Method for estimating delays in parallel redundant data transfer networks

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***Abstract*—This paper presents a unified method for estimating latencies in a parallel redundant network with losses. The proposed method is based on mathematical statistics and, in the opinion of the authors, is more instructive in small networks than typical estimations that are based on the Markov chain model, which is recommended by ITU. The method requires known CDFs of latencies of parallel networks, as well as their packet loss rates. The CDFs can be built from experimental data or can be approximated in accordance to assumed distribution function. The method eliminates the need to calculate the transition probabilities that are required in the Markov chain. Also, the method can be used for various number of parallel networks. However, the method is applicable only for independent networks**

Keywords—redundancy; network latency; parallel redundancy protocol

I. Introduction

The use of parallel redundancy is widely used in safety- and time-critical control data transmission networks to increase overall availability, as well as to reduce latencies in the redundant data transfer service. Such networks use N+1 link protection, typically limited to 1+1 (parallel redundancy of two networks). Typically, the homogeneous Markov chain model is used to estimate the performance of a redundant network. This model is described in [1]. It allows to take into account various additional factors, such as the repairs of various elements and sub-systems of a network. This model utilization is complicated and pay off itself in large trusted networks.

For today, there is a tendency to increase interest in the implementation of parallel redundancy in small networks, especially through two wired Ethernet or two wireless channels. In such small projects, the authors usually do not utilize formidable method described in the ITU recommendation [1].

Instead of the recommendations mentioned above, in small networks the parameters of the resulting redundant network solution typically are estimated in different ways. In [2] the authors apply the Markov chain model to predict the availability of the proposed network solution. However, in that research, the Round Trip Time (RTT) as well as the Jitter of the resultant redundant network are measured directly during the experimental verification of the results. In most other projects, the parameters (such as RTT, Jitter, IPDV) as well as the availability and packet loss of the proposed redundant solution are estimated using various simulation applications. For example, in [3], [4] the authors use OPNET simulation tool to predict all the above mentioned parameters. Attempt to anticipate the results of various types of wireless equipment are presented in [5]. These are also estimated using a simulation tool, called OMNet++ .

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In this paper, we present an approach to estimating latencies (or RTT) as well as IPDV (IP packet Delay Variation) of a redundant network. This method can be used for a redundant solution that consists of *n* parallel networks. The method requires known CDFs of latencies (or RTTs) for all networks that will operate in parallel. The CDFs can be built from the experimentally obtained RTT values or can be approximated in accordance to predefined distribution function. Since the calculations are proposed for non-trusted networks, the impact of packet loss also is considered. This method can be a good solution if it is necessary to estimate the latencies of a resulting redundant solution when latencies and packet loss rates of networks can be easily measured experimentally, while probabilities of transitions of Markow chain are not known. .

II. Mathematical Model

In the general case, a parallel redundant network can be built from *n* networks. To build a robust redundant system, all networks should to be independent. This means that their delay values will also be independent.

Let's define the latency values of each network as Ti, where i=1,2,…,n is the network number. Since the networks are independent, the values of Ti will also be independent. Further, each Ti can be defined as an independent random variable with a continuous probability function $F_{Ti}(t_i)$. The type of probability function depend on type of network. The probability function also can be built from the experimental data.

We should also take into account that some packets may be lost (undelivered). Lost packets have a latency equal to infinity. Let's define the packet loss as q_i, where i=1,2,…,n is a network number. Since it is assumed that independent networks are used, packet loss qi will also be independent.

Further, let's denote conditional random variable T_i^*, where i=1,2,…,n is the network number. The conditional random variables T_i^* are equal to Ti when Ti $\leq \infty$ (packet was delivered) or equal to infinity ∞ if packet is lost. Therefore, T_i^* are independent random variables with corresponding specific random continuous distribution functions, which with probability (1-q_i) are equal to $F_{Ti}(ti)$ if packet was delivered or equal to infinity ∞ if packet is lost.

Since only the first arriving packet is processed in a parallel redundant network and all subsequent ones are discarded, the resulting random variable Z of the parallel redundant network can be expressed as a minimum of independent random variables (assuming zero packet loss):

$$Z = \min(T_1, \dots, T_n) \quad (1)$$

Therefore, the distribution function of Z (assuming zero packet loss) will be expressed as:

$$\boldsymbol{F_Z(z) = P(Z \le z) = 1 - \prod_1^n P(T_i) > z =}$$
$$\boldsymbol{= 1 - \prod_1^n \left(1 - F_{Ti}(z)\right)} \quad (2)$$

This is a standard approach of finding the minimum of n random variables.

Now it is necessary to take into account that some packets may be lost. The packet loss rate is defined as qi. Let's denote T_i^* as a conditional random variable of Ti, when Ti < ∞ (packet has not been lost). Then it is also necessary to define Z* as a conditional random variable of Z, when Z < ∞ (at least one packet from all networks has been delivered). Then the conditional distribution function of a parallel redundant system with n parallel networks and packet loss rate qi can be defined as:

$$Z^* = min\left(T_1^*, \dots, T_n^*\right) \quad (3)$$

And the distribution function of conditional random variable Z* (when at least one packet of a parallel redundant system was delivered) will be expressed as follow:

$$\boldsymbol{F_{Z^*}(z) = P(Z^* \le z) = 1 - \prod_1^n P(T_i^*) > z =}$$
$$\boldsymbol{= 1 - \prod_1^n \{P(T_i^* > z)P(T_i^* < \infty) + P(T_i^* = \infty)\} =}$$
$$\boldsymbol{= 1 - \prod_1^n \{P(T_i^* > z) \cdot (1 - q_i) + q_i\} =} \quad (4)$$
$$\boldsymbol{= 1 - \prod_1^n \left\{\left(1 - F_{Ti}(z)\right) \cdot (1 - q_i) + q_i\right\}}$$

Now, by taking into account the packet loss rate qi of each network, let's denote Z as a conditional random variable under the condition that Z* < ∞ (at least one packet from the redundant system has been delivered). Obviously, the event Z<∞ takes place if event Z* < ∞ takes place, so distribution function of Z can be expressed by equation:

$$F_Z(z) = P\{Z < z | Z^* < z\} = \frac{P(Z^* < z)}{1 - \prod_{i=1}^n q_i} \quad (5)$$

III. A Numerical Example of a Parallel Redundant Network Consisting of N=2 Networks

The first network will have T_1 latency values with a continuous probability function $F_{T1}(t_1)$ and packet loss rage q_1. The second network will have T_2 latency values with a continuous probability function $F_{T2}(t_2)$ and packet loss rage q_2 respectively.

Now it is necessary to solve the equation (5) for n=2 networks:

$$\boldsymbol{F_Z(z) = \frac{1 - \prod_1^n \left\{\left(1 - F_{Ti}(z)\right) \cdot (1 - q_i) + q_i\right\}}{1 - \prod_{i=1}^n q_i} =}$$
$$= \frac{\boldsymbol{1 - \left(\left(1 - F_1(z)\right) \cdot (1 - q_1) + q_1\right)\left(\left(1 - F_2(z)\right) \cdot (1 - q_2) + q_2\right)}}{\boldsymbol{(1 - q_1 q_2)}} \quad (6)$$

Next, the latency values T_1 and T_2 of both networks must be experimentally obtained. First, these results will be used to estimate the q_1 and q_2 packet loss rates. It should be noted that in order to estimate the rate of packet loss, at least four packets losses should to be observed [6]. Further, CDFs of $F_{T1}(t_1)$ and $F_{T2}(t_2)$ should be created. The first way to do this is to use the available experimental data of T_1 and T_2 values. In addition, CDF of latency in IP networks can also be approximated via various types of distribution laws. In Ethernet networks, latencies are typically approximated via the gamma distribution function [7], [8]. In some special cases, for example, in heavy-loaded Ethernet networks, the distribution of latencies tends to a normal distribution function [9].

In the first example, let's assume that we have two identical Ethernet networks that are independent of each other. Let's suppose that their CDFs of latencies are also identical, as well as the packet lost rate of both networks are is equal to zero. In this example, we will assume that the latencies of these networks obeys gamma distribution. The following illustration shows CDFs of the latencies of the first and second networks, as well as the latency CDF of the redundant network.

In this example, the average delay of both networks #1 and #2 is 90 ms, while the average delay of the redundant network will be 80.9 ms (10% improvement).

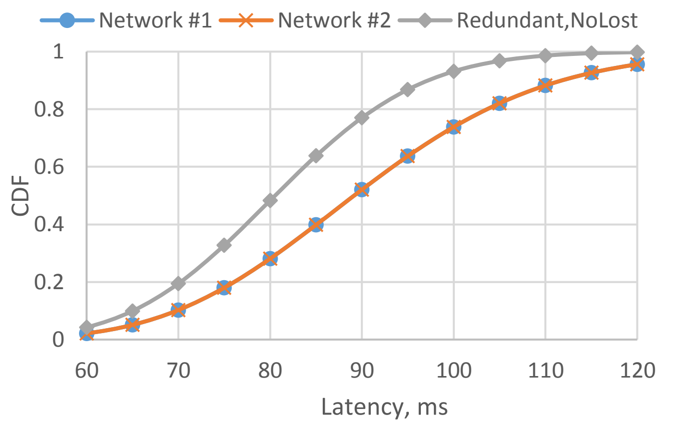

Fig. 1. Letency of redundant network, asssuming identical networks and zero packet loss in both networks

The resulting CDF can also be used to estimate IPDV (IP packet Delay Variation). The IPDV is widely used in tasks for estimating de-jittering buffer size. IPDV is defined by ITU [10] as the Upper bound on the $1\text{-}10^3$ quantile of IPTD minus the minimum IPTD (IPTD is defined by ITU as IP packet Transfer one-way Delay [10]). The problem is that Fz(z) is the continuous probability function, that is, there is no minimum. In this example, we define the minimum value of IPTD as a 0.0014 quantile. In the #1 and #2 networks we have $\chi_{0.014\_netw}$= 49 ms, $\chi_{0.999\_netw}$= 150 ms, hence the $IPDV_{network}$=101 ms. In the proposed redundant system we will have: $\chi_{0.014\_redundant}$= 47 ms, $\chi_{0.999\_redundant}$= 123 ms, hence the $IPDV_{redundant}$=76 ms, so the expected improvement in IPDV is 25%.

The impact of packet loss of one network on the expected performance of a redundant network is shown in Fig.2. In this example, two independent identical Ethernet paths with the same CDFs are used. The first network has different packet loss rate values, while the second one has zero packet loss.

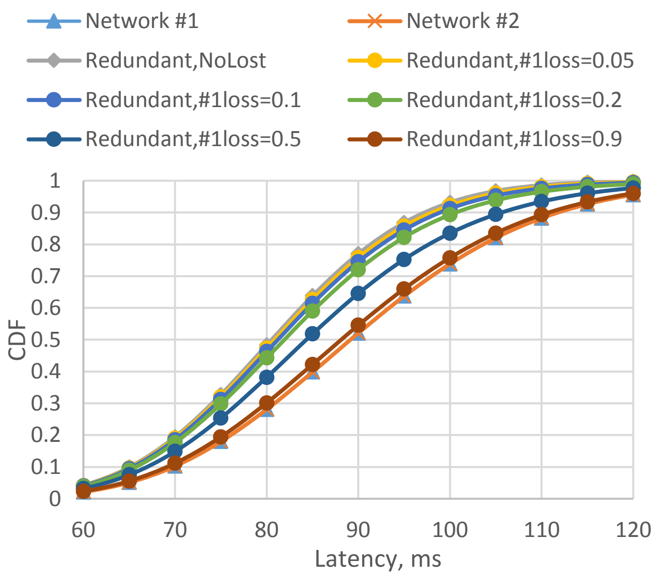

Fig. 2. Letency of redundant network, asssuming identical networks and different packet loss in the first network

TABLE I. REDUNDANT NETWORK LATENCY VS PACKET LOSS OF THE 1ST NETWORK

Packet Loss of the Network #1	Average Values of Latencies, ms		
	Network #1	***Network #2***	***Redundant***
0 %	90,00085	90,00085	80,90244
5 %	90,00085	90,00085	81,35736
10 %	90,00085	90,00085	81,81228
20 %	90,00085	90,00085	82,72212
50 %	90,00085	90,00085	85,45164
90 %	90,00085	90,00085	89,09100
100 %	90,00085	90,00085	90,00085

As can be seen, with the increase in packet loss in the Network#1, its impact on the performance of the redundant network becomes reduced. Finally, with the packet loss of 90% in the first network, the performance of the redundant network becomes almost equal to the performance of the Network#2. This in itself proves the proposed equation (5). The following table shows the expected latencies of the redundant network, depending on the packet loss of the first network.

The effect of the packet loss rate of both networks on the proposed performance of the redundant network is shown in Fig.3. In this example, two independent identical Ethernet paths with the same CDFs are used. The packet loss rate of each network is shown in the legend of the illustration. The numerical values of the expected latencies of the redundant network depending on the packet loss of the first and second networks are shown in the Table 2.

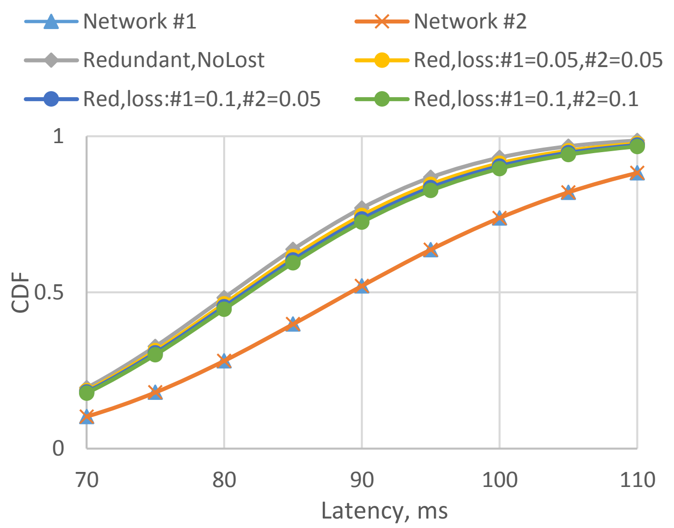

Fig. 3. Letency of redundant network, asssuming identical networks and different packet loss in the first network

TABLE II. REDUNDANT NETWORK LATENCY VS PACKET LOSS OF THE 1ST AND 2ND NETWORKS

Packet Loss: Network #1 / #2	Average Values of Latencies, ms		
	Network #1	***Network #2***	***Redundant***
0% / 0%	90,00085	90,00085	80,90244
5% / 5%	90,00085	90,00085	81,76895
10% / 5%	90,00085	90,00085	82,1826
10% / 10%	90,00085	90,00085	82,55669

The impact of a different networks utilization is shown in Fig.4. In this example two Ethernet paths are used. Let's assume that the latencies of both Ethernet networks obey the gamma distribution. The first network is the same for all experiment, whereas the second one has different parameters. The parameters of gamma distributions are shown in Table 3. In this example, it is assumed that both networks have zero packet loss rate.

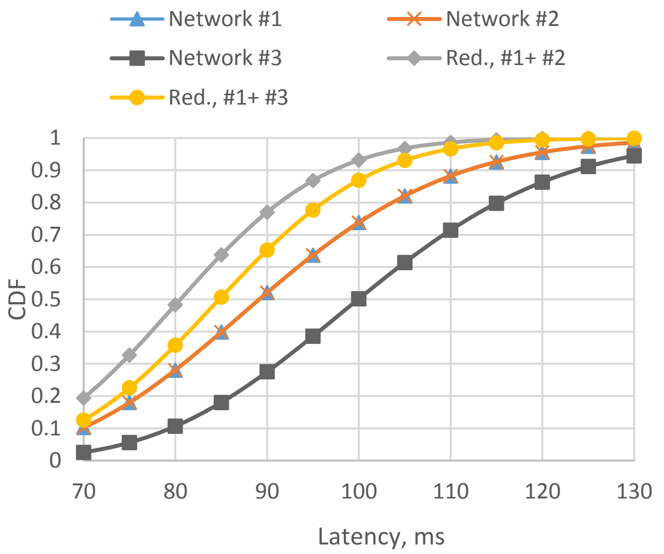

Fig. 4. Letency of redundant network, asssuming different networks and zero packet loss in both networks

TABLE III. REDUNDANT NETWORK LATENCY VS PACKET LOSS OF THE 1ST AND 2ND NETWORKS

#1 [alpha], [beta] / #2 [alpha], [beta]	Average Values of Latencies, ms		
	Network #1	*Network #2*	*Redundant*
30, 3.005 / 30, 3.005	90,00085	90,00085	80,90244
30, 3.005 / 34, 2.968	90,00085	100,01241	85,08475
30, 3.005 / 40, 2.900	90,00085	109,61877	88,29479

IV. CONCLUSIONS

The goal of this paper is to provide the method of estimating latencies (or RTTs) of the redundant network from known latencies and packet loss rates. The authors suppose that this method is more instructive for small redundant networks than typical calculations that are based on the Markov chain model, recommended by ITU. The proposed method require known latency (or RTT) CDFs as well as the packet loss rate of all parallel networks. The CDFs can be obtained from experimental data, or experimental data can be approximated according to a known distribution law (in our examples, we use gamma distribution as the most suitable for switched Ethernet). The method assumes that all parallel networks are independent to each other (otherwise the result will be more optimistic than it should be). The method is applicable to various number of parallel networks, whereas the examples are shown for two parallel networks only.

REFERENCES

[1] ITU, "ITU-T G.911 Parameters and calculation methodologies for reliability and availability of fibre optic systems," *ITU Telecommun. Stand. Sect.*, 1997.

[2] M. Rentschler and P. Laukemann, "Performance analysis of parallel redundant WLAN," *IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA*, no. September 2012, 2012.

[3] M. Rentschler *et al.*, "Simulation of parallel redundant WLAN with OPNET," *IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA*, pp. 1–8, 2013.

[4] M. Hendawy *et al.*, "Application of parallel redundancy in a Wi-Fi-based WNCS using OPNET," *Can. Conf. Electr. Comput. Eng.*, vol. 1, pp. 1–6, 2014.

[5] M. Rentschler *et al.*, "Simulative comparison of parallel redundant wireless systems with OMNet++," in *IEEE International Symposium on Industrial Electronics*, 2014.

[6] Van Der Waerden, *Mathematische statistik*. Berlin-Gottingen-Heidelberg: Springer-Verlag, 1957.

[7] A. Bhattacharjee and S. Nandi, "Bivariate gamma distribution: A plausible solution for joint distribution of packet arrival and their sizes," in *Proceedings of 2010 13th International Conference on Computer and Information Technology, ICCIT 2010*, 2010.

[8] P. Holleczek, R. Karch, R. Kleineisel, S. Kraft, J. Reinwand, and V. Venus, "Statistical characteristics of active IP One Way Delay measurements," in *International Conference on Networking and Services 2006, ICNS'06*, 2006.

[9] T. Elteto and S. Molnar, "On the distribution of round-trip delays in TCP/IP networks," pp. 172–181, 2003.

[10] ITU, "ITU-T Y.1541 - Network performance objectives for IP-based services," 2011.

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