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ON THE COMBINED EFFECTS OF BIT ERROR RATE AND DELAY-DISTRIBUTION TAIL ON TCP PERFORMANCE

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ABSTRACT

The original design of the TCP retransmission timeout was implemented ignoring the recent measurement studies on the dynamics and features of network traffic and delay. Such studies have reported the highly variable characteristics of network delay, considered to be heavy-tailed distributed. Accordingly, depending on the heavy characteristics of the tail of the delay distribution, the actual implementation of TCP's retransmission timeout might be too conservative, or rather insufficient.

This work aims to assess the optimal design of the retransmission timeout when heavy-tailed delay profiles are present. In our experiments, we have considered the case of low-bit error rate scenarios typical from wired networks as well as the high bit-error rates, typical from wireless networks. We show that the current implementation of the retransmission timeout is in broad terms very conservative, except in cases with extremely heavy tails.

KEYWORDS

TCP retransmission timeout, Heavy-tails, high BER environments, Weibull probability distribution.

1. INTRODUCTION

TCP is designed to provide an end-to-end reliable connection over the Internet. Such reliability is achieved by performing a retransmission when a packet loss occurs. To this end, the sender infers a lost packet when the receiver does not acknowledge received packets. This can occur for two reasons: either the packet or the acknowledgement is lost. There are two ways for the sender to identify this situation: it either receives duplicate acknowledgements as the receiver re-acknowledges the packet received before the lost packet; or due to the expiring of the retransmission timer.

Clearly, there is no possible way for the transmitter to infer the reason for the packet loss, which could be due to either network congestion or transmission error. In light of this, when a packet loss occurs, the sender cannot decide whether it should decrease the throughput to help the network recover from its congested state, or whether it should increase the throughput to increase the number of successful packet arrivals at the receiver.

When TCP was designed, wired physical media were dominant, which exhibit low bit-error rates (BER), and TCP was designed accordingly. However, in recent years, wireless and mobile technologies are becoming increasingly popular, thus requiring to revise whether or not some assumptions made in the design of TCP still hold, since wireless networks show different physical characteristics to wired media. Basically, such characteristics can affect the performance of the upper layer protocols, which brings into question the suitability of current implementations of TCP.

Wireless network problems are many fold: firstly, mobile environments have substantially higher bit-error rates than their wired equivalents; secondly, session disconnections occur frequently due to handovers and channel fading; thirdly, the bandwidth available to users is

limited and variable; and finally, the network topology is very dynamic, due to users moving between cells.

The actual proposals to mitigate these problems have focused on three main directions: link-layer protocols, split-connection protocols and end-to-end protocols. The former set of protocols try to amend the limitations of wireless scenarios with forward error correction (FEC) and automatic repeat request (ARQ). Examples of protocols are the Radio Link Protocol, AIRMAIL and Scoop among others. The second set propose to split the TCP connection into two: one connection for the wired path and another for the wireless path. Examples in this direction are MTCP, I-TCP, M-TCP and WAP. Finally, the last set of solutions require the adaptation and adjustment of current TCP versions such as Tahoe, Reno, newReno and SACK to better deal with the features of wireless channels.

The latter category offers the advantage of maintaining the end-to-end semantics of TCP but requires the investigation and selection of suitable TCP-parameter values that are optimal in high BER situations. One of these parameters is the retransmission timeout. This work aims to give insight on the suitability of the traditional design of the retransmission timeout in mobile environments assuming the delay dynamics considered under fractal network traffic.

The remainder of this work is organised as follows: section 2 outlines the actual design of the TCP retransmission timeout and reviews previous work on traffic and delay dynamics which should be taken under consideration in an optimal design. Section 3 introduces the mathematics that will be considered in the experiments, whose results shall be analysed in section 4. Finally, section 5 comprises the discussion and expected further works.

2. PREVIOUS WORK

The high variability of a network's load and its impact on individual packets traversing it is well known. For this reason, the retransmission timeout, rto , cannot be fixed beforehand but must be estimated and adjusted to reflect the variable network conditions. The actual BSD RTO implementation, dating 1988 [1], considers this matter and makes an Exponentially-Weighted Moving Average estimation of the average round-trip time (referred to as \hat{r}_n) and its standard deviation (named $\hat{\sigma}_n$) at time n , as follows:

$$\begin{aligned}\hat{r}_n &= \hat{r}_{n-1} + g(m - \hat{r}_{n-1}) \\ \hat{\sigma}_n &= \hat{\sigma}_{n-1} + h(|m - \hat{r}_{n-1}| - \hat{\sigma}_{n-1}) \\ rto &= \hat{r}_n + k\hat{\sigma}_n\end{aligned}\quad (1-3)$$

where $g=h=1/8$ in its early implementation [1], and $g=1/8$, $h=1/4$ in a further refinement [2]; m is the actual RTT measurement, which typically excludes estimates from retransmitted packets according to the Karn's algorithm (RFC2988). Additionally, $k=4$ states that packets arriving later than the estimated mean plus four times the standard deviation are probabilistically very unlikely to occur, thus should be considered as lost.

However, further studies on traffic measurements, dating from year 1994, introduced new concepts on the statistical dynamics of traffic volumes and their impact in the characteristics of delay, which have not been previously considered in the calculation of the rto parameter of TCP. Such observed characteristics are self-similarity and long-range dependence [3,4,5,6]. A good summary of the state of the art in network traffic modelling can be found in [7].

Several models meeting these two empirical features of traffic have been proposed in the literature. Examples include the fractional Gaussian noise, fractional ARIMA time series, fractional sum-difference models, etc. [8,9] It has further been reported that when inputting traffic generated by any of such models into queuing systems, the queue-length distribution is

long or heavy-tailed. Particularly, for the fGn model, the queue length is observed to be asymptotically Weibull distributed [8,10,11].

The properties of long or heavy-tailed distributions have been extensively studied by the research community [12]. The long tail implies that values far from the mean occur with non-negligible probability unlike distributions with exponential decay, thus leading to high variance (sometimes even infinite). For these reasons, it is worth studying whether setting the retransmission timeout at $rto=r_n+4\sigma_n$ is a good or a bad choice assuming long-tail delays. In what follows, delays shall be assumed to be Weibull distributed, since this light heavy-tailed probability distribution has been extensively used in the literature for modelling network delays.

3. EXPERIMENTS SETUP

Let us assume that a network application transmits N packets over a channel with packet loss probability p . In average, $N(1-p)$ will safely arrive at the other end at time r , whilst Np will be lost and shall need retransmission. Again, $Np(1-p)$ packets will be correctly retransmitted arriving at time $r+rto$ whereas the remaining Npp packets will be lost and require an additional retransmission. From those requiring a second retransmission, again $Npp(1-p)$ packets will arrive at time $r+2rto$ and the rest $Nppp$ packets require an additional retransmission. Taking this procedure to the infinite brings the following calculation of average total time taken in the whole N packet communication:

$$r_{total} = N(1-p) \sum_{n=0}^{\infty} p^n (\bar{r} + n \cdot rto) \quad (4)$$

The average taken by each packet is:

$$r_{av} = \frac{r_{tot}}{N} = (1-p) \sum_{n=0}^{\infty} p^n (\bar{r} + n \cdot rto) \quad (5)$$

which can be considered as a measure of performance of the choice of the k value in the design of rto .

In a wireless scenario, the packet loss probability p depends on both the Frame Error Rate, namely FER , and the choice of k in the rto design. This is:

$$p = FER + P(r > \bar{r} + k\sigma) - FER \times P(r > \bar{r} + k\sigma) \quad (6)$$

The product $FER \times P(r > \bar{r} + k\sigma)$ shall be ignored since it is much smaller than the other two.

Also, the value of FER depends on the packet size, L (in bytes), and the Bit Error Rate (BER) typically found in the range 10^{-5} to 10^{-9} in wireless scenarios: The relationship between FER and BER is:

$$FER = 1 - (1 - BER)^{L \times 8} \quad (7)$$

Figure 1 (left) shows the impact of choosing a particular packet size in the Frame Error Rate for various values of BER .

Additionally, the value for $P(r > \bar{r} + k\sigma)$ can be calculated from the Weibull distribution function as follows:

$$P(r > \bar{r} + k\sigma) = \exp\left(-\left(\frac{\bar{r} + k\sigma}{\alpha}\right)^s\right) = \exp\left(-\left(\Gamma(1 + \frac{1}{s}) + k\sqrt{\Gamma(1 + \frac{2}{s}) - \Gamma(1 + \frac{1}{s})^2}\right)^s\right) \quad (8)$$

where α and s are the scale and shape parameters of the Weibull distribution respectively. The former is tightly related to the location of the distribution maximum, whereas the latter is representative of the tail behaviour. It is worth remarking that the probability of exceeding the retransmission timeout value only depends on the tail parameter s .

Figure 1 (right) shows the effect of the congestion properties by means of heavier tails or lighter tails, represented by the s parameter of the Weibull distribution on the probability of packets arriving excessively late.

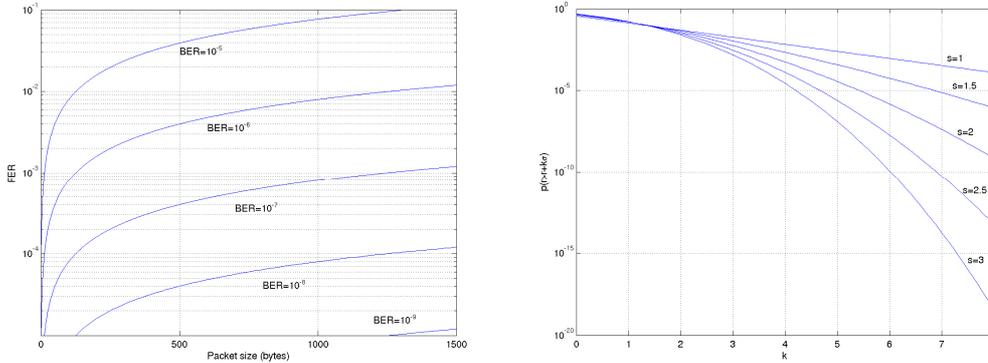


Figure 1: The effect of packet size and tail behaviour in global packet loss probability p .

In summary, as shown in figure 1 and previous equations, the packet loss probability depends on various aspects. Firstly (figure 1 left), the BER of the channel highly effects the global FER . Obviously, such impact depends on the size of the packet, since the larger the packet size, the more likely one of its bits arrives corrupt. Secondly (figure 1 right), the channel characteristics also affect the packet loss probability. Channels that exhibit heavier tails (small values of s), imply highly variable delays. In such channels, packet arrivals later than $rto=r_n+4\sigma_n$ occur relatively often, thus the choice of $k=4$ might lead to a large number of unnecessary retransmissions.

Hence, the optimal choice of k in the design of the retransmission timeout depends on two aspects mainly: the channel dynamics given by the parameter tuple (BER, s) , and the maximum packet length of the network named L , typically given by the MTU. The next section analysis the optimal choice of this parameter in various scenarios.

4. RESULTS AND CONCLUSIONS

As a measure of performance, we have considered the average delay experienced by packets, as given in eq. 5. It is worth remarking that such equation represents a trade off between the number of unnecessary retransmissions and the unnecessary waiting time for packets which will never arrive.

Figure 2 shows the average delay in units of round-trip times. With a constant Weibull tail of $s=2$, we have simulated various scenarios with variable packet size L and variable BER conditions. As shown, only under BER conditions of 10^{-5} , the global performance decays for values of $k>3$. Under lower BER conditions, the average performance appears to be independent of packet size. Also, it can be shown that a value of k ranging 3-4 provides good results in all cases.

However, this results have been obtained assuming a Weibull tail of $s=2$. Figure 3 shows the impact of different values of the Weibull tail parameter s in the average delay measure of performance. As shown, the different channel conditions in terms of delay variability have a higher impact than the value of L studied in the previous experiment. As shown, the optimal value of k varies from 2.5 to 6, depending on the delay variability, represented by parameter s . This results shows the importance of the delay variability, and essentially reflects the fact that, when delays are highly variable (small s values) the probability of late packet arrivals is larger,

thus augmenting the number of unnecessary retransmissions to recover from lost packets which are not actually lost, but are late. Intuitively, the heavier the probability tail, the larger the value of optimal k .

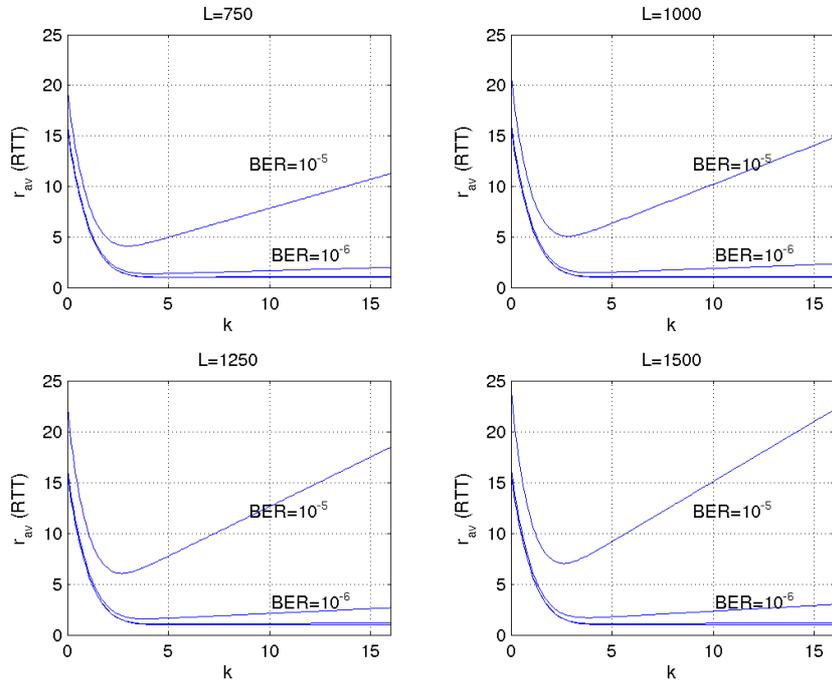


Figure 2: Plots of Average RTT against k for various packet sizes L and BER

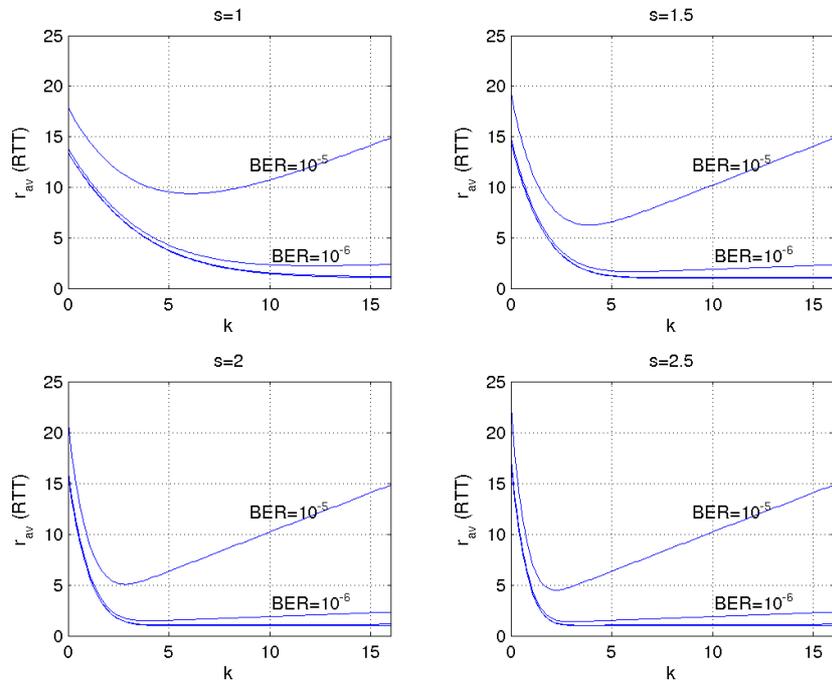


Figure 3: Plots of Average RTT against k for various Weibull tails s and BER

In conclusion, depending on the actual characteristics of the channel given by the tuple (BER, s) , a large value of k would preferable over a small one, and vice versa. As a rule of thumb, the

choice of $k=3-4$ is typically optimal, except of those channels with extremely high delay variability (small values of s). In such cases, a choice of $k=5-10$ shows better results.

5. FINAL REMARKS AND FURTHER WORK

This work suggests a modification of the TCP retransmission timeout, which is currently set at $rto=r_n+4\sigma_n$. This value has shown to be insufficient for highly variable delay scenarios, and too conservative in scenarios with delays more bounded and tight to their mean. The optimal solution employs making an estimate of the s parameter of the Weibull tail and set k accordingly. Further work shall investigate methods to accurately make such estimate in real time and its subsequent implementation in the retransmission timeout algorithm as follows:

$$\begin{aligned}\hat{r}_n &= \hat{r}_{n-1} + g(m - \hat{r}_{n-1}) \\ \hat{\sigma}_n &= \hat{\sigma}_{n-1} + h(|m - \hat{r}_{n-1}| - \hat{\sigma}_{n-1}) \\ \hat{s}_n &= f_1(\hat{s}_{n-1}, m) \\ k &= f_2(\hat{s}_n) \\ rto &= \hat{r}_n + k\hat{\sigma}_n\end{aligned}$$

The computation of functions f_1 and f_2 can provide great flexibility to optimally adjust the retransmission timeout in all types of scenarios, regardless of their particular characteristics. This includes:

- Wireless channels, which typically show either high *BER* or long delays if packet if link-layer retransmissions are employed to recover from packet corruption (RFC 2757). Both cases are considered in this work.
- 2.5G and 3G scenarios, which typically show long delays due to physical layer processing FEC and interleaving (RFC 3481). Such physical layer characteristics may be responsible for showing heavy tails in the delay profile and will require a larger value for k .

Finally, further work shall also investigate the impact of k in terms of bandwidth performance. Since the choice of k determines packet loss, it is expected to be responsible for the TCP throughput dynamics. In other words, the unadjusted k can cause unnecessary packet losses thus causing a reduction in TCP throughput in uncongested scenarios.

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