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Performance of Base Stations in Railway Digital Radio Communication Networks

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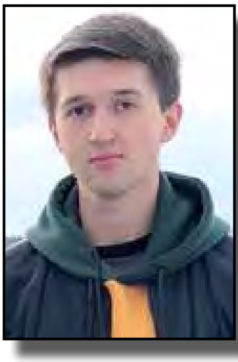

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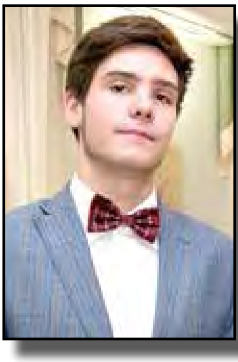

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ABSTRACT

Base station (BS) is a terminal device of a radio communication network, while railway radio communications play an important role in ensuring safety of passenger and cargo transportation.

A proposed method for calculating the performance of base stations in railway digital radio communication networks is intended to calculate for the BS the probabilities of being in certain state.

BS was decomposed and such functional elements as circuit groups and a radio frequency path were identified, as well as the central module ensuring the exchange of information with elements of this BS and with other BSs. A detailed study of each element has increased accuracy of the proposed method. Following the Markov model, BS is presented as a system in which all possible states are considered. Models for BS with two and three circuit groups have been constructed. The parameters of each functional element of the model can be obtained through observation over a certain period. The solution of the system of equations for each of the models presented in the article will allow obtaining the values of the system being in a certain state. The obtained characteristics can be used to calculate the reliability of the entire radio communication network, and then to assess quality of service provided to the users of this network.

Conclusions are made about the possibilities of using the obtained models when designing new railway communication networks and when calculating quality indices of existing ones. The proposed models can be applied not only to railway radio communication networks but also to mobile communication networks of commercial operators.

Keywords: *digital radio communication network, railway telecommunication systems, call quality, train traffic safety.*

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INTRODUCTION

Radio communication as a type of telecommunications has been widely used on railways. Initially, it was used only for exchange of voice information between mobile and fixed subscribers. Considering development of high-speed traffic, as well as rapid growth of telecommunications and information technologies, emergence of new generations of mobile communications, radio communications began to significantly increase the functionality. Now it is used for transmission of telemetric information, automatic control of rolling stock (auto-driving), video conferencing. The newest systems of interval regulation of trains' traffic (radio blocking) are being built over the radio channel, which are replacing the track circuits. Such positioning systems are described in [1].

Several works [2; 3] consider the issues of choosing the best standard and topology of the railway digital radio communication network. The work [4] should be considered an important contribution in the field of effective use of communication network elements, while the results of measurements of some characteristics are presented in ITU-R report [5]. The latest mobile technologies (for example, LTE and 5G) described in detail in [4; 6] are gaining popularity in some countries.

Digital train radio communication networks within the railway network of the Russian Federation are organised based on TETRA, GSM-R or DMR standards, while the probability of good communication at any place and time must be at least 95 %[1], the availability of radio communication networks for high-speed transport must be at least 99, 95 % [7]. Therefore, at present, sufficient attention is paid to the issues of stable and reliable operation of radio communications. They are considered in [8; 9], and the issues of calculating survivability of a digital radio communication network are described in [10].

While designing a communication network, several tasks are posed: quality indicators are calculated for each class of service for subscribers considering changes in the load, gravity structure, channel capacity, as well as failure of network components; the load of equipment and communication channels, the need for redundancy are estimated. These tasks are solved through modelling and subsequent system analysis [11]. The models in this study will simplify finding some characteristics of the communication network.

The *objective* of the study was to develop a method to calculate the performance of base stations within railway digital radio communication networks and the probabilities for BS of being in certain states. The main *method* of the study was analytic modelling used in the theory of telecommunication traffic to solve similar problems.

RESULTS

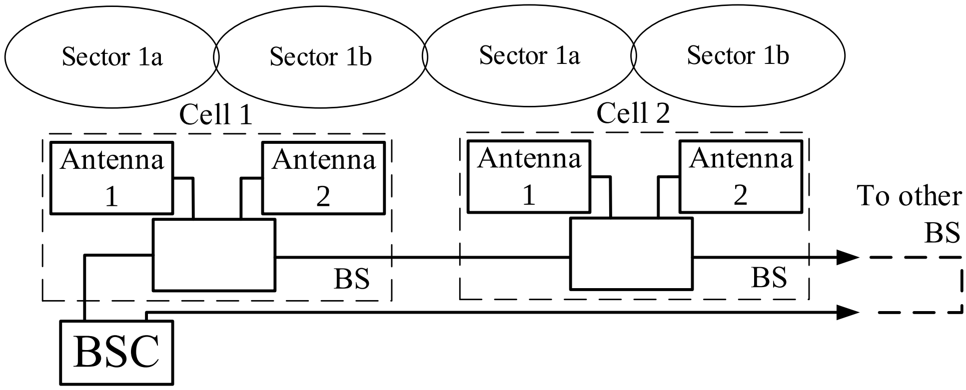
Let us consider a simplified diagram of a digital radio communication network of railway transport on a given section of the railway. No radio coverage redundancy exists. The radio communication network contains a certain number of base stations (BS), interconnected by a terrestrial communication channel (Pic. 1).

The BS connection scheme is sequential, since, according to the requirements [5], they must be connected to the Base Station Controller (BSC) according to the «spatial ring» principle. Each antenna serves a specific sector of the cell. All requests for connections from mobile terminals are transmitted from BS through communication channels to BSC. It connects the required BS to operation, which connects the terminal of the called subscriber through the radio communication channel. Radio coverage of the required area is provided through the antennas of each sector.

A functional model of a base station of a digital radio communication network is shown in Pic. 2. The numbers 1 and 2 denote the radio frequency path of the base station (antennas, antenna-feeder devices, etc.) of the left and right sectors, number 3 – the switching, control and connection modules that provide information exchange with other base stations over circuit groups (numbers 4 and 5), as well as interaction with the RF path. For simplicity, component 3 will be called further-on a switch.

It is proposed to consider BS as a system with several functional elements. To obtain the dependences of the required characteristics on all parameters of the system, analytical modelling is used, which is widespread in the theory of telecommunications traffic when solving such problems. Description and examples of some

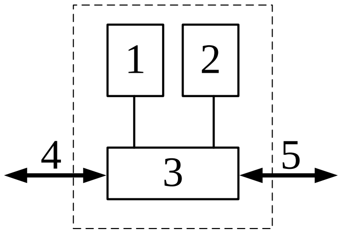
[1] GOST R [Russian State Standard] 54959-2012. Railway electric communications. Train radio communications. Technical requirements and control methods. Date of enactment: April 1, 2013. [Electronic resource]: https://docs.cntd.ru/document/1200095030. Last accessed 12.01.2021.



Pic. 1. Simplified diagram of railway digital radio communication network (compiled by the authors).

models are given in [12], and the solution of such problems is described in [13], and regarding the railway transport [14].

For our functional model of BS (Pic. 2), we will construct a graph of possible transitions between operability states (Pic. 3). Let λ be the failure flow intensity of each element of the model, μ – recovery flow intensity, P_i – probability of the system being in the state $i=\overline{[0,10]}$.



Pic. 2. A functional model of a base station with two sectors, two circuit groups and a switch (compiled by the authors).

The scheme of the model's functioning makes it possible to distinguish ten discrete states in which the system could be:

0 – Both sectors of the base station are operational, all circuit groups are operational, switching is in progress.

1 – Both sectors of the base station are operational, one of the circuit groups is faulty, switching is in progress.

2 − Both sectors of the base station are operational, both circuit groups are faulty, switching is in progress.

3 – Only one of the sectors of the base station is operational, all circuit groups are operational, switching is in progress.

4 − Only one of the sectors of the base station is operational, one of the circuit groups is faulty, switching is in progress.

5 – Only one of the sectors of the base station is operational, both circuit groups are faulty, switching is in progress.

6 – Both sectors of the base station are inoperative, all circuit groups are in good order, switching is in progress.

7 − Both sectors of the base station are inoperative, one of the circuit groups is faulty, switching is in progress.

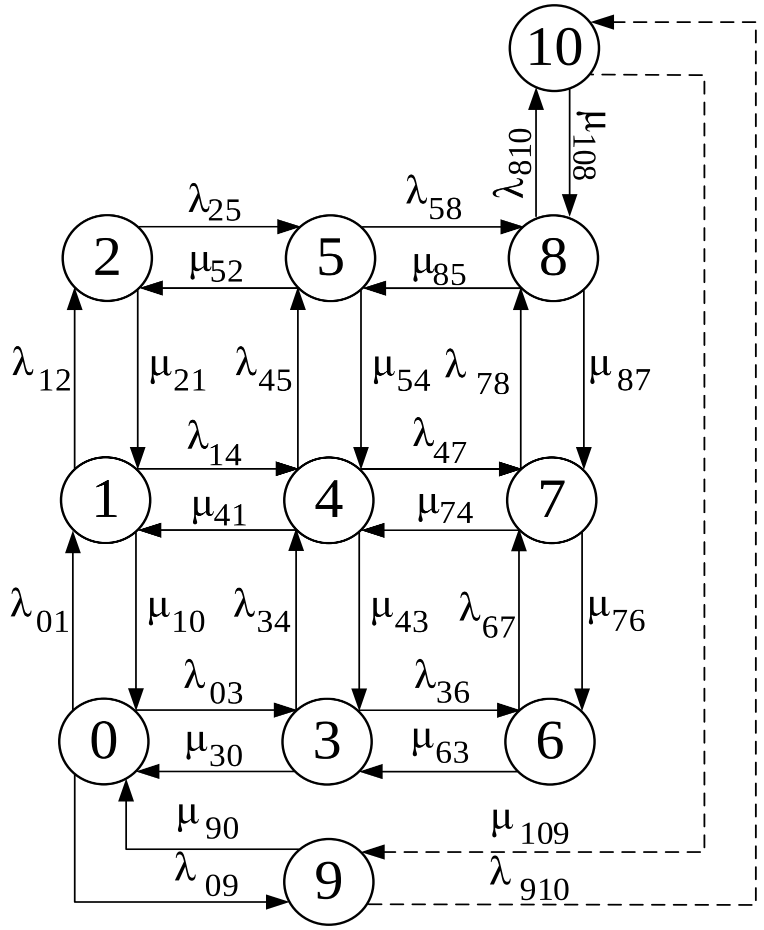
8 – Both sectors of the base station are inoperative, both circuit groups are faulty, switching is in progress.

9 – Both sectors of the base station are operational, all circuit groups are operational, switching is not performed.

10 – Both sectors of the base station are inoperative, all circuit groups are faulty, switching is not performed.

State 0 indicates that the system is fully operational. States 1, 3 and 4 indicate that the base station has received serious damage but it is functioning as intended with a deterioration in quality of service. In states 2, 5–9, the system is considered inoperative, even when its individual components are functioning. End state 10 indicates complete failure of base station components.

Let's compose a system of equations according to the following rules: the probability of the base station being in state P_i is to the left of the equal sign. To the right of the equation there is the sum of the products of the probabilities of all transitions entering (incoming arrows in Pic. 3) into state *i* of the system by the intensities of the states from which these flows originate, minus the probability of the considered state *i*, multiplied by the total intensity of transitions that remove the system (outgoing arrows in Pic. 3) from the given state *i*. To solve such a system, it is necessary to add one more equation that



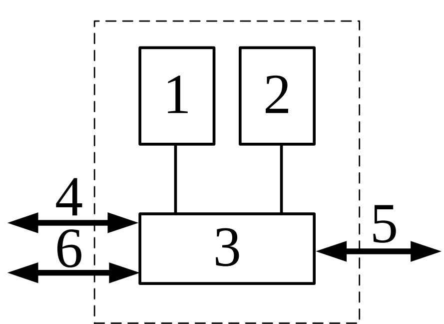
Pic. 3. The graph of states of the operability model of a base station with two sectors, two circuit groups and a switch (compiled by the authors).

determines the normalisation condition, since the sum of the probabilities of all states is equal to one.

Let us write the system of equilibrium equations according to the graph:

$$P_0(\lambda_{01}+\lambda_{03}+\lambda_{09}) = P_1\mu_{10}+P_3\mu_{30}+P_9\mu_{90};$$

$$P_1(\mu_{10}+\lambda_{12}+\lambda_{14}) = P_0\lambda_{01}+P_2\mu_{21}+P_4\mu_{41};$$



Pic. 4. A functional model of a base station with two sectors, three circuit groups and a switch (compiled by the authors).

$$P_2(\mu_{21}+\lambda_{25}) = P_1\lambda_{12}+P_5\mu_{52};$$

$$P_3(\lambda_{36}+\mu_{30}+\lambda_{34}) = P_6\mu_{63}+P_0\lambda_{03}+P_4\mu_{43};$$

$$P_4(\mu_{41}+\lambda_{45}+\lambda_{47}+\mu_{43}) = P_1\lambda_{14}+P_5\mu_{54}+P_7\mu_{74}+P_3\lambda_{34}; \quad (1)$$

$$P_5(\mu_{54}+\mu_{52}+\lambda_{58}) = P_4\lambda_{45}+P_2\lambda_{25}+P_8\mu_{85};$$

$$P_6(\mu_{63}+\lambda_{67}) = P_3\lambda_{36}+P_7\mu_{76};$$

$$P_7(\mu_{76}+\lambda_{78}+\mu_{74}) = P_6\lambda_{67}+P_8\mu_{87}+P_4\lambda_{47};$$

$$P_8(\mu_{85}+\mu_{87}+\lambda_{810}) = P_5\lambda_{58}+P_7\lambda_{78}+P_{10}\mu_{108};$$

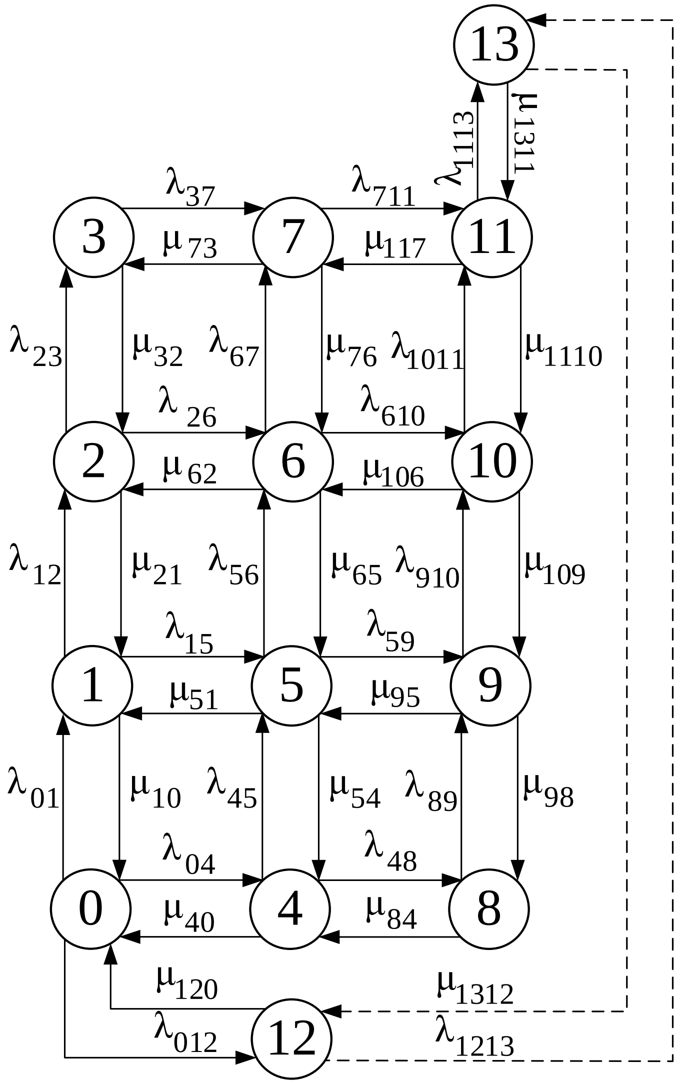
$$P_9(\mu_{90}+\lambda_{910}) = P_0\lambda_{09}+P_{10}\mu_{109};$$

$$P_{10}(\mu_{109}+\mu_{108}) = P_9\lambda_{910}+P_8\lambda_{810}.$$

Let us indicate the normalising condition:

$$\sum_{i=0}^{10} P_i = 1.$$

Let us set the following numerical values of the model parameters – failure and recovery intensities: $\lambda_{01} = 0,009 \cdot 10^{-6}$, $\lambda_{12} = 0,008 \cdot 10^{-6}$, $\lambda_{25} = 1 \cdot 10^{-6}$, $\lambda_{58} = 1 \cdot 10^{-6}$, $\lambda_{78} = 1,89 \cdot 10^{-6}$, $\lambda_{67} = 1,29 \cdot 10^{-6}$, $\lambda_{36} = 0,0011 \cdot 10^{-6}$, $\lambda_{03} = 0,011 \cdot 10^{-6}$, $\lambda_{34} = 0,9 \cdot 10^{-6}$,



Pic. 5. The graph of states of the operability model of a base station with two sectors, three circuit groups and a switch (compiled by the authors).

$\lambda_{14} = 0{,}115 \cdot 10^{-6}$, $\lambda_{45} = 0{,}205 \cdot 10^{-6}$, $\lambda_{47} = 0{,}145 \cdot 10^{-6}$, $\lambda_{09} = 0{,}0019 \cdot 10^{-6}$, $\lambda_{910} = 0{,}01 \cdot 10^{-6}$, $\lambda_{810} = 0{,}122 \cdot 10^{-6}$, $\mu_{10} = 9{,}99 \cdot 10^{-6}$, $\mu_{21} = 9{,}77 \cdot 10^{-6}$, $\mu_{52} = 2{,}63 \cdot 10^{-6}$, $\mu_{85} = 3{,}45 \cdot 10^{-6}$, $\mu_{87} = 2{,}21 \cdot 10^{-6}$, $\mu_{76} = 1{,}01 \cdot 10^{-6}$, $\mu_{63} = 4{,}56 \cdot 10^{-6}$, $\mu_{30} = 9{,}99 \cdot 10^{-6}$, $\mu_{43} = 4 \cdot 10^{-6}$, $\mu_{41} = 9 \cdot 10^{-6}$, $\mu_{54} = 1{,}01 \cdot 10^{-6}$, $\mu_{74} = 5 \cdot 10^{-6}$, $\mu_{90} = 9{,}89 \cdot 10^{-6}$, $\mu_{109} = 1{,}11 \cdot 10^{-6}$, $\mu_{108} = 2 \cdot 10^{-6}$. The choice of the model parameters is due to achievement of the maximum value of the probability of the operational state of the BS (state 0).

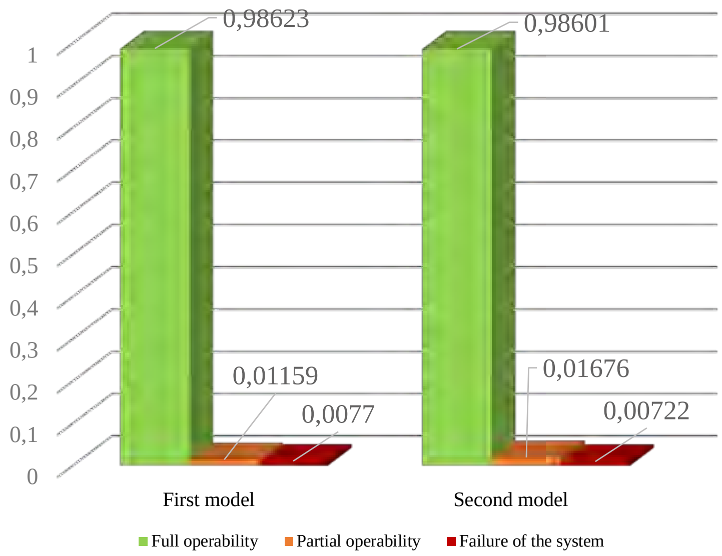
Next, the resulting system of equations is calculated by the Gauss–Seidel iterative method.

The obtained values are presented below:

$P_0 = 0{,}98623$; $P_1 = 0{,}00496$; $P_2 = 0{,}00066$; $P_3 = 0{,}00663$; $P_4 = 0{,}00445$; $P_5 = 0{,}00270$; $P_6 = 0{,}00019$; $P_7 = 0{,}00107$; $P_8 = 0{,}00079$; $P_9 = 0{,}00189$; $P_{10} = 0{,}00037$.

Thus, the probability of operability of all components of the base station will be $P_0 = 0{,}98623$. The probability of the base station operability with deterioration in quality of service will be $P_1 + P_3 + P_4 = 0{,}01159$. The probability of the base station not performing its functions will be $P_2 + P_5 + P_6 + P_7 + P_8 + P_9 = 0{,}00733$, and the worst outcome is possible with the probability $P_{10} = 0{,}00037$.

Next, we will consider a functional model of a BS of a digital radio communication network of a different type, the model of which is shown in Pic. 4. This model employs three circuit groups which are designated by numbers 4–6.



Pic. 6. Diagram of BS operability (compiled by the authors based on the results of the proposed calculation).

Let's construct a new graph of possible transitions between the states of BS operability (Pic. 5).

In this model, we select 13 discrete states:

0 – Both sectors of the base station are operational, all circuit groups are operational, switching is in progress.

1 – Both sectors of the base station are operational, one of the circuit groups is faulty, switching is in progress.

2 − Both sectors of the base station are operational, both circuit groups are faulty, switching is in progress.

3 – Both sectors of the base station are operational, all circuit groups are faulty, switching is in progress.

4 – Only one of the sectors of the base station is operational, all circuit groups are operational, switching is in progress.

5 – Only one of the sectors of the base station is operational, one of the circuit groups is faulty, switching is in progress.

6 – Only one of the sectors of the base station is operational, both circuit groups are faulty, switching is in progress.

7 – Only one of the sectors of the base station is operational, all circuit groups are faulty, switching is in progress.

8 – Both sectors of the base station are inoperative, all circuit groups are in good order, switching is in progress.

9 − Both sectors of the base station are inoperative, one of the circuit groups is faulty, switching is in progress.

10 – Both sectors of the base station are inoperative, both circuit groups are faulty, switching is in progress.

11 – Both sectors of the base station are inoperative, all circuit groups are faulty, switching is in progress.

12 – Both sectors of the base station are operational, all circuit groups are operational, switching is not performed.

13 – Both sectors of the base station are inoperative, all circuit groups are faulty, switching is not performed.

State 0 indicates that the system is fully operational. States 1, 2, 4, 5 and 6 indicate that a significant failure of its components has occurred in BS, but it functions as intended with a deterioration in quality of service. In states 3, 7–12, the system is considered inoperative, even when its individual components are functioning. End state 13 indicates complete failure of base station components.

For the new model, the system of equations will look like this:

$$P_0(\lambda_{01}+\lambda_{012}+\lambda_{04}) = P_1\mu_{10}+P_{12}\mu_{120}+P_4\mu_{40};$$

$$P_1(\mu_{10}+\lambda_{12}+\lambda_{15}) = P_0\lambda_{01}+P_2\mu_{21}+P_5\mu_{51};$$

$$P_2(\mu_{21}+\lambda_{26}+\lambda_{23}) = P_1\lambda_{12}+P_6\mu_{62}+P_3\mu_{32};$$

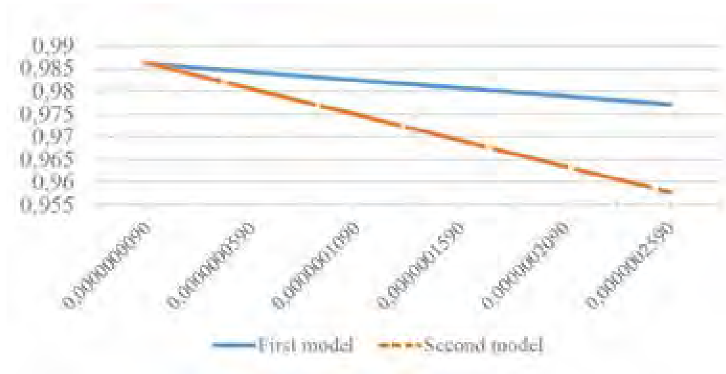
$$P_3(\lambda_{37}+\mu_{32}) = P_7\mu_{73}+P_2\lambda_{23};$$

$$P_4(\mu_{40}+\lambda_{45}+\lambda_{48}) = P_0\lambda_{04}+P_5\mu_{54}+P_8\mu_{84};$$

$$P_5(\mu_{54}+\mu_{51}+\lambda_{56}+\lambda_{59}) = P_4\lambda_{45}+P_1\lambda_{15}+P_6\mu_{65}+P_9\mu_{95};$$

$$P_6(\mu_{65}+\mu_{62}+\lambda_{67}+\lambda_{610}) = P_5\lambda_{56}+P_2\lambda_{26}+P_7\mu_{76}+P_{10}\mu_{106}; \quad (2)$$

$$P_7(\mu_{76}+\lambda_{711}+\mu_{73}) = P_6\lambda_{67}+P_{11}\mu_{117}+P_3\lambda_{37};$$



Pic. 7. The graph of dependence $P_0 = f(\lambda_{01})$ (compiled by the authors based on the results of the proposed calculation).

$$P_8(\mu_{84}+\lambda_{89}) = P_4\lambda_{48}+P_9\mu_{98};$$

$$P_9(\mu_{98}+\mu_{95}+\lambda_{910}) = P_8\lambda_{89}+P_5\lambda_{59}+P_{10}\mu_{109};$$

$$P_{10}(\mu_{109}+\mu_{106}+\lambda_{1011}) = P_9\lambda_{910}+P_6\lambda_{610}+P_{11}\mu_{1110};$$

$$P_{11}(\mu_{1110}+\mu_{117}+\lambda_{1113}) = P_{10}\lambda_{1011}+P_7\lambda_{711}+P_{13}\mu_{1311};$$

$$P_{12}(\mu_{120}+\lambda_{1213}) = P_0\lambda_{012}+P_{13}\mu_{1312};$$

$$P_{13}(\mu_{1311}+\mu_{1312}) = P_{11}\lambda_{1113}+P_{12}\lambda_{1213};$$

$$\sum_{i=0}^{14} P_i = 1.$$

For the model with three circuit groups, let us set the following values of failure and recovery intensities, which practically do not differ from the parameters of the model with two circuit groups: $\boldsymbol{\lambda}_{01} = 0{,}009\bullet10^{-6}$, $\lambda_{12} = 0{,}008\bullet10^{-6}$, $\lambda_{37} = 1{,}5\bullet10^{-6}$, $\lambda_{711} = 1{,}11\bullet10^{-6}$, $\lambda_{1113} = 0{,}111\bullet10^{-6}$, $\lambda_{67} = 1{,}29\bullet10^{-6}$, $\lambda_{1011} = 1{,}11\bullet10^{-6}$, $\lambda_{23} = 1{,}24\bullet10^{-6}$, $\lambda_{89} = 2{,}14\bullet10^{-6}$, $\lambda_{48} = 1{,}11\bullet10^{-6}$, $\lambda_{45} = 0{,}205\bullet10^{-6}$, $\lambda_{04} = 0{,}011\bullet10^{-6}$, $\lambda_{15} = 1{,}67\bullet10^{-6}$, $\lambda_{910} = 0{,}01\bullet10^{-6}$, $\lambda_{59} = 1{,}222\cdot10^{-6}$, $\lambda_{56} = 1{,}246\bullet10^{6}$, $\lambda_{26} = 2{,}456\bullet10^{-6}$, $\lambda_{012} = 0{,}01\bullet10^{-6}$, $\lambda_{1213} = 0{,}111\bullet10^{-6}$, $\lambda_{610} = 2\bullet10^{-6}$, $\mu_{10} = 9{,}99\bullet10^{-6}$, $\mu_{21} = 9{,}77\bullet10^{-6}$, $\mu_{73} = 2{,}12\bullet10^{-6}$, $\mu_{117} = 0{,}1\bullet10^{-6}$, $\mu_{1311} = 5{,}55\bullet10^{-6}$, $\mu_{76} = 1{,}01\bullet10^{-6}$, $\mu_{1110} = 8{,}76\bullet10^{-6}$, $\mu_{32} = 1{,}11\bullet10^{-6}$, $\mu_{98} = 1{,}234\bullet10^{-6}$, $\mu_{84} = 9{,}99\bullet10^{-6}$, $\mu_{54} = 1{,}01\bullet10^{-6}$, $\mu_{40} = 99\bullet10^{-6}$, $\mu_{51} = 1{,}5464\bullet10^{-6}$, $\mu_{109} = 1{,}11\bullet10^{-6}$, $\mu_{95} = 2{,}1453\bullet10^{-6}$, $\mu_{65} = 8{,}76\bullet10^{-6}$, $\mu_{120} = 9{,}99\bullet10^{-6}$, $\mu_{1312} = 900\bullet10^{-6}$, $\mu_{106} = 5{,}67\bullet10^{-6}$.

The obtained values are presented below:

$P_0 = 0{,}98601$; $P_1 = 0{,}00875$; $P_2 = 0{,}00414$; $P_3 = 0{,}00311$; $P_4 = 0{,}00032$; $P_5 = 0{,}00213095$; $P_6 = 0{,}00140$; $P_7 = 0{,}00119$; $P_8 = 0{,}00013$; $P_9 = 0{,}00105$; $P_{10} = 0{,}00053696$; $P_{11} = 0{,}00017$; $P_{12} = 0{,}00098$; $P_{13} = 0{,}00002$.

Thus, the probability of operability of all components of the base station will be $P_0 = 0{,}98601$. The probability of the base station operability with deterioration in the quality of service will be $P_1 + P_2 + P_4 + P_5 + P_6 = 0{,}01676$. The probability of the base station not performing its functions will be $P_3 + P_7 + P_8 + P_9 + P_{10} + P_{11} + P_{12} = 0{,}0072$, and the worst outcome is possible with the probability $P_{13} = 0{,}00002$.

Next, let's compare the results. The probabilities of operability of each model are shown in the diagram (Pic. 6). In the results obtained, we admit an error inherent in iterative methods for solving a system of equations.

Now let's consider how the full operability of BS will change with a change in intensity of the flow of failures $\boldsymbol{\lambda}_{01}$. The results obtained for each model are shown in Pic. 7.

Based on the results obtained, the following conclusions can be drawn:

- The model with 3 circuit groups is less reliable with a difference of 0,02 %.
- The probability of partial operability of BS is higher in the second model.
- The probability of complete BS failure in the second model is less than in the first model.
- With an increase in intensity of the flow of failures $\boldsymbol{\lambda}_{01}$ by 2 times, full operability of BS for the first model decreases by about 0,18 %, and for the second model by 0,05 %. From this we conclude that the presence of the third circuit groups reduces the probability of BS not performing its functions.

It can also be assumed that with radio coverage of neighbouring cells, the probability of operability of the entire digital radio communication network will increase.

CONCLUSIONS

The developed models are of practical value and can be used for designing railway digital radio communication networks, as well as for calculation of quality characteristics of the existing network. To improve the accuracy of calculations, the obtained values of full or partial operability can be used together with the first Erlang formula, which determines the probability of blocking calls for a given specific load and the number of channels. The product of two probabilities will represent the final result.

When using various architectures of GSM-R standard networks described in the recommendations [5], the obtained characteristics of BS operability are supposed to be used in calculating the structural reliability of the communication network. By changing the parameters of the developed model, it is possible to choose an architecture that will be cost-effective and will provide the specified operability of the digital radio communication network.

In general, it can be assumed that the emergence of new technologies and high speeds described in [15; 16] will result in the emergence of new architectures of railway communication networks and methods for calculating their operability.

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