M. A. Reed
T. D. Smetanka

Implications of a Selective Acknowledgment Scheme on Satellite Performance

Data link response time is becoming more of a concern today with the onset of satellite transmissions of computer data. The long propagation delay inherent to satellite communications may lead to a degradation in data link response time as compared to the same transmission over purely terrestrial links. Furthermore, data link errors need be considered in any such study of response time of satellite data links. A model has been developed to study data link response time under a selective acknowledgment retransmission protocol. The model not only calculates mean link response time, but also the second moment of the response time. This model is then applied to various interactive data transmission schemes over a half-duplex (HDX) satellite link with terrestrial tails, although modifications can easily be made to analyze pure terrestrial or satellite links. The model parameters include bit error rate (BER), terrestrial as well as satellite propagation delay, modem transit delay, MAXOUT (maximum number of unacknowledged data frames), frame size (bits), and message size (bits).

Introduction

Satellite data transmission, as any new technology, entails many questions which need to be addressed. One such question concerns the effects that the long propagation delay inherent in satellite data links has upon response time in an interactive environment. Since one station must wait for a reply from its corresponding station before sending the next message, link response time is critical to the user. Most analyses of this link response time in the past have not been concerned with retransmissions caused by link errors, but this is vital for a study of satellite links where a single retransmission may take 1/2 second or more to complete.

A typical satellite transmission system is depicted in Fig. 1. The secondary station, such as a terminal outside Los Angeles, originates a message in digitized format. A modem then converts the signal to analog for transmission over the link. A terrestrial tail carries the message to Los Angeles where an earth station transmits the message to a geosynchronous satellite located 35 800 km (22 300 miles) above the earth. The signal is rebroadcast to another earth station located in Washington, DC, which then sends the message over a terrestrial tail to the primary station. Here the message is reconverted back to digital by the primary's modem. The reverse path is followed for transmissions from the primary station to its corresponding secondary station. This scenario represents the HDX point-to-point data transmission system studied. The terrestrial tails are necessary in cases where the data processing equipment is remote from its corresponding earth station [1–2]. Data link errors range from one in 1000 to one in 100 000 bits in error [3] [without the use of FEC (forward error correction)] on the terrestrial

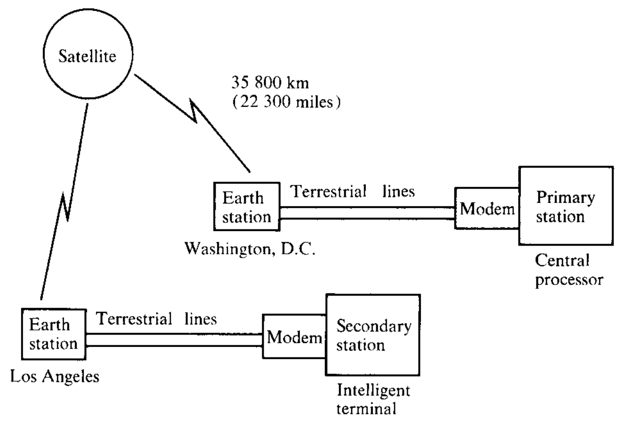

Figure 1 A typical satellite link with terrestrial tails.

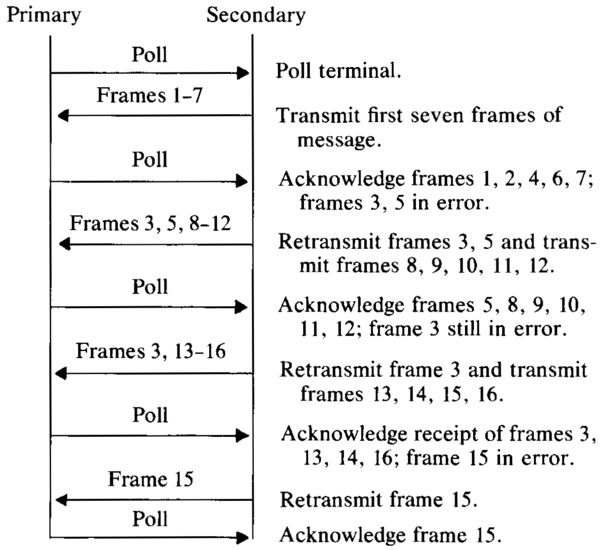

Figure 2 An example of a selective acknowledgment transmission sequence for a 16-frame message, where *MAXOUT* is 7 frames.

tails and one in 1 000 000 bits in error [4] or better on the satellite link. Therefore, the terrestrial tail becomes the "weakest link" in regard to data link errors for a satellite configuration which involves terrestrial tails.

A selective acknowledgment retransmission scheme on HDLC, a high-level, bit-oriented, data-link protocol, is assumed to control the flow of data frames in this analysis [5-7]. A frame contains both user information and control data needed for transmitting each frame. The control data is assumed to be 56 bits per frame in this analysis.

HDLC allows up to 127 ($MAXOUT = 127$) frames of data to be outstanding before an acknowledgment of these frames is required. But by setting *MAXOUT* less than 127, it is possible to require fewer frames to be outstanding than the maximum allowed by HDLC. *MAXOUT* may be used, for example, to limit the number of frames outstanding in order to conserve line buffers. It is assumed that the transmission of acknowledgment messages is error-free for this study.

Figure 2 exemplifies the selective acknowledgment scheme considered here. It is similar to HDLC's presently designed selective reject (SREJ) procedure in that only those particular frames received in error need be retransmitted. However, HDLC allows only one "SREJ" to be outstanding at a time, thus precluding more than one previously errored frame from being sent per transmission. Conversely, the selective acknowledgment technique proposed here allows all frames received in error after a given transmission sequence to be selectively retransmitted in the next transmission sequence, thereby permitting interspersed non-errored frames to be released from buffering at the receiving station. Notice in Fig. 2 that fewer than *MAXOUT* frames may be sent in a given transmission sequence. This would occur, for example, when a single message source is actively transmitting into the HDX link.

Other retransmission schemes have been analyzed, such as GO-BACK-N-ARQ (automatic request for repeat of an errored frame and all subsequent frames outstanding) [8-16]. Although GO-BACK-N-ARQ requires less buffering at the receiving station than the above techniques do, it may also lead to longer data link response times as a result of retransmitting more frames.

Most studies previously conducted have been concerned with the effects of data link errors on batch transmissions, where throughput rather than response time is the critical performance characteristic [17-21]. The need for a response time formulation directed towards interactive applications was therefore recognized. In addition, because of the complexity of the problem, previous analyses have only derived the mean throughput, while the following model provides the derivation of the second as well as the first moment of response time.

Mathematical model

In order to formulate a model for link response time under selective acknowledgment, five dependent variables need be determined:

μ_B = Average number of frames transmitted including those in error (for a message of n frames and $MAXOUT = M$).

σ_B = Standard deviation of the number of frames transmitted.

μ_L = Average number of transmissions required (for a message of n frames and $MAXOUT = M$).

σ_L = Standard deviation of the number of transmission levels required.

$\sigma_{B,L}$ = Covariance of the joint distribution of frames sent and transmissions required.

The average response time (for a message of n frames with $MAXOUT = M$) is

$$\mu_{RT} = t_B\mu_B + t_L\mu_L, \tag{1}$$

and the standard deviation of response time is

$$\sigma_{RT} = \sqrt{t_B^2\sigma_B^2 + t_L^2\sigma_L^2 + 2t_Bt_L\sigma_{B,L}}\ , \tag{2}$$

where

t_B = transmission time per frame,

t_L = overhead time per transmission level.

Further, $t_B = S/BPS$, (3)

where S = frame size in bits,

BPS = transmission speed (bits per second),

and

$$t_L = 4(d_{\mathrm{mt}} + d_{\mathrm{tp}} + d_{\mathrm{sp}}) + \frac{\mathit{acknowledgment\ size}\ (\text{bits})}{BPS} + d_{\mathrm{A}}, \quad (4)$$

where

d_{mt} = modem transit delay,

d_{tp} = terrestrial propagation delay for one tail,

d_{sp} = satellite propagation delay for one leg,

d_{A} = any additional configuration dependent delays (assumed 0 in this analysis), such as satellite turnaround time, additional system protocol, encoding/decoding time of messages, etc.

Define

B = The discrete random variable denoting the number of frames required to transmit a message of n frames, where $MAXOUT = M$.

$P_B^{n,m}(b)$ = The probability distribution of B.

L = The discrete random variable denoting the number of levels required to transmit a message of n frames, where $MAXOUT = M$.

$P_L^{n,m}(l)$ = The probability distribution of L.

$P_{B,L}^{n,m}(b, l)$ = The joint probability distribution of B and L.

RT = The random variable denoting message response time.

BER = Overall bit error rate of the transmission link.

And let

$\ulcorner x$ = Least integer greater than or equal to x,

$\llcorner x$ = Greatest integer less than or equal to x,

$x \ulcorner y$ = Greater of x and y,

$x \llcorner y$ = Smaller of x and y.

Frame error probability

Assume that the bit errors are independent and identically distributed (i.i.d.). Considering that if any one bit in a frame is in error the frame itself is taken to be in error, an expression for frame error probability is

$$p = 1 - (1 - BER)^S \quad (5)$$

and

$$q = 1 - p. \quad (6)$$

If the i.i.d. assumption is invalid, alternate equations for p and q should be developed from the known distributions.

The probability distribution of *B*

As defined, the selective acknowledgment scheme requires that only the particular frame(s) in error on a given level be retransmitted on the next level. Consequently, if b frames ($b \geq n$) are needed in order to send an n frame message, then $(b - n)$ of these b frames must be in error. Determination of the probability distribution of B now reduces to the combinatorial problem of finding the number of ways that these $(b - n)$ errors can occur in b frames. Recognizing the loss of one degree of freedom in the total number of possible frames that can be in error, since the last frame must be error-free, there are ${}_{(b-1)}C_{(b-n)}$ ways in which the errors can occur. Thus,

$$P_B^{n,m}(b) = \binom{b-1}{b-n} p^{b-n} q^n \qquad b \geq n,$$

$$= 0 \qquad b < n, \quad (7)$$

with mean

$$\mu_B = \frac{n}{q} \quad (8)$$

and standard deviation

$$\sigma_B = \frac{\sqrt{np}}{q}. \quad (9)$$

The probability distribution of *L*

Case 1: $M \geq n$

Define

k_i = The discrete r.v. denoting the number of frames sent on level i.

e_i = The discrete r.v. denoting the number of frames in error on level i.

Since $M \geq n$, all n frames will be transmitted on the first level. On each subsequent level, the number of frames sent will be the number of frames which were in error on the previous level, i.e.,

$$k_1 = n, \quad (10)$$

$$k_{i+1} = e_i \qquad i \geq 1. \quad (11)$$

As an intermediate result, we are seeking the probability distribution functions of k_{i+1}. Clearly,

$$P(k_1 = x) = 1 \qquad x = n,$$
$$= 0 \qquad \text{otherwise.}$$

$$P(k_{i+1} = x) = P(e_i = x)$$
$$= \sum_{y=x}^{n} P(k_i = y)P(e_i = x \mid k_i = y), \tag{12}$$

where $P(e_i = x \mid k_i = y)$ is the binomial distribution,

$$P(e_i = x \mid k_i = y) = \binom{y}{x} p^x q^{y-x} \qquad 0 \le x \le y. \tag{13}$$

Recursive use of Eq. (12) yields a general expression for the distribution of k_{i+1},

$$P(k_{i+1} = x) = \binom{n}{x} p^{ix}(1 - p^i)^{n-x}. \tag{14}$$

Now that the distribution functions of k_{i+1} have been found, it is a simple matter to determine the distribution of L. If exactly l levels are required, then on level $(l + 1)$ zero frames will be "transmitted." But we must subtract from $P(k_{l+1} = 0)$ the probability that zero frames are "transmitted" on level l, to ensure that level l is indeed required. Therefore,

$$P_L^{n,m}(l) = (1 - p^l)^n - (1 - p^{l-1})^n, \tag{15}$$

with mean

$$\mu_L = \sum_{i=1}^{n} (-1)^{i+1} \binom{n}{i} (1 - p^i)^{-1} \tag{16}$$

and standard deviation,

$$\sigma_L = \left(\left\{ \sum_{i=1}^{n} (-1)^{i+1} \binom{n}{i} \left[\frac{1 + p^i}{(1 - p^i)^2} \right] \right\} - \mu_L^2 \right)^{1/2}. \tag{17}$$

Case 2: $M < n$
Define

r_i = The discrete r.v. denoting the number of message frames which remain to be sent after level i has been transmitted, with the initial condition, $r_0 = n$.

Note that there must be at least $\lceil n/M$ levels when $M < n$, of which $(\lceil n/M) - 1$ must be "full" (containing M frames). Thus, for $i \le (\lceil n/M) - 1$,

$$P(r_i = x \mid r_{i-1} > M) = P(r_i = x). \tag{18}$$

In this region, the distribution of r_i is the binomial distribution of $(iM + x - n)$ errors in iM frames, i.e.,

$$P(r_i = x \mid r_{i-1} > M) = \binom{iM}{iM + x - n} p^{iM+x-n} q^{n-x}$$
$$x \in [(n - iM), n],$$
$$i \le (\lceil n/M) - 1. \tag{19}$$

For $i > (\lceil n/M) - 1$, Eq. (18) is still applicable as long as $x > M$. As a result,

$$P(r_i = x \mid r_{i-1} > M) = \binom{iM}{iM + x - n} p^{iM+x-n} q^{n-x}$$
$$x > M,$$
$$i > (\lceil n/M) - 1. \tag{20}$$

Finally, the case where $x \le M$ and $i > (\lceil n/M) - 1$ must be considered. In this region Eq. (18) is not true, since it is possible for $r_{i-1} \le M$. Therefore, we must examine only the situations where $r_{i-1} > M$, and then proceed to level i to find the conditional distribution of r_i,

$$P(r_i = x \mid r_{i-1} > M)$$
$$= \sum_{y=M+1}^{x+M} P(r_{i-1} = y)P(e_i = M - (y - x) \mid k_i = M)$$
$$x \in [1,M],$$
$$= p^{iM-(n-x)} q^{n-x} \sum_{y=M+1}^{x+M} \binom{(i - 1)M}{n - y} \binom{M}{y - x}$$
$$x \in [1,M],$$
$$i > (\lceil n/M) - 1, \tag{21}$$

where e_i and k_i are defined in the previous section.

Now consider the format of transmissions in order to have exactly l transmission levels. There must exist some l^* (where $l^* < l$) such that the first l^* levels are "full" and x frames ($x \in [1,M]$) remain to be sent after level l^*. Once l^* and x are determined, the probability that these x frames are sent in $(l - l^*)$ levels is simply $P_L^{x,x}(l - l^*)$, which was derived for the situation where $M \ge n$.

Summing over all possible combinations of l^* and x,

$$P_L^{n,M}(l) = \sum_{l^*=(\lceil n/M)-1}^{l-1} \sum_{x=1}^{M} P(r_{l^*} = x \mid r_{l^*-1} > M) P_L^{x,x}(l - l^*)$$
$$l \ge \lceil n/M,$$
$$= 0 \qquad \text{otherwise.}$$

Substitution of the derived probability distributions yields

$$P_L^{n,M}(l) = \sum_{l^*=(\lceil n/M)-1}^{l-1} \sum_{x=1}^{M} \sum_{y=M+1}^{x+M} p^{l^*M-(n-x)} q^{n-x} \binom{(l^* - 1)M}{n - y}$$
$$\times \binom{M}{y - x} [(1 - p^{l-l^*})^x - (1 - p^{l-l^*-1})^x]$$
$$l \ge \lceil n/M,$$
$$= 0 \qquad \text{otherwise.} \tag{22}$$

The mean and standard deviation of L can be calculated by the formulae:

$$\mu_L = \sum_{l=\lceil n/M}^{l_{\max}} l P_L^{n,M}(l), \tag{23}$$

$$\sigma_L = \left\{\left[\sum_{l=\lceil n/M}^{l_{\max}} l^2 P_L^{n,M}(l)\right] - \mu_L^2\right\}^{1/2}, \tag{24}$$

where $l_{\max}$ is chosen so that $l^i P_L^{n,M}(l)$ is negligible for every $l > l_{\max}$, $i = 1, 2$, provided that L has the bounded first and second moments. The finite sums can be computed to any desired degree of accuracy by quantifying the stopping criteria. Computationally, this involves the comparison of each additional term in Eqs. (23) and (24) to the current sums, once $P_L^{n,M}(l)$ reaches the region where it is monotonically decreasing. When these additional terms then fall below preselected fractions of the accumulated sums, the calculations are terminated.

The joint distribution of *B* and *L*

Case 1: $M \geq n$

Let us rearrange Eq. (15) to yield the following form:

$$P_L^{n,M}(l) = q^n \sum_{i=1}^{n} (-1)^{i+1} \binom{n}{i} \sum_{j=0}^{\infty} p^{j+i(l-1)} \times \left[\binom{n+j-1}{j} - \binom{n+j-1-i}{j-i}\right], \tag{25}$$

where, by definition,

$$\binom{x}{y} = 0 \quad \text{if} \quad x < y \quad \text{or} \quad y < 0.$$

Notice that in order to have exactly b frames sent, there must be $(b-n)$ frames in error. So the power of p in Eq. (25) must always equal $(b-n)$. Therefore,

$$\hat{j} = b - n - i(l-1).$$

Selecting only the $\hat{j}$th term from Eq. (25), we have

$$P_{B,L}^{n,M}(b, l) = q^n p^{b-n} \sum_{i=1}^{n} (-1)^{i+1} \binom{n}{i} \times \left[\binom{b-i(l-1)-1}{b-n-i(l-1)} - \binom{b-il-1}{b-n-il}\right]. \tag{26}$$

The number of terms in the summation can be reduced by eliminating the cases where both combinatorial terms in brackets are zero. In addition, the region of applicability for this equation is restricted to $b \in [(l+n-1), ln]$. Thus,

$$\begin{aligned} P_{B,L}^{n,M}(b, l) &= q^n p^{b-n} \sum_{i=1}^{\left\lfloor \frac{1\lceil(b-n)}{(l-1)\lceil(1/n)} \right.} (-1)^{i+1} \binom{n}{i} \times \left[\binom{b-i(l-1)-1}{b-n-i(l-1)} - \binom{b-il-1}{b-n-il}\right] \\ &\qquad l+n-1 \leq b \leq ln, \\ &\qquad l \geq 1, \\ &= 0 \qquad \text{otherwise.} \end{aligned} \tag{27}$$

Case 2: $M < n$

As in the derivation of $P_L^{n,M}(l)$ for $M < n$, we can define an l^* such that levels 1 through l^* are "full" and x frames remain to be sent after level l^*. To find the joint distribution of B and L, we seek the probabilities that l^*M frames are transmitted in the first l^* levels and the remaining x frames ($x \in [1, M]$) require $b - l^*M$ frames to be sent in $(l - l^*)$ levels. Summing over the appropriate values for l^* and x,

$$P_{B,L}^{n,M}(b, l) = \sum_{l^*=(\lceil n/M)-1}^{l-1} \sum_{x=1}^{M} P(r_{l^*} = x \mid r_{l^*-1} > M) \times P_{B,L}^{x,x}((b - l^*M), (l - l^*)), \tag{28}$$

where

$$\begin{aligned} P_{B,L}^{x,x}&((b - l^*M), (l - l^*)) \\ &= q^x p^{b-l^*M-x} \sum_{i=1}^{\left\lfloor \frac{1\lceil(b-l^*M-x)}{(l-l^*-1)\lceil(1/x)} \right.} (-1)^{i+1} \binom{x}{i} \\ &\quad \times \left[\binom{b-l^*M-i(l-l^*-1)-1}{b-l^*M-x-i(l-l^*-1)} - \binom{b-l^*M-i(l-l^*)-1}{b-l^*M-x-i(l-l^*)}\right] \\ &\qquad l - l^* + x - 1 \leq b - l^*M \leq (l-l^*)x, \\ &= 0 \qquad \text{otherwise.} \end{aligned} \tag{29}$$

Observe that the non-zero range of Eq. (29) further restricts the values of x in Eq. (28).

Additional restrictions must also be imposed on l, l^*, and b since there must be at least one, and no more than M, frames transmitted on each level:

$$l \geq \lceil n/M, \tag{30}$$

$$l + n - \lceil n/M \leq b \leq lM, \tag{31}$$

$$l^* \leq \frac{b-l}{M-1}. \tag{32}$$

The special case of $M = 1$ is discussed in the next section.

Summarizing,

$$\begin{aligned} P_{B,L}^{n,M}(b, l) &= q^n p^{b-n} \\ &\times \sum_{l^*=(\lceil n/M)-1}^{(l-1)\lfloor\lfloor\left(\frac{b-l}{M-1}\right)} \; \sum_{x=1\lceil\lceil\left(\frac{b-l^*M}{l-l^*}\right)}^{M\lfloor(b+1-l+l^*-l^*M)} \; \sum_{y=M+1}^{x+M} \; \sum_{i=1}^{\left\lfloor \frac{1\lceil(b-l^*M-x)}{(l-l^*-1)\lceil(1/x)} \right.} \eta \\ &\qquad l \geq \lceil n/M, \\ &\qquad l + n - \lceil n/M \leq b \leq lM, \\ &\qquad 1 < M < n, \end{aligned} \tag{33}$$

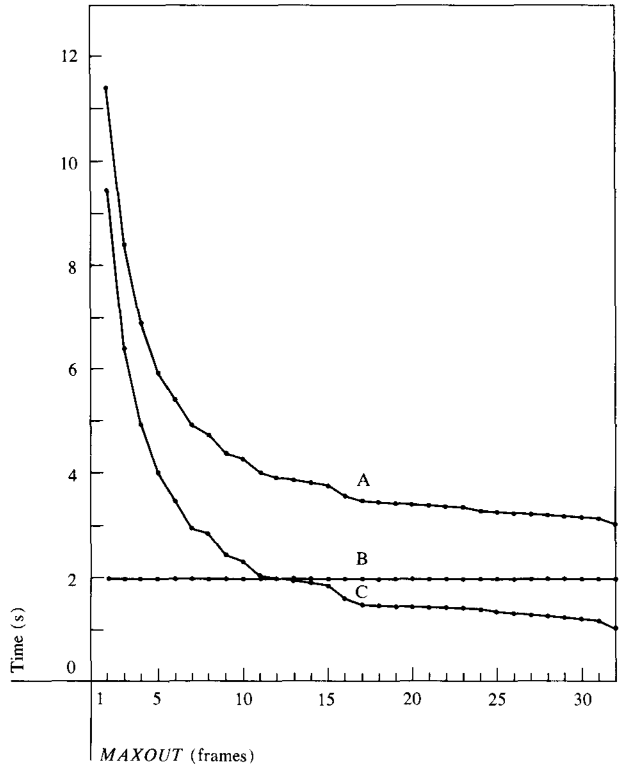

Figure 3 The components of satellite data link response time for an interactive 32-frame message with 512 data bits per frame, a 9600-BPS transmission speed, a 10^{-4} *BER* (bit error rate), and a 0.552-second overhead delay per transmission: curve A, link response time; curve B, frame transmission time; curve C, overhead time.

where

$$\eta = (-1)^{i+1}\binom{x}{i}\binom{(l^*-1)M}{n-y}\binom{M}{y-x} \times \left[\binom{b-l^*M-i(l-l^*-1)-1}{b-l^*M-x-i(l-l^*-1)} - \binom{b-l^*M-i(l-l^*)-1}{b-l^*M-x-i(l-l^*)}\right].$$

The covariance of B and L, for any value of M, can be computed from

$$\sigma_{B,L} = \sum_{l=\lceil n/M}^{l_{\max}} \sum_{b=l+n-\lceil n/M}^{l(n\lfloor M)} P_{B,L}^{n,M}(b, l)[(b-\mu_B)(l-\mu_L)], \quad (34)$$

where $l_{\max}$ is chosen, as before, so that $P_{B,L}^{n,M}(b, l)$ is negligible for every $l > l_{\max}$.

The special case of $M = 1$

Since only one frame is transmitted on each level, the probability distribution of levels is the same as that of frames. And the joint distribution of frames and levels is also the same. Therefore,

$$P_B^{n,M}(x) = P_L^{n,M}(x) = P_{B,L}^{n,M}(x,y) = \binom{x-1}{n-1} p^{x-n} q^n \qquad b = l = x = y, \quad x \geq n,$$
$$= 0 \qquad \text{otherwise;} \quad (35)$$

$$\mu_B = \mu_L = \frac{n}{q}\,; \quad (36)$$

$$\sigma_{B,L} = \sigma_B^2 = \sigma_L^2 = \frac{np}{q^2}\,. \quad (37)$$

Examples and applications

Consider a satellite link with terrestrial tails as depicted in Fig. 1. Define the modem transit delay, terrestrial propagation delay [22], and satellite propagation delay as:

$d_{\mathrm{mt}} = 0.01$ seconds,

$d_{\mathrm{tp}} = 161$ km (0.001 seconds/24 km) = 0.0067 seconds,

$d_{\mathrm{sp}} = (35\,800$ km$)/(3 \times 10^5$ km per second$) = 0.1198$ seconds,

acknowledgment size = 56 bits.

Therefore, the overhead delay per transmission is $t_L = 0.552$ seconds. Let the message size be 16 384 bits of data with 56 bits of control data appended to each frame of the message. Assume a 9600 BPS (bits-per-second) data link where the overall *BER* is one bit in 10 000 determined by the terrestrial tails' *BER*.

Figure 3 displays the link response time vs *MAXOUT* for the message blocked into 32 frames, each containing 512 data bits. The two components of link response time, overall overhead time and the actual message transmission time, are also shown. The superposition of these two components leads to the link response time [see Eq. (1)]. Queuing delays which are configuration dependent, such as waiting for polls or for completion of other terminals' transmissions from the same station, may also be added to the formulated response time to obtain a total transmission delay. An inherent characteristic of selective acknowledgment is that the actual message transmission time (defined by total bits sent including those retransmitted divided by link speed in BPS) is independent of *MAXOUT*. Also, the overall overhead time is monotonically decreasing as a function of *MAXOUT*. Therefore, if line buffers are not a constraining factor on the system, *MAXOUT* should be made to equal the number of frames in the message to optimize response time. Unfortunately,

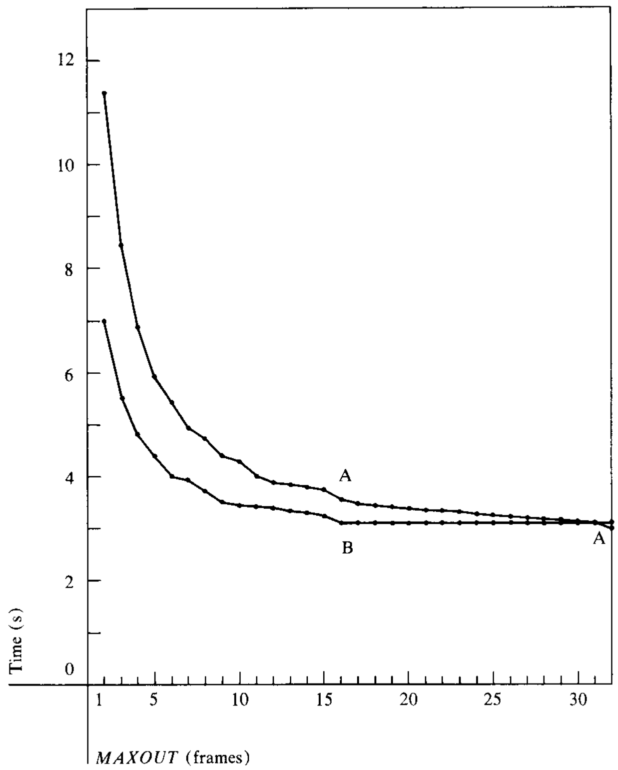

Figure 4 A comparison of the average link response times for a fixed-size message blocked into 32 and 16 frames, as *MAXOUT* increases for a 9600-BPS transmission speed, 10^{-4} *BER* (bit error rate), and 0.552-second overhead delay per transmission: curve A, 32-frame message (512 data bits per frame); curve B, 16-frame message (1024 data bits per frame).

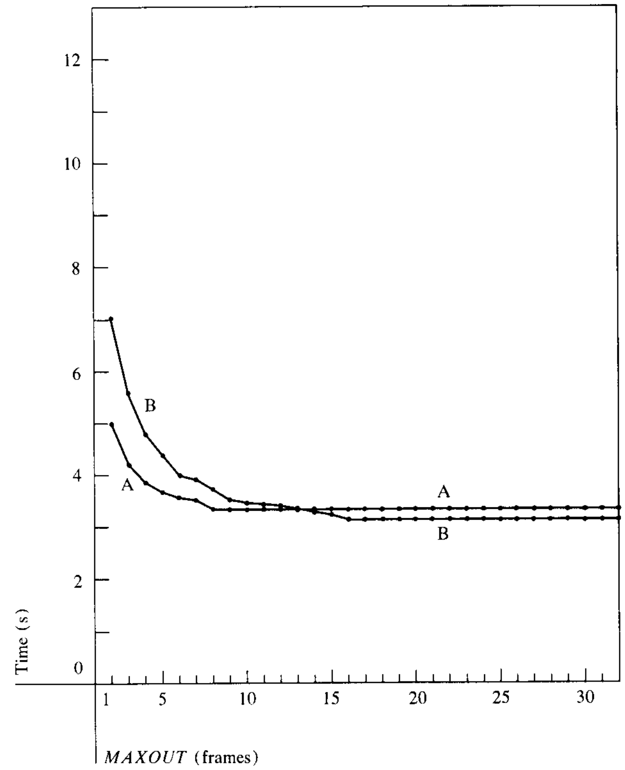

Figure 5 A comparison of the average link response times for a fixed-size message blocked into 16 and 8 frames, as *MAXOUT* increases for a 9600-BPS transmission speed, a 10^{-4} *BER* (bit error rate), and a 0.552-second overhead delay per transmission: curve A, 8-frame message (2048 data bits per frame); curve B, 16-frame message (1024 data bits per frame).

line buffers are usually a primary constraint; therefore, the model predicts link response time under any given *MAXOUT* restriction.

Figure 4 compares the link response time vs *MAXOUT* for the message blocked into either 32 frames (512 data bits each) or 16 frames (1024 data bits each). Here, the 16-frame message is lower in response time for all values of *MAXOUT* except for *MAXOUT* = 32 or larger. When *MAXOUT* is greater than or equal to 32 frames, by blocking the message 32 times rather than 16, 0.05 seconds can be saved on the link response time. One must realize that for any given *MAXOUT*, twice as many bits of data can be sent for a message blocked into 1024 bits per frame as compared to 512 bits per frame.

Figure 5 is analogous to Fig. 4, except the message is blocked into 16 and 8 frames comparatively. Here, once *MAXOUT* becomes 13 or larger, the 16-frame message will decrease response time below that of the 8-frame message.

Figure 6 depicts the 95th percentiles for the given message blocked into 32, 16, or 8 equal frames. This is derived using Eq. (2) with the assumption of a normal distribution. Certain installations (e.g., military operations) might require a maximum response time criteria on the system (95 percent of the link response times for a given application are less than or equal to a given value). Figure 6 illustrates that a blocking factor of 32 or 16 for the message with a corresponding *MAXOUT* of 32 or 16, in this case, is much better in the 95th percentile than that of a message blocked into 8 frames.

Conclusions

An analytic technique has been derived which predicts the performance of an interactive application over a "noisy" HDX terrestrial/satellite transmission link under selective acknowledgment. The technique could also be applied to pure terrestrial as well as pure satellite links. The effects of link speed, message size, frame size, *MAXOUT*, and link error rate (*BER*) upon the link response time can be used to answer such questions as:

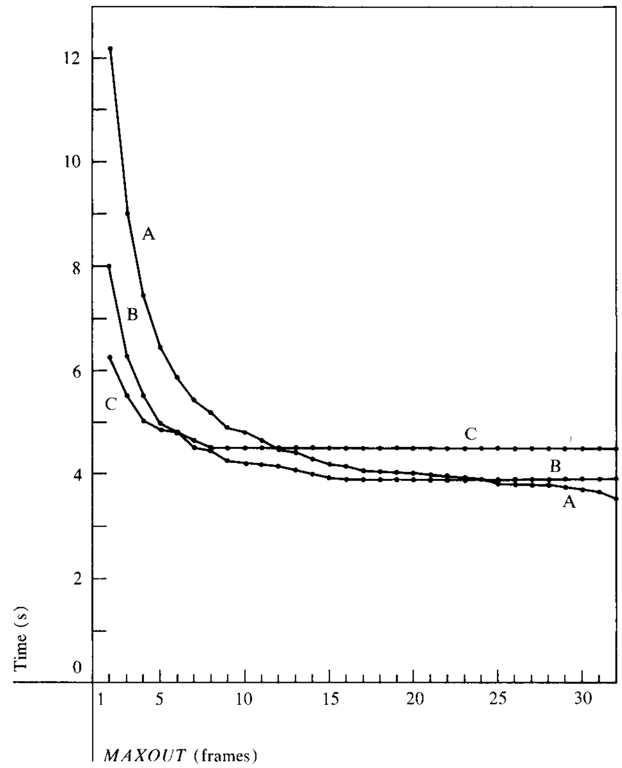

Figure 6 The one-tailed, 95th-percentile response times for a fixed-size message blocked into 32, 16, and 8 frames, as *MAXOUT* increases: curve A, 32-frame message (512 data bits per frame); curve B, 16-frame message (1024 data bits per frame); curve C, 8-frame message (2048 data bits per frame).

1. Is a higher link speed or higher grade link cost justified for the expected response time improvements?
2. Realizing that as *MAXOUT* increases, buffering also need increase at both the sending and receiving stations, what is a realistic value for both *MAXOUT* and thus the determined link response time?
3. What blocking factor will minimize response time?
4. What is the 95 percent confidence interval for a given transmission of a message?

References

1. A. A. Alexander, R. M. Gryb, and D. W. Nast, "Capabilities of the Telephone Network for Data Transmission," *Bell Syst. Tech. J.* **39**, No. 3, 431-476 (1960).
2. H. O. Burton and D. D. Sullivan, "Errors and Error Control," *Proc. IEEE* **60**, No. 11, 1293-1301 (1972).
3. J. Martin, *Systems Analysis for Data Transmission*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1972, p. 202.
4. E. R. Cacciamani and K. S. Kim, "Circumventing the Problem of Propagation Delay on Satellite Data Channels," *Data Commun.* **4**, No. 4, 19-24 (1975).
5. "Data Communications—High Level Data Link Control Procedures—Frame Structure," International Organization for Standardization (ISO) Document No. ISO3309-1976, American National Standards Institute, New York.
6. "Data Communications—High Level Data Link Control Procedures—Elements of Procedures (independent numbering)," International Organization for Standardization (ISO) Document No. ISO/DIS4335(1976), American National Standards Institute, New York.
7. J. P. Gray, "Line Control Procedures," *Proc. IEEE* **60**, No. 11, 1301-1312 (1972).
8. M. A. Reed and T. D. Smetanka, "How to Determine Message Response Time for Satellites," *Data Commun.* **6**, No. 6, 42-47 (1977).
9. M. A. Reed and T. D. Smetanka, "Error Considerations in Determining Satellite Data Link Response Time," *Proceedings of the 1977 IEEE National Telecommunications Conference*, IEEE Pub. No. 77CH1292-2 CSCB, Session 3b-3.
10. T. D. Smetanka, "Data Transmission Errors," *Mini-Micro Systems* **11**, No. 6, 74-75 (1978).
11. B. Reiffen, W. G. Schmidt, and H. L. Yudkin, "The Design of an Error Free Data Transmission System for Telephone Circuits," *AIEE Trans. Commun. Electron.* **80**, 224-231 (1961).
12. W. G. McGruther, "Throughput of High Speed Data Transmission Systems using Block Retransmission Error Control Schemes Over Voice Bandwidth Channels," *Conf. Rec., Int. Conf. Commun.*, IEEE Pub. No. 72CHO622-1-COM, 15-19-15-24 (1972).
13. International Telegraph and Telephone Consultative Committee (Special Study Group A), "Considerations in the Transmission of Data via Satellite Linked Connections," Document COM Sp. A-120-E, U.S. Dept. of Commerce, Washington, DC, December 1970.
14. International Telegraph and Telephone Consultative Committee (Special Study Group A), "Tests of Error Control Equipment Constructed in Accordance with Recommendation V.41," Document COM Sp. A-34-E, U.S. Dept. of Commerce, Washington, DC, November 1973.
15. A. G. Gatfield, "ARQ Error Control on the Satellite Channel," *Conf. Rec., Int. Conf. Commun.*, IEEE Pub. No. 74CHO859-9 CSCB, 22B-1-22B-5 (1974).
16. A. R. K. Sastry, "Error Control Techniques for Satellite Communications: An Overview," *Conf. Rec., Int. Conf. Commun.*, IEEE Pub. No. 74CHO859-9 CSCB, 6A-1-6A-5 (1974).
17. I. G. Niemegeers and F. J. Mowle, "Modelling and Performance Analysis of Maximum Data Rate and Time Delay of an SDLC Protocol," Document PB-276 000, U.S. Department of Commerce, Washington, DC, May 1977.
18. A. K. Kaul, "Performance of High-Level Data Link Control in Satellite Communications," *COMSAT Tech. Rev.* **8**, No. 1, 41-87 (1978).
19. A. Gatfield, "Error Control on Satellite Channels Using ARQ Techniques," *COMSAT Tech. Rev.* **6**, No. 1, 179-188 (1976).
20. K. C. Traynham and R. F. Steen, "SDLC and BSC on Satellite Links: A Performance Comparison," *ACM Computer Commun. Rev.* **7**, No. 4, 3-14 (1977).
21. E. R. Cacciamani, "The Impact of Satellite Communications on Data Throughput," *Telesyst. J.* **3**, No. 5, 1-11 (1976).
22. *Planning and Installation of a Data Communication System Using IBM Line Adapters*, IBM Publication GA24-3435-5, Mechanicsburg, PA, 26-27 (1974).

Received July 11, 1978; revised October 26, 1978

M. A. Reed is with the IBM System Communications Division, Gaithersburg, Maryland 20034; T. D. Smetanka is located at the IBM System Communications Division laboratory, Research Triangle Park, North Carolina 27709.