

# TECHNICAL RESEARCH REPORT

Enhanced Throughput for Satellite Multicasting

*by Daniel Friedman, Anthony Ephremides*

**CSHCN T.R. 99-20**  
**(ISR T.R. 99-39)**



*The Center for Satellite and Hybrid Communication Networks is a NASA-sponsored Commercial Space Center also supported by the Department of Defense (DOD), industry, the State of Maryland, the University of Maryland and the Institute for Systems Research. This document is a technical report in the CSHCN series originating at the University of Maryland.*

**Web site <http://www.isr.umd.edu/CSHCN/>**

# Enhanced Throughput for Satellite Multicasting

Daniel Friedman and Anthony Ephremides\*  
Center for Satellite and Hybrid Communication Networks  
Institute for Systems Research  
University of Maryland  
College Park, MD 20740  
{danielf, tony}@isr.umd.edu

## ABSTRACT

Faithful information delivery in satellite multicasting requires appropriate error control. If multicast automatic-repeat-request (ARQ) is employed, a retransmission does not benefit receivers which do not require it, and consequently the throughput suffers greatly as the number of receivers increases. This performance degradation might be alleviated substantially by conducting retransmissions through terrestrial paths from the transmitter to each receiver instead of through the multicast satellite link. By sending a retransmission directly to the receiver(s) which requires it, higher throughput can be provided in such a *hybrid* network than in a pure-satellite network. In this work, we examine the throughput improvement provided by the hybrid network.

## INTRODUCTION

Satellites are excellently suited for distributing information simultaneously to multiple locations. As in nearly all communication systems, some sort of error control scheme is required in satellite multicasting to assure satisfactory fidelity of the information provided to each destination. Error control schemes may be broadly classified as forward error correction (FEC) or automatic-repeat-request (ARQ), and both can be applied for satellite communication. FEC has been used in satellite/space communication for decades, having grown from successful application by NASA for communication with interplanetary probes [1, 2]. However, satellite channel characteristics vary with time, and at any given time multiple receivers may perceive different channel qualities. Applying FEC for satellite multicast communication accordingly requires using an error-correcting code strong enough to protect data against the worst-case channel impairments. Unfortunately the error correction capability provided by powerful FEC code comes at the cost of sending many check symbols which constitute overhead in the communication. Further, this overhead penalty is exacted even at times of good channel quality, since FEC is not an adaptive error control technique. This is particularly troubling since good channel conditions will be experienced a majority of the time when using a well-designed satellite link [3].

ARQ protocols adapt to different channel qualities by retransmitting data only as needed. Also, an error-detecting code capable of detecting  $t$  or fewer errors in  $k$  information symbols requires fewer overhead symbols than would an FEC code designed to correct  $t$  errors in the same  $k$  symbols [1, 2]. Hence ARQ can provide high fidelity with less overhead than FEC during times of good channel quality, which tend to prevail as mentioned above. A drawback of ARQ not suffered by FEC is the need for a feedback channel, but this requirement is often an acceptable concession for achieving information transfer with excellent fidelity.

A difficulty arises in applying ARQ in multicast settings. The typical problem in a multicast ARQ system is that since retransmissions are sent over the multicast channel, those retransmissions required by only a few receivers do not

---

\*This work was supported in part by the Center for Satellite and Hybrid Communication Networks under NASA cooperative agreement NCC3-528.

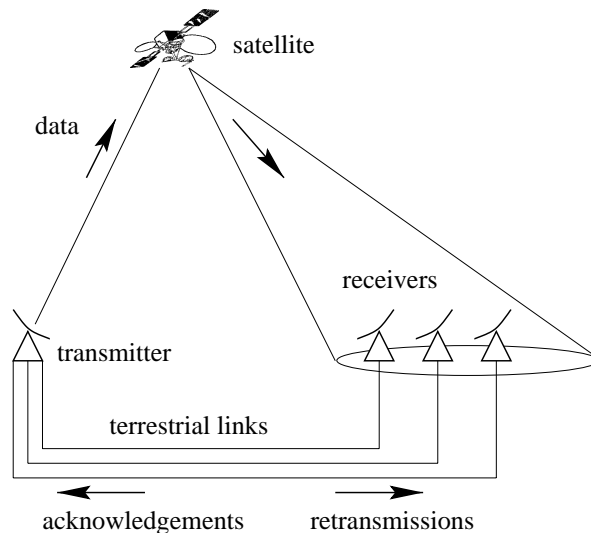


Figure 1: Multicasting in a hybrid network.

benefit the other receivers. The other receivers wait unproductively during such retransmissions for a new information frame. 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. it suffers a relatively high frame error rate, then the throughput to all stations is essentially limited to the throughput achievable to that poorer listener [4].

The throughput might be improved considerably if the retransmissions could somehow be sent only to the receivers which need them. 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 multicast satellite link, and an improvement in throughput may be so achieved. Furthermore, if the ARQ acknowledgements are set terrestrially as well, then the receiver stations do not require satellite transmission capability and the cost of such stations may be correspondingly reduced.

In this work, 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 calculate approximately the throughput for unicasting and multicasting in pure-satellite and hybrid networks. Numerical examples are presented in the following section. We immediately extend these examples to discuss the efficiency of the protocol. We conclude with a discussion of additional considerations to be regarded in applying the hybrid network for ARQ multicasting.

## ANALYSIS

### *Point-to-Point Case*

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

1. Infinite supply of information frames available for transmission, so the transmitting is never idled for want of a fresh frame to send.
2. Unlimited buffer size, unlimited window size; ideal selective-repeat ARQ protocol.
3. All acknowledgements are delivered without errors.
4. The probability a frame sent via the satellite link arrives in error at the receiver is  $p_s$ , while the terrestrial link frame error rate is  $p_t$ .

5. An ARQ information frame sent either via satellite or terrestrially comprises  $h$  header (overhead) bits and  $\ell$  information bits.
6. Acknowledgements are sent only for frames received without errors.
7. The satellite channel bit transmission rate  $r_s$  exceeds  $r_t$ , the terrestrial channel bit transmission rate.
8. In the hybrid network, all retransmissions are sent terrestrially. (We will examine a consequence of this particular assumption below.)

We remark that the first of these assumptions is implicit in most selective-repeat ARQ throughput analyses although it is rarely mentioned.

The ultimate purpose of the ARQ system is to deliver error-free information frames in proper order to a consuming process at the receiver. Hence we define as our performance measure the throughput,  $\nu$ , calculated as the expected number of information bits released per second to the consuming process.

*Pure-Satellite Network:* To calculate the throughput in unicast and multicast pure-satellite networks, define  $\beta$  as the expected number of frames sent by the transmitter per frame delivered to all receivers. With this definition,  $\beta$  is a measure of *inefficiency* (while its reciprocal is a measure of efficiency).

This inefficiency measure for a pure-satellite architecture with one receiver we shall denote as  $\beta_{1,satellite}$ , and is given by [1, 2]:

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

The throughput in this setting,  $\nu_{1,satellite}$ , is then

$$\begin{aligned} \nu_{1,satellite} &= \left( \frac{\ell}{\ell + h} \right) \frac{r_s}{\beta_{1,satellite}} \\ &= \left( \frac{\ell}{\ell + h} \right) (1 - p_s) r_s. \end{aligned}$$

*Hybrid Network:* We may model the protocol operation in the hybrid network as the queuing system shown in Figure 2. We do not consider propagation delays in this model since we have assumed unlimited window size and unlimited buffering. In this model, information frames are sent continually via satellite to the receiver. With probability  $1 - p_s$  a frame sent via the satellite link is successfully received. Hence the average rate at which frames are delivered successfully via the satellite link is the average frame flow rate at point "A" in the figure,  $r_s (1 - p_s) / (\ell + h)$  frames per second.

A frame which is corrupted in satellite transmission is queued at the transmitter for retransmission. A retransmitted frame may be successfully received with probability  $1 - p_t$ , or the retransmission may be unsuccessful, in which case the frame is queued for another retransmission. Hence a frame may be retransmitted multiple times before it is successfully delivered. Denote as  $\lambda_t$  the average frame flow rate at the input to the retransmissions queue, point "B." We will say the system is *stable* if the average input rate to the retransmissions queue is less than the rate at which retransmissions can be sent, i.e.

$$\lambda_t < r_t / (\ell + h), \quad (2)$$

,and *unstable* otherwise.

Now if the system is stable, conservation of flow indicates  $r_s p_s / (\ell + h) + \lambda_t p_t = \lambda_t$  or

$$\lambda_t = \frac{r_s}{\ell + h} \left( \frac{p_s}{1 - p_t} \right),$$

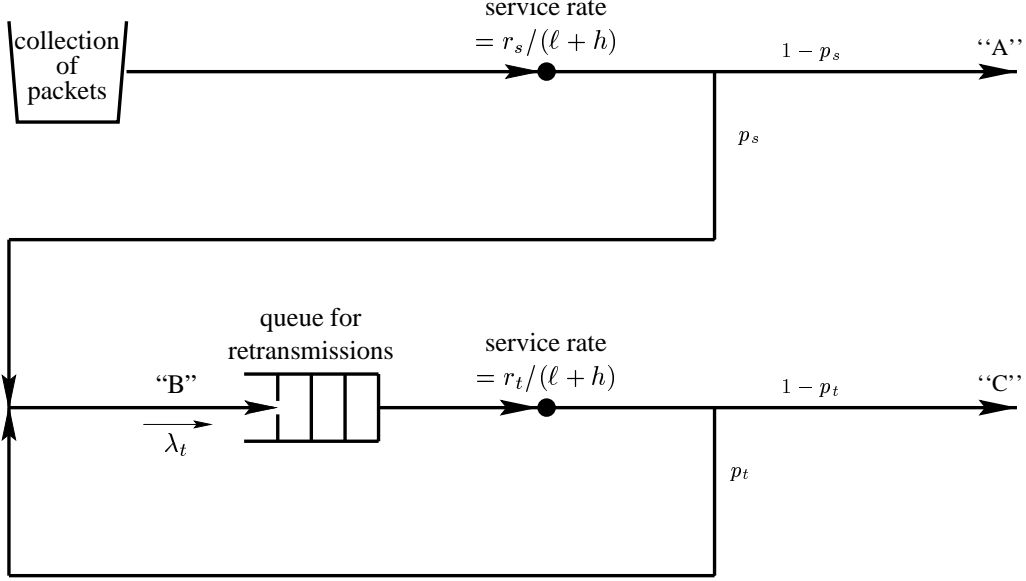


Figure 2: Queueing model for hybrid network.

which in combination with (2) implies another expression of the stability condition,

$$\frac{r_s}{\ell + h} \left( \frac{p_s}{1 - p_t} \right) < \frac{r_t}{\ell + h}. \quad (3)$$

The corresponding average rate at which frames arrive successfully at the receiver via the terrestrial link is the average frame flow rate at “C”,  $\lambda_t (1 - p_t)$ . If the system is unstable, then this same flow rate is limited to  $r_t (1 - p_t) / (\ell + h)$ .

Hence we have  $\nu_{1,hybrid}$ , the throughput in a single-receiver hybrid architecture,

$$\nu_{1,hybrid} = \begin{cases} \frac{r_s}{\ell + h} & , \text{ if stable} \\ \frac{r_s}{\ell + h} (1 - p_s) + \frac{r_t}{\ell + h} (1 - p_t) & , \text{ if unstable} \end{cases}$$

These results may be combined with (3) to yield the more compact expression

$$\nu_{1,hybrid} = \frac{\ell}{\ell + h} \min\{r_s, r_s (1 - p_s) + r_t (1 - p_t)\},$$

in which the first term in the minimization corresponds to stable operation and the second corresponds to unstable operation.

It should be noted that Figure 2 does not necessarily represent an *implementation* of a hybrid network. In particular, one might expect prolonged unstable operation would lead to overflow of a finite retransmissions buffer. However, if the system is implemented with a common window for frames sent on the satellite and terrestrial links, then it is possible to assure no overflow of frames from the retransmissions buffer during prolonged unstable operation. Even so, the window size cannot be unlimited in an implementation, and so the flow of fresh information frames on the satellite link may have to be cyclically suspended and resumed to allow for many terrestrial retransmissions if the system is unstable in the sense described above.

### *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. (The results presented here also apply for  $M = 1$ .)

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 ARQ protocol operation is according to the Dynamic Retransmissions Group Reduction (DRGR) technique described in [5]. The essential feature of this selective-repeat ARQ protocol is that the transmitter maintains a history of which stations have acknowledged which frames. Accordingly, if receiver  $m \in \{1, 2, \dots, M\}$  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.

We define the throughput of the multicast system as the average of the unicast throughputs to all receivers.

*Pure-satellite 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 request through their acknowledgements. Otherwise a new frame is sent.

Let  $m_j$  denote the number of receivers which successfully receive a 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. This probability may be found counting all possible combinations of the number of transmissions required to deliver frame  $\mathcal{F}$  to each of the  $M$  receivers, given  $\mathcal{F}$  was transmitted  $j$  times, yielding

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

where the multinomial coefficient is given by

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

An simpler way to calculate  $\gamma(j)$  is to consider the complement of the events of the destinations not receiving  $\mathcal{F}$  after  $j$  transmissions, yielding

$$\gamma(j) = (1 - p_s^j)^M.$$

By its definition,  $\gamma(j)$  is the cumulative distribution function for the number of transmissions required to successfully deliver a frame to all receivers. Then we may calculate  $\beta_{M,satellite}$ , the expected number of frames sent per frame delivered to all  $M$  receivers in the pure-satellite network, as:

$$\beta_{M,satellite} = \sum_{j=1}^{\infty} j[\gamma(j) - \gamma(j-1)] \quad (4)$$

Hence the throughput for multicasting in a pure-satellite network,  $\nu_{M,satellite}$  is

$$\nu_{M,hybrid} = \left( \frac{\ell}{\ell + h} \right) \frac{r_s}{\beta_{M,satellite}}$$

with  $\beta_{M,satellite}$  calculated as above. We remark that evaluating (4) with  $M = 1$  yields (1), and so the expressions for  $\beta$  and  $\nu$  in the single- and multiple-receiver cases of the pure-satellite network are consistent.

*Hybrid Network:* Although a multicast transmitter in a hybrid network must keep track of more information and service more receivers with retransmissions than its unicast counterpart, the receivers in the multicast setting are the

same as the unicast receiver. Hence  $\nu_{M,satellite}$ , the throughput for multicasting in a hybrid network, is the same as for unicasting in the hybrid network:

$$\begin{aligned}\nu_{M,hybrid} &= \nu_{1,hybrid} \\ &= \frac{\ell}{\ell+h} \min\{r_s, r_s(1-p_s) + r_t(1-p_t)\}\end{aligned}$$

In particular, the throughput in the hybrid network is independent of the number of receivers in the network.

## 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. The channel bit transmission rates are  $r_s = 1536000$  and  $r_t = 33600$  bits per second in the satellite and terrestrial channels, respectively.
4. There are  $\ell = 1776$  information bits and  $h = 32$  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 16-bit CRC for error detection. The value of  $\ell$  was chosen to maximize the throughput in a point-to-point satellite network, which is the reference network for comparison purposes. This maximization is calculated by a straightforward differentiation method presented in [6]. For this maximization,  $q_s$  was taken to be  $10^{-5}$ , the median value of the satellite link BERs examined below.)
5. In calculating  $\beta_{M,satellite}$ , we approximated the infinite summation of (4) by truncating the summation at the minimum  $j$  such that  $\gamma(j) > 1 - 10^{-10}$ . (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 3. The reduction of throughput with increase in number of receivers in the pure-satellite network is clearly indicated in the figure. The figure also shows the throughput in the hybrid network meets or exceeds that in the pure-satellite network and is independent of the number of receivers.

Of course, achieving the higher throughput of a hybrid network requires the terrestrial links from the transmitter to each receiver. This need for additional bandwidth naturally prompts asking about the efficiency of the hybrid network. Several efficiency measures can be defined, each with its own merits and pitfalls. We choose to define the throughput efficiency,  $\eta$ , as the throughput divided by the sum of the network link bandwidths. That is, the efficiency in the pure-satellite network of  $M$  receivers is  $\eta_{M,satellite} = \nu_{M,satellite}/r_s$ , while the efficiency in a corresponding hybrid network is  $\eta_{M,hybrid} = \nu_{M,hybrid}/(r_s + Mr_t)$ . Applying these definitions to the setting and results of the foregoing examples yields the results shown in Figure 4. For the hybrid network,  $\eta_{M,hybrid}$  decreases as  $M$  increases, as is evidenced in the figure. The figure also indicates the pure-satellite network is more efficient than the hybrid network unless the satellite link BER is fairly high (say,  $10^{-4}$ ), and only up to some number of receivers (say, 100)—at which point the efficiency of the pure satellite network again exceeds that of the hybrid network. So, while the hybrid network provides better throughput than the pure-satellite network, it does so at greater cost, according to at least the efficiency measure defined above. As remarked earlier, our efficiency measure is but one of several which can be defined.

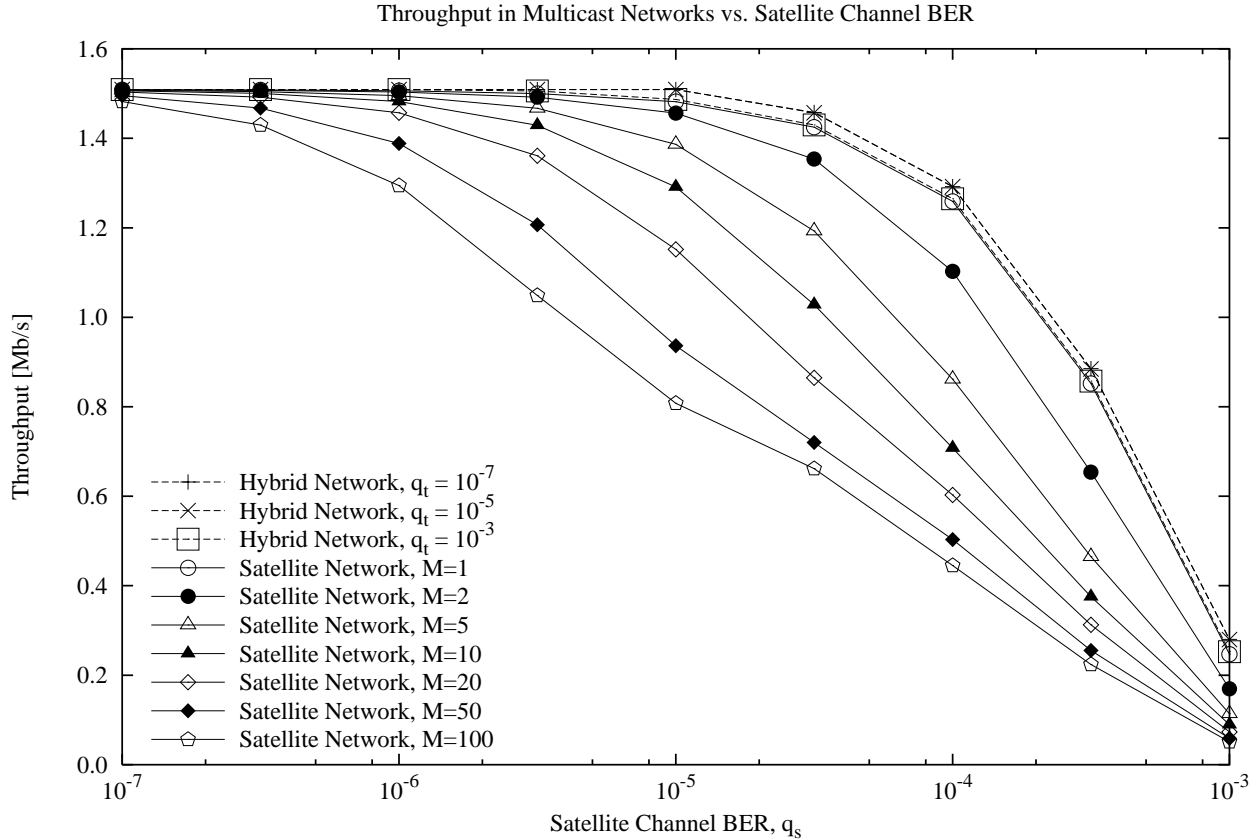


Figure 3: Throughput in point-to-multipoint networks.

## 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 suffers as the number of receivers increases. In this work we have suggested a solution to this problem, namely retransmissions should be sent over a system of point-to-point terrestrial links between the transmitter and each receiver. However, many considerations remain to be studied.

Perhaps foremost among these concerns is how to increase the efficiency of the protocol's operation in the hybrid network. At times when the satellite link experienced by one receiver is good that receiver's terrestrial channel may be underutilized. This suggests that if the transmitter can deduce the approximate quality of the satellite link to each receiver, perhaps initial transmissions of some frames can be conducted on the terrestrial links to increase the throughput and efficiency.

We must also examine the effect of packet lengths on throughput. While the frame length which maximizes throughput in a point-to-point satellite network is easily calculated ([6]), 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.

Important implementation issues arise in multicasting, and these must be examined. In addition to well-known multicast network concerns such as overwhelming the transmitter with acknowledgements, some are unique to the hybrid network. In particular, it is not clear if the transmitting station should have a single protocol governing operation on all links, or if the operation should be split into a protocol for the satellite link and separate protocols for the terrestrial links. How this split should be made and how the pieces of the transmitter's operation should be connected should similarly be explored.



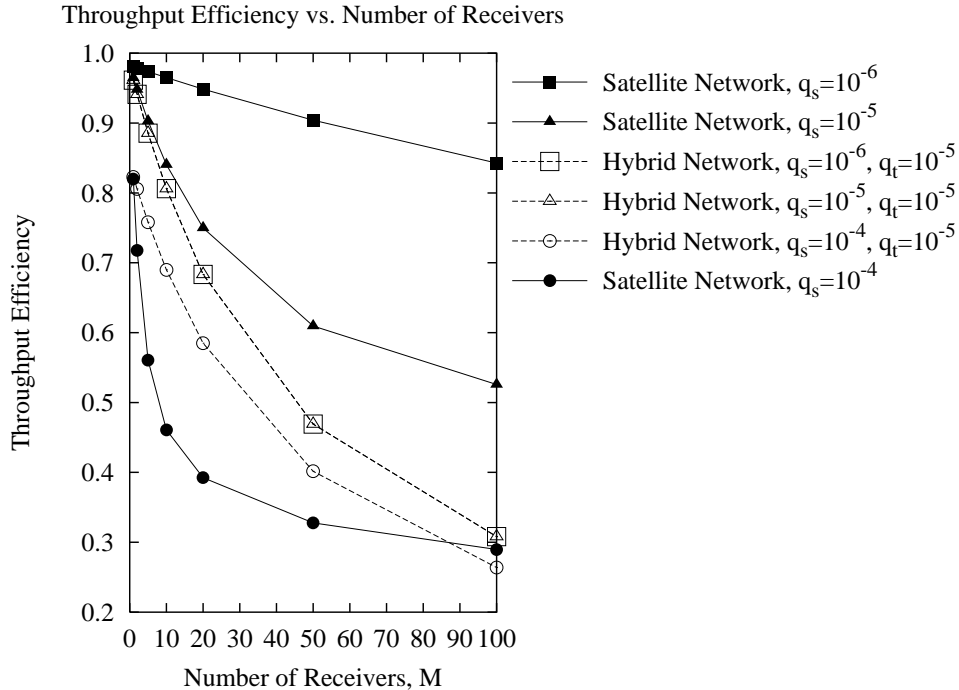


Figure 4: Throughput efficiency in point-to-multipoint networks.

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 desirable. 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. Such operation in a tree-shaped terrestrial is similar to the operation of the Reliable Multicast Transport Protocol [7, 8].

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 [9, 10, 11]. (The reader is cautioned that the term “hybrid ARQ,” which is the standard term 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 [9], 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, form a series of BCH codewords of decreasing rate. Employing such an FEC technique would not only improve throughput in a hybrid network, it would reduce terrestrial retransmissions and so increase the terrestrial bandwidth possibly available for original transmissions, as described at the beginning of this section.

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.

\*

- [1] S. Lin and D. J. Costello, Jr., *Error Control Coding: Fundamentals and Applications*. Prentice-Hall, 1983.
- [2] S. B. Wicker, *Error Control Systems for Digital Communication and Storage*. Prentice-Hall, 1995.
- [3] T. Pratt and C. W. Bostian, *Satellite Communications*. Wiley, 1986.
- [4] Y. Yamauchi, "On the packet radio multicast scheme for the personal communications era," in *International Conference on Communication Systems (ICCS '94)*, Singapore, pp. 576–580, IEEE, 1994.
- [5] K. Sabnani and M. Schwartz, "Multidestination protocols for satellite broadcast channels," *IEEE Transactions on Communications*, vol. 33, pp. 232–240, Mar. 1985.
- [6] M. Schwartz, *Telecommunication Networks: Protocols, Modeling, and Analysis*. Addison-Wesley, 1987.
- [7] S. Paul, K. Sabnani, J. Lin, and S. Bhattacharyya, "Reliable multicast transport protocol (RMTP)," *IEEE Journal on Selected Areas in Communications*. To appear in special issue on Network Support for Multipoint Communications. (Also available at <http://bell-labs.com/users/sanjoy/rmtp2.ps>).
- [8] S. Paul, K. Sabnani, and D. Kristol, "Multicast transport protocols for high-speed networks," in *Proceedings of the International Conference on Network Protocols*, pp. 4–14, 1994.
- [9] A. Shiozaki, "Adaptive type-II hybrid broadcast ARQ system," *IEEE Transactions on Communications*, vol. 44, pp. 420–422, April 1996.
- [10] H. Liu, Q. Zhang, M. E. Zarki, and S. Kassam, "Wireless video transmission with adaptive error control," in *1996 International Symposium on Information Theory and its Applications (ISITA '96)*, Victoria, British Columbia, pp. 371–374, 1996.
- [11] H. Zhao, T. Sato, and I. Kimura, "A hybrid-ARQ protocol with optimal adaptive error control for multidestination satellite communications," in *International Conference on Communication Systems (ICCS '94)*, Singapore, pp. 420–424, 1994.