markov Chain (MC). Each state in the MC represents a frequency non-selective slow Rician fading. We assume only the transitions to adjacent states are allowed where the states are ordered according to decreasing values of bit error probabilities. Transition process between states is described by the transition probability matrix. The analysis of experimental data [9] indicates that the states are relatively stable, i.e., $S_{ii} \approx 1,\ \ i \in \{0, 1, 2\}$. Adopting state transition matrix from [9], the state diagram is shown in Fig. 4.

The implementation of the protocol is carried out in the user space with UDP sockets. For the simulation, we assume satellite and terrestrial link transfer delay are exponentially distributed with averages of 266 msec and 34 msec, respectively.

For the proposed error control schemes, we consider a set of five RS codes whose code rates R_c range from 0.1 to 0.9 (RS(255, 25), RS(255, 77), RS(255, 127), RS(255, 179), and RS(255, 229)). Using different channel parameter scenario, we will show the proposed scheme achieve the better throughput performance.

TABLE I
Parameters for Example 1

State = i	0	1	2
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

A. Example 1

The channel parameters and state probabilities for this experiment are given in Table I. Fig. 5 compares the throughput of the RAEC protocol with those of static hybrid ARQ protocols. As can be seen, the RAEC (solid line) provides the better throughput. Although lower rate codes have more error combating capability, they have lower throughput efficiency due to larger redundancy bits. When SNR is less than 5.65dB, the code with $R_c = 0.7$ has better throughput than code with $R_c = 0.9$. Thus, the optimum throughput performance for the static protocols changes depending on the channel conditions. This is the another disadvantage of static protocol. At SNR=10dB, the RAEC protocol achieves about 22.4 percent of gain relative to the code with $R_c = 0.9$.

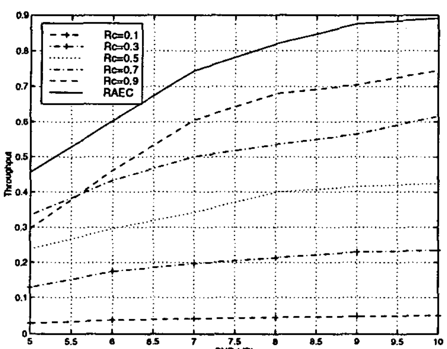

Fig. 5. Throughput vs. SNR(dB)

B. Example 2

In this example, worse channel condition is chosen by changing state probabilities of both states 0 and 1 to 0.3 in example 1. Fig. 6 shows the throughput comparison of the RAEC protocol with fixed code rate schemes. The RAEC (solid line) provides the better throughput. Note that even if the static code rate achieving maximum throughput changes at a certain rage of SNR, throughput of RAEC protocol is still higher than those of static protocols. At SNR=10dB, the RAEC protocol achieves about 22.97 percent of gain relative to the code with $R_c = 0.9$.

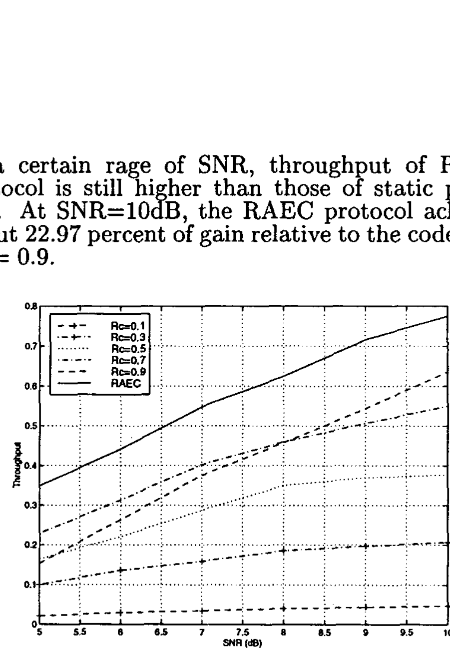

Fig. 6. Throughput vs. SNR(dB)

VI. Conclusions

This paper presents a rate-adaptive error control (RAEC) protocol for multimedia multicast services in the hybrid networks. The proposed protocol provides user fairness to multicast group and adaptation of the code rate according to the channel conditions. Throughput performance shows that the proposed RAEC protocol outperforms the static hybrid ARQ protocol under different satellite channel conditions. At SNR=10dB, the RAEC protocol achieves about 22 percent of gain relative to the code with $R_c = 0.9$.

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