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A Scheme to Improve Throughput for ARQ-Protected Satellite Communication

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A Scheme to Improve Throughput for ARQ-Protected Satellite Communication

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Abstract

Automatic-repeat-request (ARQ) error control is often employed to assure high fidelity information transmission. However, ARQ error control can provide poor throughput for satellite multicasting. The throughput in such communication may be improved by the combination of a terrestrial network parallel to the satellite network and a judiciously modified ARQ protocol. In particular, retransmitted ARQ frames can be sent terrestrially in such a hybrid network, allowing higher throughput than in a pure-satellite network. This work presents analytic results to establish the potential for improving the throughput of satellite multicast communication employing ARQ error control by the adoption of such a hybrid network architecture.

Introduction

A satellite is excellently suited for multicast communication. As in all communication systems, an error control scheme is required for multicasting. Such schemes may be broadly classified as forward error correction (FEC) and automatic repeat request (ARQ) protocols. While numerous error control schemes for point-to-point communication (unicasting) appear in the literature, relatively few for point-to-multipoint communication (multicasting) have been presented (see [1, 2, 3, 4, 5, 6, 7, 8] for a representative selection). Error control for multicasting is hence fertile research territory.

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We have chosen to begin our venture into this territory by examining ARQ protocols for multicast delivery of data. The typical problem in a multicast ARQ system is that since retransmissions are sent over the multicast channel, those required by only one receiving station do not benefit the other receivers. Accordingly the throughput for the system falls drastically as the number of receivers increases. Furthermore, if one receiving station is a "poorer listener" than other stations, i.e. suffers a relatively high frame error rate, then the throughput to all stations is essentially limited to the throughput achievable to that poorer listener [9].

If the retransmissions could somehow be sent only to the receivers which require them, the throughput might be improved considerably. It is natural, then, to suggest supplementing a satellite multicast system with a set of point-to-point terrestrial links between the transmitter and each receiver, as depicted in Figure 1. In such a system, retransmissions may be sent terrestrially instead of via the satellite multicast link, and an improvement in throughput might be possible. Further, if the ARQ acknowledgements are sent terrestrially as well, then the receiving stations do not require satellite transmission capability, and the cost of such stations may be correspondingly reduced.

In this article, we examine the throughput offered by such a *hybrid* (satellite and terrestrial) network configuration for unicast and multicast selective-repeat ARQ operation. In the next section we examine the throughput for unicasting and multicasting in pure-satellite and hybrid networks. Numerical examples are presented in the following section. Finally, we conclude with some thoughts for future work.

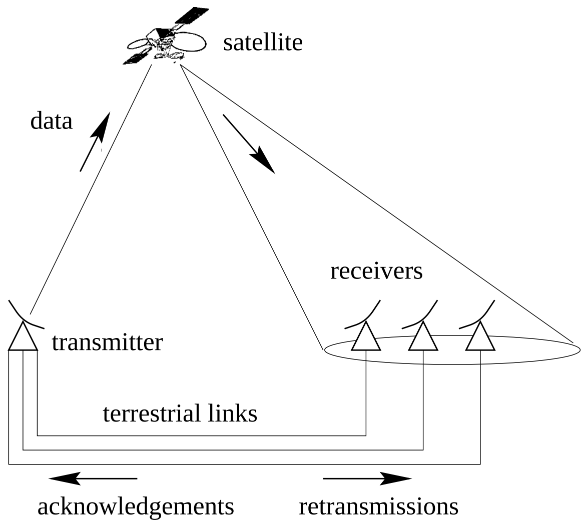

Figure 1: Multicasting in a hybrid network.

Analysis

Point-to-Point Communication

We first examine unicasting in a pure satellite network. We make the following assumptions and notational definitions:

1. Infinite buffering, infinite window size; ideal selective-repeat ARQ protocol.
2. All acknowledgements are delivered without errors.
3. The satellite frame error rate (the probability a frame sent via satellite arrives in error at the receiver) is p_s, while the terrestrial frame error rate is p_t.
4. There are ℓ information bits and h non-information (overhead) bits per information frame sent either via satellite or via a terrestrial link.
5. In the hybrid network, all retransmissions are sent terrestrially.
6. We define the *throughput*, η, as the expected value of the ratio of the number of information bits delivered to a receiver per bit sent to that receiver. We will attach subscripts to η to denote the number of receivers (1 or M) and the type of network (satellite or hybrid).

We remark this last assumption can be demonstrated by straightforward analysis to be valid for plausible, implementable combinations of satellite link and terrestrial link bandwidths and error rates.

Let β denote the expected number of frames sent to a receiver per frame delivered to that receiver. (In point-to-point pure-satellite and hybrid networks, and in a pure-satellite multicast network, β is equivalent to the number of frames transmitted per frame delivered.) For the pure-satellite network we have [10, 11]:

$$\beta_{1,satellite} = \sum_{i=1}^{\infty} i\,(1-p_s)\,p_s^{i-1} = \frac{1}{1-p_s}.$$

The throughput is then

$$\eta_{1,satellite} = \frac{\ell}{\ell+h}\frac{1}{\beta_{1,satellite}} = \frac{\ell}{\ell+h}\,(1-p_s)\,.$$

In the hybrid network, each frame is sent initially via satellite, and all retransmissions are sent terrestrially, so we have:

$$\begin{aligned}\beta_{1,hybrid} &= 1\,(1-p_s) + p_s\,(1-p_t)\sum_{i=2}^{\infty} i p_t^{i-2} \\ &= (1-p_s) + \frac{p_s}{p_t}\left[\frac{1}{1-p_t} - (1-p_t)\right] \\ &= \frac{1-p_t+p_s}{1-p_t}\,.\end{aligned}$$

This yields for the throughput:

$$\eta_{1,hybrid} = \frac{\ell}{\ell+h}\left[\frac{1-p_t}{1-p_t+p_s}\right]\,.$$

Point-to-Multipoint Communication

For analyzing multicast networks, we preserve the assumptions of the point-to-point analysis and add the following:

1. There are $M > 1$ receivers.
2. The noise processes experienced by all receivers are independent and identical.
3. There is no competition among receivers for access to the acknowledgment channel.
4. The propagation delays for acknowledgements traveling from the receivers to the transmitter are the same for all acknowledgements.

5. The transmitter maintains a history of which stations have acknowledged which frames. Accordingly, if receiver m ($m = 1, 2, \ldots, M$) has positively acknowledged receipt of frame $\mathcal{F}$, an acknowledgement is not required from m for any retransmissions of $\mathcal{F}$ which may be required for other receivers in the network.

In the multicast pure-satellite network, the transmitter continuously sends frames via the satellite multicast channel to the M receivers, which generate respective acknowledgments to send to the transmitter. Upon receiving acknowledgments from the receivers, the transmitter retransmits the frame if one or more receivers so requested through their acknowledgements. Otherwise a new frame is sent.

Let m_j denote the number of receivers which successfully receive some frame $\mathcal{F}$ after exactly j multicast transmission attempts to deliver $\mathcal{F}$. Also let $\gamma(j)$ denote the probability with which the frame $\mathcal{F}$ is successfully delivered to all M receivers with j or fewer transmissions. Then, by counting all possible combinations of the number of transmissions required to deliver $\mathcal{F}$ to each of the M receivers, given $\mathcal{F}$ was transmitted j times, we obtain

$$\gamma(j) = \sum_{\substack{m_1=0 \\ \sum_{h=1}^{j} m_h = M}}^{M} \cdots \sum_{m_j=0}^{M} \left[\binom{M}{m_1, m_2, \cdots, m_j} \times \prod_{k=1}^{j} \left[p_s^{k-1} (1-p_s) \right]^{m_k} \right]$$

where the multinomial coefficient is given by

$$\binom{M}{m_1, m_2, \cdots, m_j} = \frac{M!}{m_1! m_2! \cdots m_j!}.$$

Suppose a random variable A assumes the value j if the transmitter must send frame $\mathcal{F}$ exactly j times to elicit positive acknowledgements for $\mathcal{F}$ from all M receivers. If we define $\gamma(0) = 0$, then $\gamma(j)$ is the cumulative distribution function for the random variable A. Then we may calculate β, the expected number of frames sent per frame delivered to all receivers, as:

$$\beta_{M,satellite} = E[A] = \sum_{j=1}^{\infty} j [\gamma(j) - \gamma(j-1)]$$

Hence the throughput for multicasting in a pure-satellite network is

$$\eta_{M,hybrid} = \frac{\ell}{\ell + h} \frac{1}{\beta_{M,satellite}}$$

with $\beta_{M,satellite}$ calculated as above.

In the hybrid network, each frame is initially sent via satellite and all retransmissions are sent terrestrially. Hence, for multicasting in a hybrid network, the expected number of frames sent to a receiver per frame delivered to that receiver is the same as for unicasting in the hybrid network:

$$\eta_{M,hybrid} = \eta_{1,hybrid} = \frac{\ell}{\ell + h} \left[\frac{1 - p_t}{1 - p_t + p_s} \right].$$

Numerical Examples

We now turn to some numerical examples to better understand the throughput expressions derived above. For these examples, we will make the following further assumptions:

1. Binary symmetric channel (BSC) models characterize the terrestrial channels and the logical satellite channels between the transmitter and each receiver. The crossover probabilities (bit-error rates, BERs) are q_s for all logical satellite channels and q_t for all terrestrial channels.

2. The terrestrial channel BER is $q_t = 10^{-5}$.

3. There are $\ell = 2200$ information bits and $h = 48$ overhead bits in all ARQ information frames, whether sent via satellite or via a terrestrial link. (The value of h was chosen supposing the ARQ frame has a 16-bit sequence number and a 32-bit CRC for error detection. The value of ℓ was chosen to maximize the throughput in a point-to-point satellite network, which is the reference network for comparison purposes, as calculated by a straightforward differentiation method presented in [12].)

4. In finding $\beta_{M,satellite}$, we approximated the infinite summation by truncating the summation at the minimum j such that $\gamma(j) > 1 - 10^{-3}$. (We justify this truncation not only as a fair approximation, but also because, in an actual network, a station which requests retransmissions too frequently would likely be recognized by the transmitter as suffering from excessive noise, and would accordingly be disconnected from the communication.)

Calculated throughput values for point-to-point communication are presented in Figure 2. As shown in the figure, the throughput in the hybrid

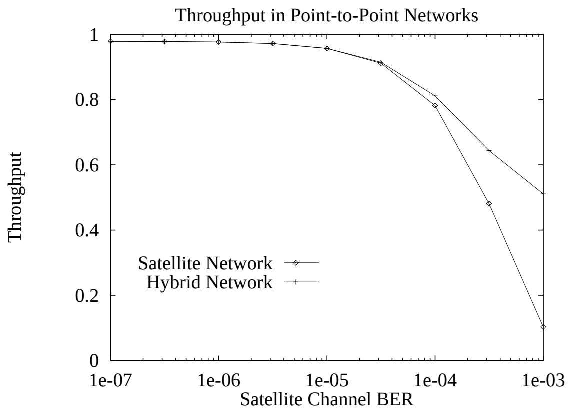

Figure 2: Throughput in point-to-point networks ($\ell = 2200$, $h = 48$, $q_t = 10^{-5}$).

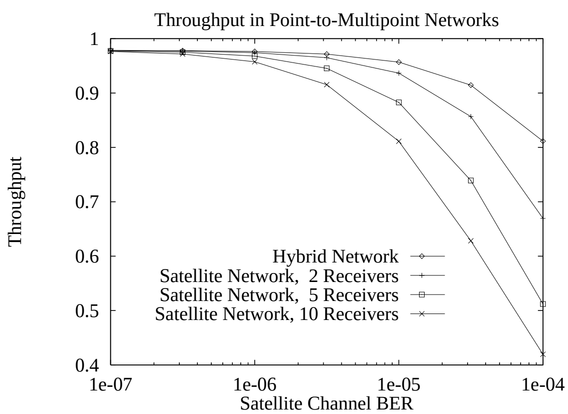

Figure 3: Throughput in point-to-multipoint networks ($\ell = 2200$, $h = 48$, $q_t = 10^{-5}$).

network comes to exceed that in the satellite network as the satellite channel BER increases. This is easily explained by the terrestrial link having lower BER than the satellite link and by the shifting of retransmissions onto the terrestrial link with the adoption of a hybrid network. Note, however, that as the satellite channel BER increases, the terrestrial bandwidth required to support retransmissions approaches the satellite channel transmission rate.

Figure 3 presents throughputs for multicast networks of two, five, and ten receivers. As is characteristic in satellite multicasting, the throughput is seen to fall rapidly as the satellite channel BER increases, especially as the number of receivers increases. However, the hybrid network provides throughput significantly superior to that available in the satellite network. While remarks concerning required terrestrial bandwidth as in the unicast case apply in the multicast case as well, the throughput improvement achievable with a hybrid network in the multicast case can be appreciable.

Additional Considerations

The inherent problem in ARQ multicasting, as stated in the introduction, is that retransmissions sent over the multicast channel do not benefit stations which do not require them. Consequently the throughput falls drastically as the number of receivers increases. In this work we have suggested a solution to this problem, namely retransmissions be sent over a system of point-to-point terrestrial links between the transmitter and each receiver. However, many considerations remain to be studied.

We have not, for example, yet examined the effect of packet lengths on throughput. While the frame length which maximizes throughput in a point-to-point satellite network is easily calculated ([12]), the optimal frame length for unicasting in a hybrid network, and for multicasting in satellite and hybrid networks, remains to be found. Adaptively changing the frame length may offer a throughput advantage, particularly at high bit error rates in the satellite channel.

We have also not yet studied terrestrial network topologies other than a star topology. Our proposed solution does not necessarily preclude other configurations. On the contrary, other topologies are not only acceptable, but perhaps even desireable. In particular, suppose the terrestrial network is a tree of terrestrial links, with the transmitter at the root node and a receiver at each non-root node. Such a tree could not only support multicasting in a hybrid network as we have described above, but would also allow a retransmission request sent by one receiver node to be serviced by the nearest ancestor node having the requested frame. The transmitter's load in servicing retransmission requests would then be reduced.

Similar possibilities arise if the terrestrial network is a wireless network, as in, for example, the case of mobile receiving nodes. For example, mobile receivers, with omnidirectional antennas, can broadcast retransmission requests to other receivers possibly nearby and receive frames over the terrestrial wireless channel. A terrestrial tree for retransmissions, albeit a continuously changing tree, is perhaps applicable for mobile receivers as well.

Hybrid ARQ schemes for multicasting, which employ FEC techniques for improving throughput have appeared in the literature recently, and these suggest possibilities in the context of hybrid networks [7, 8, 13]. (The reader is cautioned that the term "hybrid ARQ," which is standard in the literature for ARQ schemes incorporating FEC, is not related to our term of "hybrid network" for a parallel arrangement of satellite and terrestrial networks.) In [7], for example, an adaptive type-II multicast hybrid ARQ scheme is proposed. Rate-compatible BCH codes are used for error correction in this scheme. Each time another retransmission is requested for a particular frame, the transmitter sends an increasing number of parity digits, which, when combined with the original data frame, from a series of BCH codewords of decreasing rate. Such an FEC technique would not only improve throughput, it would reduce the bandwidth required for retransmissions in a hybrid network. This is particularly important since, as we remarked in discussing our numerical examples which use a pure ARQ protocol, the bandwidth required for terrestrial retransmissions in a hybrid network approaches the satellite channel bandwidth as the satellite channel deteriorates.

There are clearly many aspects of multicast ARQ to explore. In addition to exploring such aspects, we intend to also consider how to tolerate and/or recover from errors in systems where the multicasted information has delay constraints, such as voice and video multicast systems. Because of the delay constraints, ARQ is not suited well for error control in such settings, and other schemes for mitigating error effects must be devised.

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