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Estimation of High-Speed Performance of the Transport Protocol with the Mechanism of Forward Error Correction

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Abstract. We propose a model of a virtual connection controlled by the transport protocol with a forward error correction mechanism in the group failure mode with restrictions on the values of protocol parameters in the form of a Markov chain with discrete time. The analysis of the impact of protocol parameters window size and the duration of the timeout of waiting confirmation, the probability of distortion of the segments in the individual links of the transmission path data, the duration of the round trip delay, the parameters of the mechanism to restore the distorted segments on the throughput of the transport connection. In the area of protocol parameters, the characteristics of the transmission channel and parameters of the forward error correction mechanism found in the area of superiority of the control procedures of the transport protocol with forward error correction over the classic procedure with decision feedback on the criterion of the throughput of a transport connection. The expediency of applying of the method of forward error correction for transport links with large round-trip delay.

Keywords: transport protocol, data transmission path, forward error correction, Markov chain, throughput of a transport connection, window size, duration of the timeout, round-trip delay, loss rate.

1. Introduction

One of the most important indicators of the quality of subscribers interaction in computer networks is the capacity of transport connections. This operating characteristic is largely determined by the logic of the transport protocol, its parameters — the width of the window and of timeout duration [1], as well as additional mechanisms for increasing the speed by reducing the number of retransmissions of the distorted data [2–4] in channels with a high error rate. Currently, the direct error correction technology [2–4] is widely used as an additional service in transport protocols, along with the method of forward error correction decisive feedback to reduce the amount of retransmitted traffic. The study of the transport connection and analysis of its potential capabilities was performed in [2–10]. But the analytical results were obtained only for a single-link data transmission path [5–7], or with restrictions on protocol parameters [8–10]. Known forward error correction technologies are used by the transport protocol, usually as a service of lower-level network architecture [2–4]. A comprehensive analysis of the advantages and the effectiveness of the methods of forward error correction were performed only

at qualitative level, as well as numerically for some individual cases and did not allow us to highlight areas of possible application of methods in the area of protocol parameters and transport connection parameters. However, the potential of the transport protocol using the methods of forward error correction has not been studied yet. There are no analytical dependencies of overall effect of protocol parameters, characteristics of the data transmission path and parameters of the correction method on the speed of the transport connection. The influence of the relations between the duration of the round-trip delay and the protocol parameters on the throughput of the data transmission path of data controlled by transport protocol was not studied. The paper proposes a mathematical model of the process of data transfer with forward error correction in the phase of information transport in the form of a Markov chain with discrete time, in analytical form we found the stationary distributions of probabilities for different repeat modes [1], with a restriction from below to the protocol parameter of the time-out waiting for end-to-end acknowledgment, analytical relation are obtained for the throughput, on the basis of which the analysis of the of potential possibilities of a transport connection and in the characteristic area of protocol parameters, the data transmission path and the forward error correction mechanism, an area is found in which the application of the methods of forward error correction gives the increase in the performance of the transport connection.

2. Transport connection model

Let's consider the process of transferring data between subscribers of transport protocol based on the algorithm with forward error correction decisive feedback. An example of such reliable family protocols is the TCP protocol that dominates modern computer networks [1]. We assume that the interacting subscribers have unlimited data stream for transmission, and the exchange is performed by segments of the transport protocol data of the same length. We believe that the section of hops along the transmission path data have the same speed in both directions, and the length of loop segment in a separate link is t. In general case, the path length from the source to the destination carrying the information flow and the length of the return path through which the confirmation of the received segments are transmitted can be different. We believe that the length of the data transmission path, expressed in number of hops areas in the forward direction is equal to $D_n \geq 1$. The return path, by which the confirmation is sent to the sender about the correct processing of the sequence of blocks of segments, has a length of $D_o \geq 1$. The probabilities of distortion of the segment in the communication channels are given for forward $R_n(d)$, $d = \overline{1, D_n}$ and reverse $R_o(d)$, $d = \overline{1, D_o}$ directions of transmission of each area of hops. Then the reliability of the transmission of segments along the path from the source to the destination and back again will be $F_n = \prod_{d=1}^{D_n}(1 - R_n(d))$ and $F_o = \prod_{d=1}^{D_o}(1 - R_o(d))$ respectively.

We believe that the loss of segments due to the absence of buffer memory in the nodes of the path does not occur. We believe that the transmission of data by the sender is realized by blocks containing B segments, of which $1 \leq A \leq B$ — are informative, and $B - A$ — additional redundant of the same length. We assume that all segments have checksums to detect errors in each of them. The loss (distortion) to $B - A$ arbitrary segments in the block allows to restore all segments of the block (for example, transfer of duplicates when $A = 1$, $B \geq 2$ the excess segment with the bitwise parity of all information segments using the technology of RAID arrays of the fourth level [11] when $A > 1$, $B = A+1$ etc.). Flow control is implemented by a sliding window mechanism [1] with a formal parameter of the width of the window $w \geq 1$, expressed in number of blocks. We believe that confirmations about the correctness of the blocks of segments received by the addressee are transmitted in each segment of the counter flow. If it is impossible to restore directly the transmitted block segments (distortion of more $B - A$ segments in the block), the entire block is retransmitted. Then, the process of information transfer in a virtual connection controlled by a transport protocol can be described by a Markov process with discrete time (with the cycle duration t) because the time between receiving acknowledgments has the geometric distribution with parameter F_o. This model is a generalization of the formalizations of the data transfer process proposed in [3–6] in case of a transport connection of random length and the mechanism of direct error correction. The range of possible states of the Markov chain is determined by the duration of the waiting timeout for the confirmation of S, expressed in the number of cycles of duration t. The size of the timeout is related to the length of the path, the width of the window and the size of the block by the inequalities $S \geq wB + 1$, $S \geq D_n + D_o + B - 1$. It is obvious that the sum of the lengths of forward and reverse paths can be interpreted as a circular delay of a single segment $D = D_n + D_o$ in the deterministic transport connection is expressed in the duration t. The circular delay for the block of segments will be $D + B - 1$. The States of Markov chain $i = \overline{0, wB}$ corresponds to a queue size of transmitted but not confirmed segments in the source stream, and states $i = \overline{wB + 1, S - 1}$ — the time during which the sender is not active and waits to receive confirmation about the correctness of receiving the transmitted sequence of w blocks of segments. From zero state into $(D + B - 2)$-th sender is moving with every cycle t with a probability of determine event. In states $i \geq D + B - 2$ after the expiration of next discrete cycle t, the sender starts receiving confirmation and, depending on the results of the pre-rate segment blocks, taking into account the technology of forward error correction, the sender transmits new segment blocks (with positive confirmation) or repeatedly — distorted (not responding to direct recovery). Completion of cycle of being in the state $D + B - 2$ corresponds to the time of bringing the first block of segments to the destination and receiving confirmation on it. Further growth of the state number occurs with the probability of distortion of confirmation $1 - F_o$ in

the reverse path. In states $i \geq D + B - 2$ in the selective failure mode of confirmation gives rise to $(D-1)$-th state when $w \geq K + 2$, $K = \lfloor \frac{D-2}{B} \rfloor$, where $\lfloor \cdots \rfloor$ — means "integer part" of the fraction, or to the state kB, $k = \overline{1, w-1}$ where $w \leq K + 1$, only if the blocks delivered to the destination are successfully transmitted, otherwise the transition to the 0-th state follows. Due to the fact that in states $i \geq wB$ the source suspends the sending of segment blocks, obtaining confirmation when $w \geq K + 2$ in the states $i = \overline{(w+k)B - 1, (w+k+1)B - 2}$, $k = \overline{1, K}$ leads to transition into state $D - kB - 1$, $k = \overline{1, K}$ in the selective repeat mode — always, and in the group failure mode — only with successful delivery of data (otherwise — in the 0-th state). When $w \leq K + 1$ from states $i = \overline{D + (w-k)B - 2, D + (w-k+1)B - 3}$, $k = \overline{1, w-1}$ transitions to the states occurs kB, $k = \overline{1, w-1}$ in the selective repeat mode — without conditions, and in the group repeat mode — under the condition of successful delivery of the data blocks (otherwise — to the 0-th state). In states $i = \overline{(w+K+1)B - 1, S - 2}$ for arbitrary width of the window and any repeat mode, the transition to the zero state is performed, since the size of the queue of transmitted, but not confirmed information segments is zeroed. In the state $S - 1$ the waiting timeout of confirmation from the receiver about the correctness of the received blocks of segments expires and the unconditional transition to the zero state occurs.

3. State probabilities for a transport protocol with a forward error correction mechanism

The transition probabilities π_{ij} from the initial state i to the resultant j Markov chain describing the process of transmission of information flow with forward error correction technology in the group failure mode presented in Table 1 and Table 2.

Table 1

The transition probabilities for $w \leq K + 1$

π_{ij}	i	j	k
1	$\overline{0, D + B - 3}$	$i + 1$	
$1 - F_o$	$\overline{D + B - 2, S - 2}$	$i + 1$	
$F_o \Phi^k$	$\overline{D + Bk - 2, D + B(k+1) - 3}$	$B(w - k)$	$\overline{1, w-1}$
$F_o(1 - \Phi^k)$	$\overline{D + Bk - 2, D + B(k+1) - 3}$	0	$\overline{1, w-1}$
F_o	$\overline{D + Bw - 2, S - 2}$	0	
1	$S - 1$	0	

Table 2

The transition probabilities for $w \geq K+2$

π_{ij}	i	j	k
1	$\overline{0, D+B-3}$	$i+1$	
$1-F_o$	$\overline{D+B-2, S-2}$	$i+1$	
$F_o\Phi^k$	$\overline{D+Bk-2, D+B(k+1)-3}$	$D-1$	$\overline{1,G}$
$F_o(1-\Phi^k)$	$\overline{D+Bk-2, D+B(k+1)-3}$	0	$\overline{1,G}$
$F_o\Phi^G$	$\overline{D+B(G+1)-2, B(w+1)-2}$	$D-1$	
$F_o(1-\Phi^G)$	$\overline{D+B(G+1)-2, B(w+1)-2}$	0	
$F_o\Phi^{G+k}$	$\overline{B(w+k)-1, B(w+k+1)-2}$	$D-Bk-1$	$\overline{1,K}$
$F_o(1-\Phi^{G+k})$	$\overline{B(w+k)-1, B(w+k+1)-2}$	0	$\overline{1,K}$
F_o	$\overline{B(w+K+1)-1, S-2}$	0	
1	$S-1$	0	

Here $G = \left\lfloor \frac{B(w+1)-2-(D+B-2)+1}{B} \right\rfloor = w - \left\lfloor \frac{D-1}{B} \right\rfloor$ the distance between the beginning of the termination of sender's activity $B(w+1)-2$ (complete transmission of w blocks) and the beginning of the receipt's acknowledgement $D+B-2$, expressed in the dimensions B when $w \geq K+2$, $K = \left\lfloor \frac{D-2}{B} \right\rfloor$. Out of the form of the transition probabilities, it is not difficult to see that when $F_n = 1$ we get the transition probabilities for the selective repeat mode.

4. Analysis of the speed performance of a transport connection

The most important operating characteristics of a transport connection is its throughput determined by parameters of the transport protocol, the data transmission path and the forward error correction mechanism, and overhead as well as the peculiarities of procedure of transmission control [1]. The normalized speed of the transport connection is determined by the average number of undistorted information segments delivered to the recipient (taking into account the repeat mode and the mechanism of forward recovery of distorted segments) for the average time between two consecutive receipts of confirmation onto the transmitted segment blocks [8]. Since the sender receives confirmation about successfully delivered to the recipient block of segments and confirmation to the sent blocks are transferred to each segment of the counter flow, then to the next block the sender receives B acknowledgement during the transmission of the next block Bt,

the probability of error-free delivery of which is $1-(1-F_o)^B$. Therefore, the time between receiving acknowledgements to the sent blocks from the information and redundant segments is distributed geometrically with the duration of the period B of clock cycles of duration t, and the distribution parameter equal to the reliability of receiving acknowledgements for the B attempts: $1-(1-F_o)^y B$.

Then the average time between the arrival of consecutive acknowledgements per block in the cycles of t will be $\bar{T} = B/\big(1-(1-F_o)^B\big)$. The capacity of transport connections for the group failure mode taking into account the re-transmission of all blocks of segments, starting with the first not received [8], is given by the following dependence of the:

$$Z(D,w,S,A,B) = A\Phi\frac{1-(1-F_o)^B}{B}\left\{\sum_{k=1}^{w}\frac{1-\Phi^k}{1-\Phi}\sum_{i=D+kB-2}^{D+(k+1)B-3}P_i + \right.$$
$$\left. + \frac{1-\Phi^w}{1-\Phi}\sum_{i=D+(w+1)B-2}^{S-1}P_i\right\}.$$

In the case of absolutely reliable reverse transmission data path ($F_o = 1$) throughput when $w \geq K+2$ is invariant to the window size

$$Z(D,w,S,A,B) = \frac{A\Phi}{B\big[(D-1)(1-\Phi)+B\big]},$$

and when $w \leq K+1$ is variable from

$$Z(D,w,S,A,B) = \frac{A\Phi}{B\big[D+B-1-B\Phi(w-1)\big]}.$$

Unlimited window size growth ($w \to \infty$) leads to the relation

$$Z(D,\infty,\infty,A,B) = \frac{A\Phi\big(1-(1-F_o)^B\big)}{B\big[F_o(D-1)(1-\Phi)+\big(1-\Phi(1-F_o)^B\big)\big(1+F_o(B-1)\big)\big]}.$$

5. The preferred area of application of forward error correction

The effective application of the technology of forward error correction involves searching for the length parameters of the block sequence of the segments B and the number of redundant segments $B-A$ in the error correction block that ensure the maximum speed of the transport connection with the specified characteristics and protocol parameters. The presence

of redundant segments in the transmitted sequence increases the probability of delivery of the information segments to the recipient in the group; however, this is achieved by increasing the overhead in the form of time for transferring additional data. In this connection, the problem arises of searching in the multidimensional feature space ranges of values of characteristics of transport connection (D, F_o, F_n), parameters of transport protocol (w, S) and the forward error correction mechanism (A, B), which ensures the superiority of control procedure with forward error correction to the classical protocol procedure with decisive feedback without using error correction. Comparison of control procedures is fulfilled in conditions of equal intensities of subscriber information flows offered for transmission $\lambda = Aw$. We will determine the normalized increase in performance speed from the use of forward error correction mechanism in comparison with the classical protocol procedure with decisive feedback in the form of: $\Delta(D, w, S, A, B) = Z(D, w, S, A, B) - Z(D, Aw, S, 1, 1)$. In general case, the comparative analysis can be carried out only numerically. The most significant benefit is determined by the relation between the width of the window, block size B and duration of round-trip transport connection D. For each set of values parameters of forward error correction mechanisms A and B there is a lower bound of the duration of the round trip delay of a single segment D, beyond which there are ranges of window size values and the reliability of segment transmission in the forward and reverse paths of the transport connection, providing a positive benefit. In a number of cases, by reducing the dimension of the feature space, the area of positive values of benefit can be found in a simple analytical form. Assuming that absolutely reliable reverse data path transfer $F_o = 1$ when $w \geq K + 2$ the benefit takes the simple analytical form, which is invariant to the window size $\Delta(D, w, S, A, B) = \frac{A\Phi}{B[B+(D-1)(1-\Phi)]} - \frac{F_n}{1+(D-1)(1-F_n)}$. Hence, when $A = 1$, $B = 2$ it is easy to see that the area of positive values of benefit for parameter $F_n \in [0, 1]$ exists on $D \geq 11$ the interval

$$F_n \in \left(\frac{D - 2 - \sqrt{D^2 - 12(D-1)}}{2(D-1)}, \frac{D - 2 + \sqrt{D^2 - 12(D-1)}}{2(D-1)} \right).$$

The area of positive benefit values with unlimited growth of round trip delay of a single segment ($D \to \infty$) is expanded to $F_n \in (0, 1)$. Numerical studies show that the value of benefit is growing.

6. Conclusions

The paper proposes a model for the process of transferring data segments in a transport connection controlled by a reliable transport protocol with a forward error correction mechanism and confirmation of data received by the recipient in the group repeat mode. The mathematical model is based on the description of the queue of transmitted, but not confirmed,

data segments by Markov chain with a finite number of states and discrete time. Stationary distributions of Markov chain states are obtained for different areas of window size change and duration of time-out. Analytical expressions for the transport connection capacity are found. In general, the throughput is largely determined by the ratio between the window width and the duration of the round-trip delay. It is shown that for group repeat mode the implementation of a forward error correction mechanism is suitable for transport connections with large round-trip delay.

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