Modeling TCP Long File Transfer Latency over Long Delay Wireless Multilink PPP

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***Abstract*— The modeling of TCP transfer latency has received significant attention in the last decade. Several models have been proposed for TCP performance under various conditions. All the available models predict TCP performance for a single link. Furthermore, all models relate timeouts to packet drops either due to congestion or due to transmission errors. However, TCP connections may be running over a multilink connection that aggregates the bandwidth of multiple links into a single logical pipe using the multilink point-to-point protocol (MLPPP). In such aggregate links, packet drops occur if any of the individual links experience a call drop. None of the available models account for call drops as a possible source of performance degradation.**

In this letter, we study the call drop phenomenon under MLPPP and incorporate our results into a method that predicts TCP latency for a long transfer. The performance model is experimentally evaluated by running TCP over MLPPP over multiple Iridium satellite links.

***Index Terms*— TCP modeling, MLPPP, call-drops.**

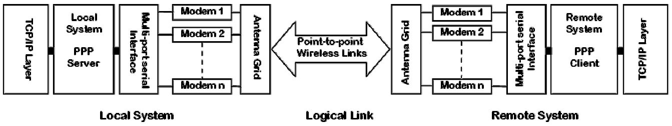

Fig. 1. MLPPP over satellite inks (adapted and modified from [2]).

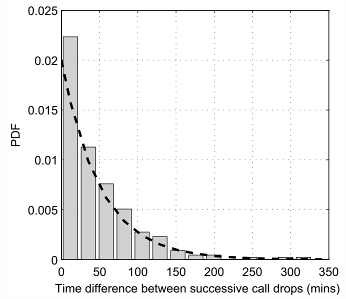

Fig. 2. Probability density function of the interval between call drops [ICTD] based on Greenland-Kansas measurements. The estimated exponential distribution (0.02exp(-0.02t)) passes the chi-square goodness-of-fit test (5% significance level).

I. INTRODUCTION

TCP is the standard transport protocol for many applications. In some cases, in order to satisfy application requirements, it becomes necessary to inverse-multiplex low bandwidth wireless links (using multilink point-to-point protocol MLPPP [1]) to achieve higher bandwidth. The use of such technologies is required to provide adequate Internet access to support field research in remote regions (e.g. Greenland and Antarctica) that are only covered by low bandwidth systems (e.g. Iridium) [2]. Utilizing MLPPP is also a possibility for establishing connectivity over multiple cellular channels. The use of such technologies posed new challenges (e.g. call drops) that have not been fully analyzed yet.

The TCP latency models developed in the last decade address a variety of factors that affect TCP throughput. For example, in [3] the authors consider the effect of timeouts on the TCP file transfer latency. Similarly, in [4], [5] and [6] the authors incorporate the effect of packet drops due to wireless errors.

This letter focuses on TCP over MLPPP, specifically the evaluation of the effect of call drops on TCP performance. In order to provide insight into the nature of the call drops process, a model of the probability density function (pdf) of the time difference between call drops is developed. Using this model, the development in [3] is extended to account for call drops. Then, the proposed model is experimentally validated by field measurements using the Iridium network. Finally, TCP performance over multiple Inmarsat connections is predicted using the proposed model by varying the call drop rate and the packet loss probability.

II. MLPPP SYSTEM MODEL

Here, the MLPPP connection over the Iridium satellite system described in [2] is used as a guideline to develop a TCP latency model that considers call drops; the system model is shown in Fig. 1. Basing the analysis on MLPPP over Iridium does not restrict the results. The Iridium network was used, however, to experimentally validate the proposed model.

III. MODELING CALL DROPS

In order to perform TCP file transfer latency analysis, a probabilistic model for the time between call drops, denoted as the inter-call drop time difference (ICTD), on each member link in the MLPPP bundle needs to be investigated. To estimate the pdf of the per link ICTD, 394 call-drop events were collected using Iridium modems as part of the field experiments carried out in Greenland and in the laboratory in 2004. The empirical pdf of these call drop measurements can be modeled using exponential distribution (see Fig. 2).

Thus, the per link call-drop process can be modeled as a Poisson process with a rate of β. Assuming n independent and identical links, then the ICTD pdf of the whole bundle (Z^{CD}) can be modeled by merging the n Poisson processes into a single Poisson process with a rate of (λ=$n\beta$) and $E[Z^{CD}] = \frac{1}{\lambda}$.

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IV. TCP OVER MLPPP MODEL

In this section, the TCP performance model in [3] is extended to include the effect of call drops. First, model assumptions are listed and then the TCP performance model is derived based on the development presented in [3].

A. Assumptions

In addition to the assumptions in [3], the following factors are taken into account:

1) Each wireless link runs a physical layer reliability assurance mechanism such as automatic-repeat-request (ARQ) discussed in [4] and [5] to compensate for wireless errors. Thus, packet losses due to wireless errors only cause retransmissions (resulting in a halving of the congestion window) but not timeouts. Hence, timeouts are assumed to be solely due to call drops and the probability of packet losses visible at the TCP layer is small.
2) The link is restored before TCP leaves the slow start phase after experiencing a timeout caused by a call-drop.
3) Delayed acknowledgements are assumed, leading to a window increase every 1/b packets (usually b =2).

B. Mathematical Model

The goal of this section is to derive a formula that considers the call-drop events in the estimation of the TCP transfer latency over a long delay MLPPP connection with average TCP throughput (B) packets/s. The TCP transfer latency for f_s bytes given the TCP maximum segment size (*MSS*) can be written as:

$$T_d = \left\lceil \frac{f_s}{MSS} \right\rceil B \quad (sec) \tag{1}$$

Here, B is estimated by extending the TCP latency model in [3] to include the effect of call drops. In this model, as in [3], the TCP flow is viewed as a complex periodic random process (see Fig. 3). Each period (S) consists of two intervals: a data transfer interval (Z^D) and a timeout interval (Z^{TO}), i.e., $S = Z^D + Z^{TO}$. Since the limits of the TCP transfer period (S) are defined by call-drop events, S is assumed to follow the call drop distribution previously denoted as Z^{CD}.

The data transfer period consists of n triple duplicate acknowledgement periods (TDP). Each TDP has a length of (A) during which (Y) packets are transmitted. In this case, it is assumed that those losses are mainly due to link errors that were not recovered by the physical layer ARQ. On the other hand, the timeout period Z^{TO} represents the time that the flow spends before it enters the slow start phase after a timeout. The number of packets sent during successive timeouts is given by R.

In order to estimate B, the TCP throughput (packets/s) in the absence of timeouts (B_{NT}), i.e., with no call drops, is considered first. B_{NT} can be written as:

$$B_{NT} = \frac{E\{Y\}}{E\{A\}} \tag{2}$$

It was shown in [3] that the mean number of packets sent during a TDP period given the packet loss probability (p) is:

$$E\{Y\} = \frac{1-p}{p} + E\{W_u\} \tag{3}$$

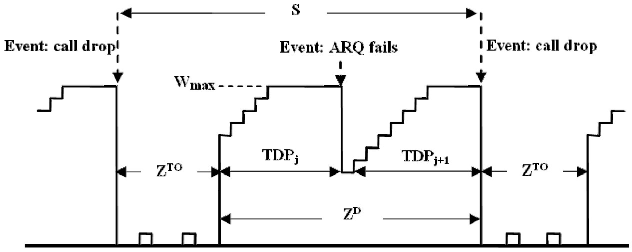

Fig. 3. TCP Flow Period (adapted and modified from [3]).

The average unconstrained congestion window size $E\{W_u\}$ was derived in [3] in terms of (p) as:

$$E\{W_u\} = \frac{2+b}{3b} + \sqrt{8\frac{1-p}{3bp} + \left(\frac{2+b}{3b}\right)^2} \tag{4}$$

Since the window size is usually restricted to a maximum value (W_{max}), then in the case considered here where the packet error rate is small, it is reasonable to assume that $E\{W_u\}= W_{max}$. The mean TDP period of length (A) given the average round trip time (RTT) was derived in [3] as:

$$E\{A\} = RTT\left(\frac{2+b}{6} + \sqrt{\frac{2b(1-p)}{3p} + \left(\frac{2+b}{6}\right)^2} + 1\right) \tag{5}$$

Substituting (3), (4) and (5) into (2) and rearranging gives,

$$B_{NT} = \begin{cases} \dfrac{\frac{1-p}{p} + \frac{2+b}{3b} + \sqrt{8\frac{1-p}{3bp} + \left(\frac{2+b}{3b}\right)^2}}{RTT\left(\frac{2+b}{6} + \sqrt{\frac{2b(1-p)}{3p} + \left(\frac{2+b}{6}\right)^2} + 1\right)} & E\{W_u\} > W_{max} \\ \dfrac{\frac{1-p}{p} + W_{max}}{RTT\left(\frac{b}{8}W_{max} + \frac{1-p}{pW_{max}} + 2\right)} & E\{W_u\} \geq W_{max} \end{cases} \tag{6}$$

If M represents the number of packets sent during a period S, then the throughput (B) (in the case of call drops) is given as,

$$B = \frac{E\{M\}}{E\{S\}} = \frac{E\{M\}}{1/\lambda} \tag{7}$$

It was shown in [3] that if T_o is the initial period for timeout then:

$$E\{Z^{TO}\} = T_0 \frac{1 + p + 2p^2 + 4p^3 + 8p^4 + 16p^5 + 32p^6}{1-p} \tag{8}$$

The value of M can be expressed as the product of the number of the TDP periods (n) and the number of packets sent in each TDP period plus the number of packets sent during Z^{TO}. Thus, the mean value of M is given by,

$$E\{M\} = E\{n\}E\{Y\} + E\{R\} \tag{9}$$

The mean value of n can be obtained by the ratio of the means of Z^D and A as follows:

$$E\{n\} = \frac{E\{Z^D\}}{E\{A\}} = \frac{E\{S\} - E\{Z^{TO}\}}{E\{A\}} = \frac{1/\lambda - E\{Z^{TO}\}}{E\{A\}} \tag{10}$$

It was also shown in [3] that the number of packets sent during Z^{TO} is given by,

$$E\{R\} = \frac{1}{1-p} \tag{11}$$

Substituting (8) and (10) into (7) gives,

$$B = \frac{E\{n\}E\{Y\} + E\{R\}}{1/\lambda} = \frac{\frac{1/\lambda - E\{Z^{TO}\}}{E\{A\}}E\{Y\} + E\{R\}}{1/\lambda} \tag{12}$$

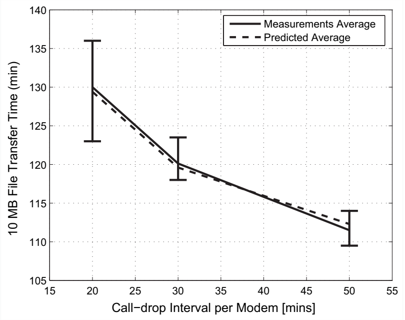

Fig. 4. Model predictions for various call-drop rates.
(Observed average is based on eight measurements at each call-dropping rate. Errorbars correspond to the 25% and 75% percentiles).

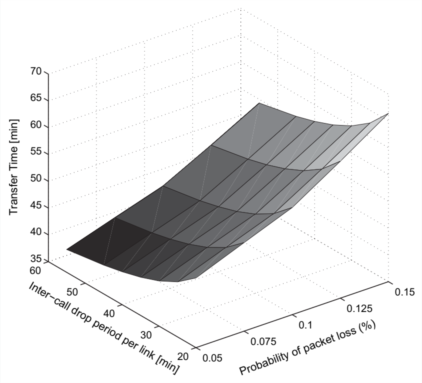

Fig. 5. Model predictions for various error rates.

But B_{NT}=$E\{Y\}$/$E\{A\}$. Hence, by substituting (6), (8) and (11) into (12) and rearranging one gets,

$$B = \left[1 - \lambda T_0 \frac{1+p+2p^2+4p^3+8p^4+16p^5+32p^6}{1-p}\right] B_{NT} + \frac{\lambda}{1-p} \qquad (13)$$

V. MODEL VALIDATION

The proposed TCP latency model (eq. 13) was tested using eight Iridium links (2.4 kbps each) connecting a site in Kansas to a site in Greenland in the summer of 2004. Several long file transfers have been performed using Iperf and gftp client. The results, as shown in Table 1, agree with the predictions of the model.

Model predictions were also tested for various numbers of links [note here that W_{max} is a function of bandwidth]. The results agreed with the field measurements (see Table 2).

Next, the model is verified as a function of λ by adding a software module to the MLPPP system that drops each modem according to a Poisson process. Due to practical limitations of the Iridium system, the model is only experimentally tested at three dropping rates: 50 min (Iridium system dropping rate), 30 min, and 20 min. A 10 MB file was transferred over a bundle comprised of 6 Iridium modems for the three drop rates and the average of the measurements was plotted (see Fig. 4). It is clear that the results of the Iridium experiments match the predictions of the proposed model.

Finally, the effect of various parameters on the transfer time is studied. Since the effect of call drops is significant when working under a long delay network, the parameters for Inmarsat GEO satellite network were used [7]. The number of modems in the bundle =4, file size =100MB, the per link bandwidth=128Kbps, RTT=0.61s (considering ARQ effect [5]), MSS=1KB and W_{max}=40KB. Fig. 5 shows the effect of the packet loss probability on the performance [low values of p are considered because the proposed latency model assumes that losses are very low due to ARQ and no timeouts occur]. Fig. 5 demonstrates that the effect of increased error rates is very high, leading to significant performance impairment.

TABLE I
FILE TRANSFERS FROM GREENLAND TO THE UNIVERSITY OF KANSAS (SUMMER 2004), T_0=60S, P = 5E-4, β = 1/50 MIN^{-1}, MSS=1448, RTT=19S, W_{max}= 47.9KB

File Size (MB)	**1.38**	**5.62**	**20.6**	**35.7**
Measured Transfer Time(min)	11	46	180	315
Predicted Transfer Time(min)	12.5	51	187	324

TABLE II
FILE TRANSFERS FROM THE GREENLAND TO THE UNIVERSITY OF KANSAS (SUMMER 2004), T_0=60S, P = 5E-4, β = 1/50 MIN^{-1}, MSS = 1448 BYTES, RTT=19S.

Number of Links	**3**	**4**	**5**	**6**	**7**	**8**
File Size(MB)	4.82	0.85	1.91	1.39	3.40	1.40
W_{max} (KB)	16.1	22.0	28.3	34.7	41	47.9
Measured Time (min)	96	15	21	13	30	12
Prediction (min)	98.1	13.4	24.1	15.4	33.2	12.7

VI. CONCLUSION

In this letter, we studied the time difference between call drops for a MLPPP system using Iridium and suggested that the call drop process can modeled by a Poisson process. We used this knowledge to extend the TCP transfer latency model in [3] to capture the effect of call drops for TCP connections over long delay MLPPP links. Then, we used the Iridium network to experimentally validate the proposed TCP transfer latency model. Finally, we used the parameters of the Inmarsat GEO satellite system as input to our model in order to investigate the TCP performance degradation as function of both: call drops and wireless packet errors.

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