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ON MILITARY NETWORKS TWO-TERMINAL RELIABILITY AND AVAILABILITY ESTIMATION BY SIMULATION

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Abstract: *Two-terminal reliability (2TR) and two-terminal availability (2TA) are useful measures of performance of communication networks, especially in military applications, when a network, usually built of low-quality and repairable nodes and links, is primarily intended to provide information traffic between two important users – source and destination terminal nodes. There are analytical methods for 2TR and 2TA calculation, but only a few of them can be applied if the network is complex, and especially if its elements are repairable. An approach to 2TR and 2TA estimation by means of the discrete events simulation has been presented in the paper. The necessary definitions have been given, as well as the simulation models elements, the algorithms of the realized GPSS World program-simulators for 2TR and 2T as well as the algorithm of group of redundant network elements failure generator. To illustrate the proposed concepts, an example with a brief analysis of the executed experiments results has also been given. The realized simulators can be useful in military communication networks early conception phases, as well as in their exploitation and maintenance planning.*
Keywords: *Availability, communication network, estimation, military, reliability, simulation.*

INTRODUCTION

Communication networks (Fig.1), especially the military ones, are complex systems, consisting of many components which are subjects to occasional failures, by nature and/or adversary's activities. With the increase of the number of network elements (nodes and links), the disruption probability of the connection between two users who interchange information across the network also increases. Mitigating factor is the possibility of reestablishment of the connection by choosing some alternative path in the network, which is available at the time of the network element failure.

For any technical system, reliability and availability characterize its best capability to persist in functioning.

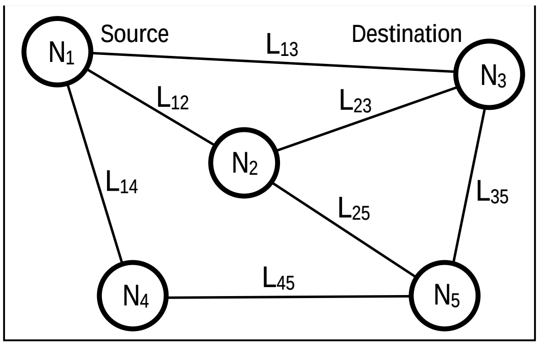

Figure 1. Communication network example: 5 nodes, 7 links

For communication networks in particular, it is necessary to determine which kind of network reliability and availability are to be estimated. They can be [1]:

- Network 2-terminal reliability (2TR) and availability (2TA): probabilities that there is at least one operational path between 2 terminal node, N_s (source) and N_d (destination) in time t = T, or in any time t, respectively;
- Network k-terminal reliability (kTR) and availability (kTA): probabilities that there is at least one operational path between at least k defined nodes in time t = T, or in any time t, respectively;
- Network total reliability (ATR) and availability (ATA): probabilities that all nodes (any two) can be connected in time t = T, or in any time t, respectively.

There are analytical methods for reliability and availability calculation or at least assessment, but only a few of them can be applied if the network is complex, especially if its elements are repairable, which is usually the case. In essence, these methods are based on counting the states in which system is operational, and by summing the probabilities for the system being in these states. If the number of these states is great, the achievement of analytical solutions for reliability and availability of a network can be difficult and often even impossible. This is the reason why simulation can be used for the solution of such problems [2], [3], and [4].

We applied two simulation methods [5] for complex communication network reliability estimation, consisting of nodes and links characterized by their mean times between failures (MTBF). However, in further research [6] and [7], we concluded that availability would be better quality indicator for users of communication network consisting of repairable elements.

In this article, we present our approach to networks 2-terminal reliability and availability estimation by applying the discrete events simulation method.

DEFINITIONS

Network is a set of network elements, interconnected for the sake of information transfer. In this research, communication network is a system consisting of at least 2 terminal nodes, connected by means of links and/or other nodes by at least 2 different ways.

Network elements are nodes and links.

Node N$_i$ is a network element for sending, receiving and routing information through communication network. A node can be terminal (source or destination of communication), or intermediate (router). All nodes in this research are capable of sending, receiving and routing the traffic over the links they are connected to.

Link L$_{ij}$ is a network element intended for connecting of adjacent nodes N_i and N_j. In this research all links are bidirectional, i.e. $L_{ij} \equiv L_{ji}$.

Connection is a communication in a network, established between two terminal nodes (source and destination).

Path is a serial connection of network elements (terminal nodes, intermediate nodes and corresponding links). It consists of at least 3 elements: 2 terminal nodes (source and destination) and 1 link. A path can have more additional elements, intermediate nodes for routing and corresponding links.

In this research, complexity of a path S_i has been introduced, as a measure of path acceptance order for connection establishment. It is defined by the expression:

$$S_i = N_i + L_i = 2N_i - 1 \tag{1}$$

Where N_i and L_i are the numbers of nodes and links in a path i, respectively.

On the occasion of establishing a connection between 2 terminal nodes, network management considers all available paths, in ascending order of their complexity.

Network traffic consists of all requirements for establishing paths and busy times of those path elements during connection life time.

Failure of network element (node or link) occurs when an element stops functioning due to its failure, and lasts until it is repaired. Failures of network elements are defined by mean time, MTBF [h], and exponential distribution of the time between failures.

Path failure occurs when any of its constituent elements fails, because all of them are serially connected in a path.

Repair of a network element is a process of putting the failed element back into operational state. Network element repair time, t_{rep}, is defined by its mean, MTTR [h], and its exponential distribution.

SIMULATION MODELS

A. *Simulation model for communication network 2TR estimation*

Reliability $R(t)$ of a technical system is a probability of the system being operational to perform the given function for the period of time from zero to t. We supposed that exponential distribution of time to failure of the elements can be applied, so the reliability of the element of the system is given by:

$$R(t) = e^{-\lambda t} \tag{2}$$

Where λ is failure rate of the element.

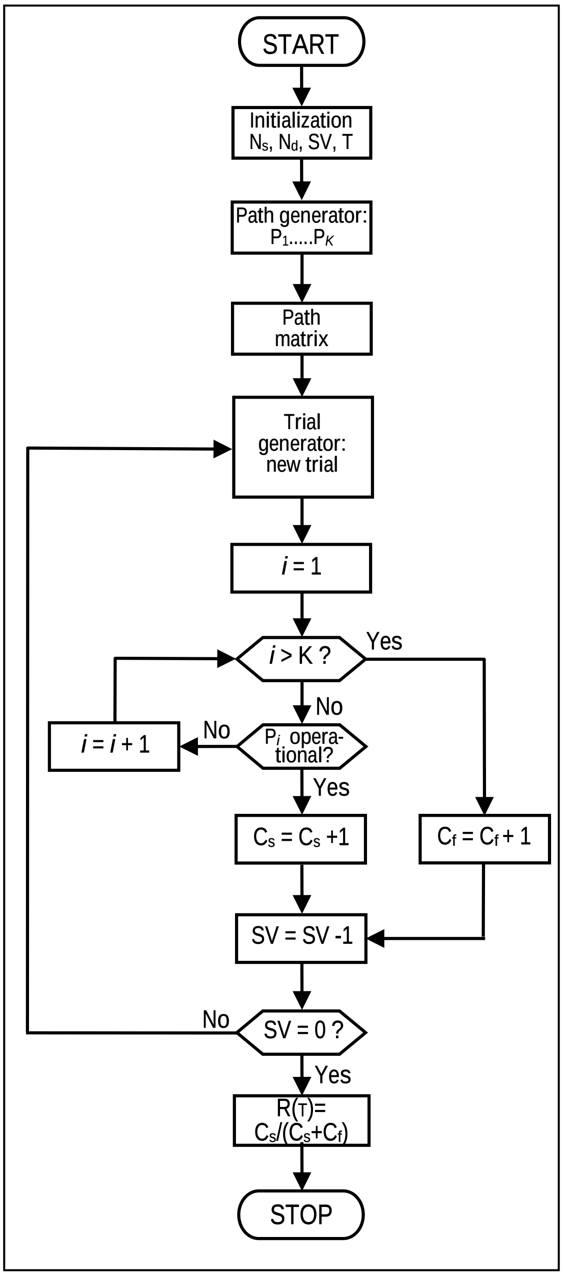

Figure 2. Network two-terminal reliability simulator algorithm

Mean time between failures (MTBF) of nodes and links are basic input data for the reliability of a communication network calculation. If exponential distribution of time to failure can be applied, the relation between MTBF and λ is MTBF=1/λ. This is adequate if the assumed network consists of electronic elements.

We assume that network fails if its elements (nodes and links) fail in such way that there is no operational communication path between source and destination nodes.

Model for communication networks two-terminal reliability is in the discrete events simulators class. The simulator prototype has been implemented by means of the GPSS World simulation language [8].

The simulator algorithm has been depicted in Fig. 2. Basic modules of the simulator are network path generator, access trial generator, and network operation simulator.

The algorithm is based on the fact that 2TR reliability is the probability that a system dispose of at least one operational path between source and destination node in the time instant t = T.

On simulator initialization, source node N_s, destination node N_d, time instant t = T in which the network 2TR is to be estimated, and the sample value (SV) of trials of communication establishing are selected.

Based on the network configuration and its operational elements, module path generator forms the path matrix, containing all available paths P_i, i = 1, … , K, leading from N_s to N_d. The matrix is sorted according to paths' complexities S_i, calculated by the expression (1).

The trial generator generates SV sample of trials to communicate through the network. At each trial, the simulator goes through all possible paths between N_s and N_d, from the simplest to the most complex one. Each path element is examined, by sampling its probability of correct functioning, calculated for the time instant t = T by the expression (2). If any path element fails, the simulator tries the next possible path, excluding every path that includes the failed element. If at the end of the trial a fully operational path is found, the communication between source and destination node can be established and the network success counter C_s is incremented by 1. If not, the network failure C_f counter is incremented by 1. After each completed trial, sample SV is decremented by 1. At the end of the simulation, when SV = 0, two-terminal reliability of the network in time instant t = T is calculated by the expression:

$$R(T) = \frac{C_s}{C_s + C_f} \qquad (3)$$

B. Simulation model for communication network 2TA estimation

Availability (A) of any technical system is a probability that, when used under given conditions, it will operate in any time [9], which is defined by the expression:

$$A = \frac{t_{use}}{t_{use} + t_f} \qquad (4)$$

Where t_{use} is system usage time and t_f is system fail time.

Our approach consists in formulation of simulation model for network 2-TA estimation, simulation of network operation and corresponding events in time interval T, gathering data of times t_{use} and t_f during the simulation experiment and network availability calculation according to the expression (4). Our model for complex communication networks 2-terminal availability is in the discrete events simulators class. The main events in the system are:

- Demand for establishment of the information traffic between nodes N_s and N_d.
- Termination of that traffic between nodes N_s and N_d.
- Network element (node or link) failure and the beginning of its repair.
- Completion of the failed network element repair.

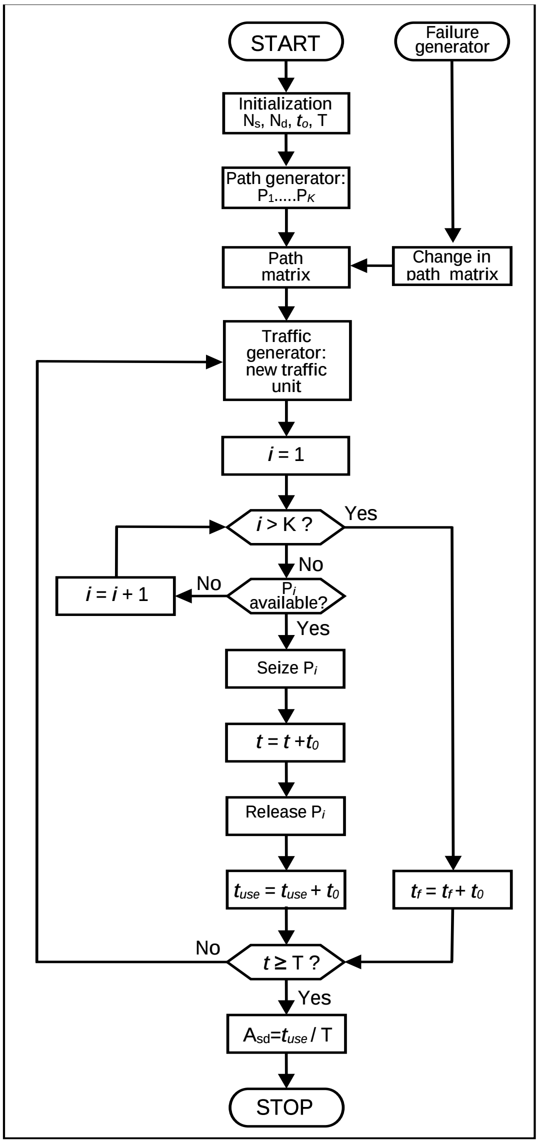

Figure 3. Network two-terminal availability simulator algorithm

In the simulation model, time is defined by the basic interval t_0 in which the existing system state does not change, and by the total simulated period T of the network operation. The moving parts of the simulated system are the information traffic units through the network, and the network elements failures. In the model, we consider the worst case, when continuous network service (information traffic between nodes N_s and N_d) is required. It has been achieved by generating new traffic unit at every basic interval t_0 by the traffic generator module. On the occurrence of every new traffic unit, path matrix content is examined, in ascending order of path complexities.

The simulator has been implemented by means of the GPSS World simulation language, so GPSS transactions [8] represent traffic units and failures. The simulator algorithm has been depicted in Fig. 3.

On simulator initialization, source and destination terminal nodes (N_s and N_d), basic time interval t_0, and total time T of simulated network operation are selected.

If there is an available path P_i from N_s to N_d, the traffic unit generated by traffic generator module seizes it, keeps it busy for 1 interval t_0, then releases it, increments use time counter t_{use} by 1 interval t_0, and finally leave the simulation.

If there is no available path, the traffic unit increments fail time t_f counter by 1 interval t_0 and leaves simulation. There are as much independent failure generators as there are network elements.

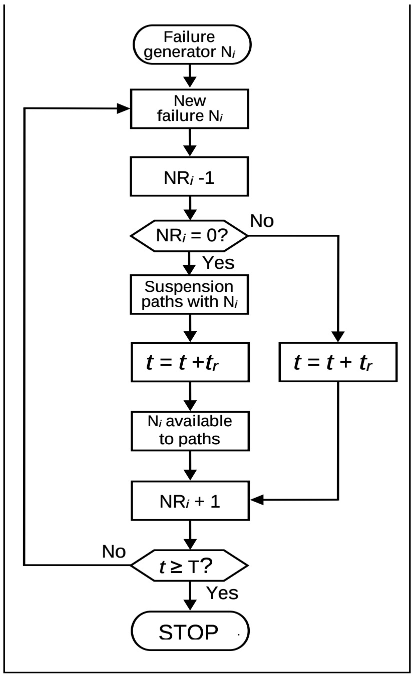

Figure 4. Failure generator algorithm

The failure generator algorithm for the redundant group of nodes, characterized by its level of redundancy NR (the number of nodes in the group connected in parallel), is presented in Fig. 4. Failure generator generates new GPSS transaction [8] which simulates that element failure, according to its MTBF-*i* and exponential distribution of the time between failures. Failure changes the path matrix, so that all paths containing the failed network element are disabled. The failed element repair is simulated by increasing the simulated time counter t by repair time t_r, calculated by the mean time of that element's repair $MTTR_i$ and its exponential distribution. On the repair completion, the path matrix is updated, by making available all paths containing the repaired element.

When the time T of the network operation expires, the simulation terminates, and 2TA is calculated by (4).

C. *Validation of algorithms*

Validations of proposed algorithms have been performed by comparing the results of realised simulators with those of the known theoretically

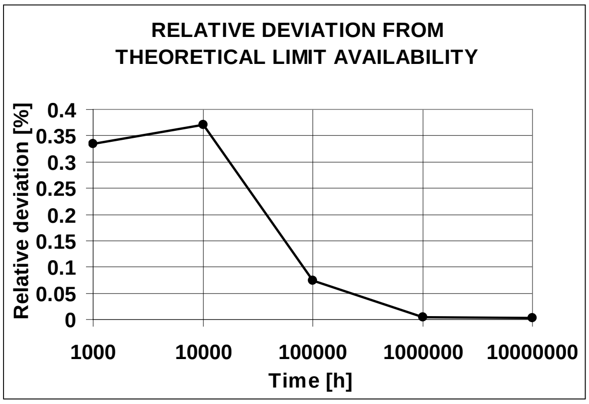

Figure 5 Validation: relative deviation of simulator's output from theoretical limit value

solved cases, as it has been proposed in [1].

As an example of such cases, let us consider the serial connection of two repairable subsystems with the same mean time to failure, MTBF = 1/λ = 3000 h, and the same mean time to repair, MTTR=1/μ = 5 h.

The theoretical limit value of such system's availability [8] is defined by the following expression:

$$\underset{t\to\infty}{A(t)} = \frac{\mu^2}{\mu^2 + 2\lambda\mu + 2\lambda^2} = 0.9966722 \qquad (5)$$

The relative deviation, in percents, of the 2TA simulator output from that theoretical limit value is depicted in Fig. 5.

In the first 1000 hrs of simulated time, that deviation is constant (0,35%), because in that time interval no one simulated failure occurred, due to MTBF of 3000 hrs. After that point of simulated time, the relative deviation of the 2TA simulator's output was less than 0,4 % in the worst case, and the convergence to the availability theoretical limit value is evident, which validates the 2TA simulator's algorithm in Fig. 3.

The validation of the proposed 2TR simulator's algorithm has been done in a similar way.

ANALYSIS OF THE RESULTS

D. The simulated example networks: NET-1 and NET-2

The example networks considered were of the same topology, consisting of 5 nodes and 7 links (Fig.1), and the simulation has been done to estimate of 2TR and 2TA between nodes N_1 and N_3.

The networks, NET-1 and NET-2, differ in the quality of the elements, which characteristics are shown in TABLE I. In the experiments we simulated the operation of networks NET-1 and NET-2 in order to estimate 2TR and 2TA in the case of nodes N_1 and N_3 acting as source (N_s) and destination (N_d) respectively. Possible paths between N_1 and N_3, sorted by complexity, are in TABLE II. The impact of every network's element failure to every possible path between is shown in TABLE III.

TABLE I.
NETWORKS NET-1 AND NET-2 ELEMENTS CHARACTERISTICS

Element	Characteristics				
	MTBF			MTTR	
	NET-1 [h]	NET-2 [h]	Distribution	NET-1/2 [h]	Distribution
Node	300	30	Expon.	5	Expon.
Link	400	40	Expon.	3	Expon.

TABLE II.
SORTED PATHS BETWEEN NODES N1 AND N3

Path	Characteristics			
	Composition	N	L	S
P1	N_1-L_{13}-N_3	2	1	3
P2	N_1-L_{12}-N_2-L_{23}-N_3	3	2	5
P3	N_1-L_{12}-N_2-L_{25}-N_5-L_{53}-N_3	4	3	7
P4	N_1-L_{14}-N_4-L_{45}-N_5-L_{53}-N_3	4	3	7
P5	N_1-L_{14}-N_4-L_{45}-N_5-L_{52}-N_2-[illegible]	5	4	9

TABLE III
IMPACTS OF NETWORK ELEMENTS FAILURES

Network element	Path				
	P_1	P_2	P_3	P_4	P_5
N_1	0	0	0	0	0
N_2	X	0	0	X	0
N_3	0	0	0	0	0
N_4	X	X	X	0	0
N_5	X	X	0	0	0
L_{12}	X	0	0	X	X
L_{13}	0	X	X	X	X
L_{14}	X	X	X	0	0
L_{23}	X	0	X	X	0
L_{25}	X	X	0	X	X
L_{45}	X	X	X	0	0
L_{35}	X	X	0	0	X

In TABLE III, "0" means that a failure of a network element disrupts a path containing it; "X" means that a network element failure has no impact to path operation.

It has been assumed that in the time instant t = 0, all network elements are operational.

E. NET-1 and NET-2 2TR estimation by simulation

In order to dynamically estimate network two-terminal reliability, one can execute several simulation experiments for different time points of interest, T_i, and put the results together in the common time diagram, as it has been done in Fig. 6.

For the example networks NET-1 and NET-1, two-terminal reliability between nodes N_1 and N_3 has been estimated in the following time points:

$T_i(h) \in \{1, 2, 5, 10, 50, 100, 500, 1000\}$

For every of time points a sample of SV = 10000000 access trials has been generated.

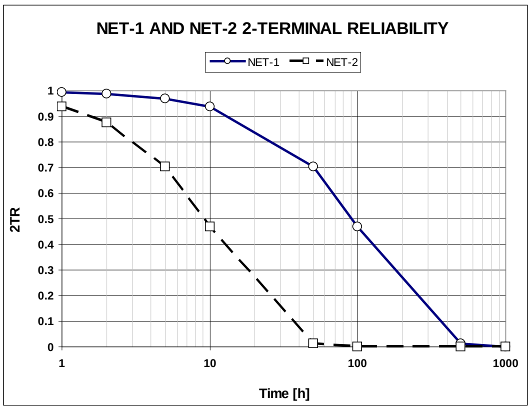

Figure 6 Networks NET-1and NET-2 two-terminal reliability estimation by simulation

It is assumed that in the time instant t = 0, all network elements are operational.

The results of the simulation (Fig. 6) show that 2TR of the network NET-1in the first hour of the system functioning is 100 %. Between 1 and 10 hours, 2TR decreases relatively slowly, to the value of 93.69 % and from 10 hours more rapidly until 500 hours, when it reaches 1.16 %. At t = 1000 h, 2TR for the network NET-1 is 0.

For the network NET-2, consisting of elements of 10 times worse quality, the results of simulation show that even in the first hour, 2TR has not exceeded the value of 98.63 %. Between 1 and 10 hours, 2TR decreases more rapidly to the value of 46.86 %, and after that even more rapidly, to the value 1.16 %, which it reaches in time point t=50 h. At t=100 h, 2TR for the network NET-2 is 0.

The simulator itself has been realised in GPSS World language. It is relatively simple to implement and can be useful in situations when it is necessary to estimate performance of communication networks consisting of non-repairable elements.

It is much more difficult to estimate how useful a communication network is when it consists of repairable elements. In such situations, it is

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convenient to calculate or at least estimate the communication network availability.

F. NET-1 and NET-2 2TA estimation by simulation

For the example networks NET-1 and NET-1 2TA estimation by simulation, ttwo groups of 3 experiments (EX-1 and EX-2) have been executed. In every experiment, total time interval T=10000000 hours of the network operation was simulated, and the basic time unit was 1 minute. The results of the experiments are given in TABLE IV and the 2TA dynamic developments in Fig. 7 and Fig.8.

In the group of experiments EX-1, the network NET-1, as it is, between the nodes N_1 and N_3 achieved 2TA = 84.7333%. Most often, NET-1 used path P_1, connecting nodes N_1 i N_3 by direct link L_{13}, with utilization U_{P1} = 96.0196%. Utilizations of alternative paths were far less, and P_5 has been used negligibly. 2TA dynamic development curve (Fig.7) shows a value of 100% in the first 100 hours of simulated time, and then converges to the value achieved at t = T.

TABLE IV
SIMULATION OF 10^7 NETWORK OPERATION HOURS

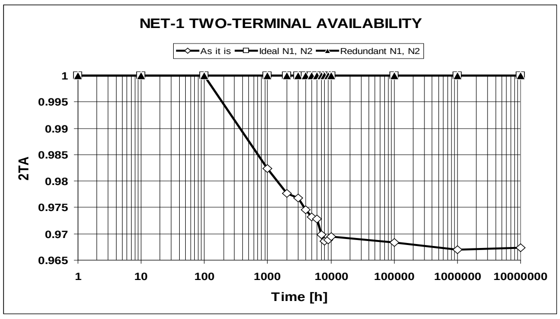
Name	Results of the experiments					
	EX-1			EX-2		
	NET-1 as it is	Ideal N_1 N_3	Red. N_1 N_3	NET-1 as it is	Ideal N_1 N_3	Red. N_1 N_3
2TA [%]	84.7333	99.9988	99.9987	71.0333	99.2580	99.2558
U_{P1} [%]	96.0196	99.2518	99.2617	66.4006	92.7594	92.8011
U_{P2} [%]	0.6927	0.7251	0.7152	3.7569	5.2742	5.2420
U_{P3} [%]	0.0056	0.0052	0.0057	0.2179	0.3040	0.3019
U_{P4} [%]	0.0156	0.0166	0.0156	0.6379	0.9035	0.8941

In order to estimate the impact of the rest of the network, the ideal, failure-free terminal nodes were used, which has been achieved by disabling the N_1 and N_3 failure generators. In that case 2TA = 99.9988%, with path utilizations similar to those in the preceding case. The 2TA dynamic development was practically constant in the whole time interval T (Fig.7). It follows that, with ideal terminal nodes N_1 and N_3, the impact of the rest of the network was practically reduced to direct link L_{13} that connected them, so impact of other paths of the network on 2TA has been negligible.

Having in mind that the use of ideal nodes is not justifiable, the introduction of redundant groups of nodes N_1 and N_3 and its impact to 2TA has also been simulated within EX-1. It has been achieved by introduction of failure generators for redundant groups of those nodes (Fig.4) and initialization of their levels of redundancy to $NR_1 = NR_3 = 2$. In that case, 2TA = 99.9987 %, and utilizations of paths are similar to those achieved when ideal N_1 and N_3 were used. The 2TA dynamic development curves are practically identical in the whole simulated interval T.

Hence the use of redundant nodes N_1 and N_3 is justified. Group of experiments EX-2 has been executed in order to explore the operation of the network NET-2, consisting of the elements with the MTBF 10 times shorter. As it is, it achieved 2TA = 71.0333%. P_1 path has been also mostly used, but now far less than in experiments of the group EX-1 (U_{P1} = 66.4006%). Besides, utilizations of alternative paths have been increased. For the network NET-2 as it is, 2TA dynamic development (Fig.8) shows the value of 100% in the first 10 hours of simulated time, and then drops to converge to the value achieved at t = T.

With ideal N_1 and N_3, 2TA = 99.2580%. Path P_1 utilization, U_{P1} = 92.7594%, and the utilizations of other paths have increased compared to the previous case. In the first 100 hours of simulated time, 2TA=100%, and then slightly drops and converges to the value achieved at the end of the simulated period T.



Fig

Figure 7 Network NET-1 2TA dynamic development

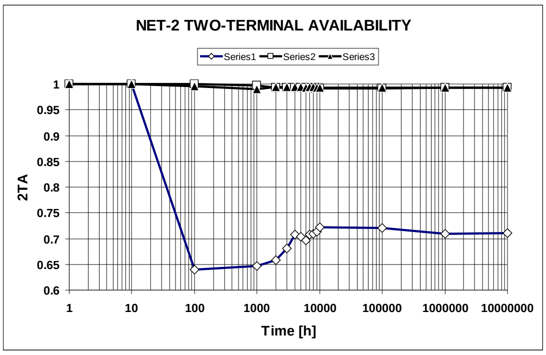


Figure 8 Network NET-1 2TA dynamic development

On the other hand, when redundant terminal nodes are used, 2TA = 99.2558%, and the paths utilizations are similar to those in case of ideal nodes N_1 and N_3. The 2TA dynamic development curves (Fig. 8) are practically identical in the whole simulated interval T. Hence the use of redundant nodes N_1 and N_3 in the case of 2. network is also justified.

The more complex network 2TA simulator is particularly useful for estimation of networks consisting of repairable elements.

It generates traffic units in each basic time interval, independently generates failures of network elements, simulates network operation and all relevant events in simulated time period, and returns 2TA values in all time points of interest, enabling users to dynamically estimate network two-terminal availability.

CONCLUSIONS

Two discrete events simulators for the estimation of communication network 2 TR and 2TA has been realised. The network 2TR simulator is easier to implement, but it is limited to estimation of performance of networks consisting of nonrepairable elements. In military applications, the 2TR simulator can be useful when it is impossible to repair network elements damaged by the adversary's activities.

The network 2TA simulator is more complex, but useful for the estimation of performance of networks consisting of repairable elements. In military applications, 2TA simulator can be useful when the network elements reparations are possible during the combat activities.

The simulators can be useful in network conception, as well as in their realisation, exploitation and maintenance.

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BIBLIOGRAPHY:

[1] M. Čabarkapa, Đ. Mijatović and N. Krajnović, "Network Topology Availability Analysis", Telfor Journal, Vol. 3, No. 1, pp. 23-27, 2011.
[2] H. K. Ping, "Network Reliability Estimation", PhD thesis, University of Adelaide, 2005.
[3] M. Luby, "Monte-Carlo Methods for Estimating System Reliability", University of California Berkeley, 1984.
[4] Y. Jiang et al. "Monte-Carlo Methods for Estimating System Reliability", proceedings of ICQRMS 2012 - International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering, 2012.
[5] S. Pokorni and R. Janković, "Reliability Estimation of a Complex Communication Network by Simulation", proceedings of 19th Telecommunications Forum TELFOR 2011, Belgrade, 2011.
[6] R. Janković and S. Pokorni, "Communication Networks Availability Estimation by Simulation", proceeding of 4th DQM International Conference on Information Technology ICDQM-2013, June 27-28, Belgrade, 2013.
[7] R. Janković, S. Pokorni, N. Nikolić, "Simulation Approach to Communication Networks Two-terminal Reliability and Availability Estimation", 6th International Scientific Conference on Defensive Technologies, Belgrade, 2014.
[8] Minuteman Software, "GPSS World Reference Manual", available at www.minutemansoftware.com
[9] N. Vujanović "Theory of Technical Systems Reliability", VINC, Beograd, 1990. (in Serbian)