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Mesh Network for Railways

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Abstract

The possibilities provided by the mesh telecommunication network on the railways are examined in the article. Mobile terminal radio stations located on trains are considered as repeaters and moving base radio stations for trains outside the coverage area of base stations of the network. Such a mesh network is represented both as the main communication network on railway lines equipped with an insufficient number of radio base stations and as a backup option in the event of a base station failure on one hand or a decrease in the signal-to-noise ratio at the terminal station due to a breakdown on the train on the other hand. The results of a theoretical mathematical calculation of the increase in the effective coverage area of a radio network gained from the use of mesh technology are presented. The results of modeling of the mesh network on the railroad are also presented together with the dependencies of the probability of communication from such factors as: the number of trains on the railway line, the number and range of the base stations, the range of terminal stations, the capacity of the network and the limitation on the number of retransmissions. For the case of using a mesh network as a backup option when a railway line is fully covered with base stations, the results of simulating the time of establishing a connection via a retransmission in the area of a base station failure are presented. Comparison of the possibilities provided by first-order mesh networks (with one repeater between the terminal and base stations) and more capacious (second and higher orders by the number of allowable repeaters) is presented. As a radio communication standard for mesh network modeling, the application of DMR (Digital Mobile Radio) is considered as a promising one for railway communications, requiring a small number of base stations.

Keywords: Moscow railway network, Moscow diameters; GSM-R, DMR, TETRA, railway mesh network, DMR mesh network.

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Mesh сеть для железных дорог

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Аннотация
В статье рассматриваются возможности, предоставляемые применением mesh-сети, для организации связи на железнодорожной сети. Анализируется использование комплекса терминальных станций радиосвязи, расположенных на поездах, в качестве ретрансляторов для поездов, находящихся вне зоны действия базовых станций сети связи. В статье такая mesh-сеть представлена как в качестве основной сети связи на железнодорожных линиях, оборудованных недостаточным количеством базовых станций радиосвязи, так и в качестве бэкап-опции на случай выхода из строя базовой станции на пути следования поезда либо понижения уровня сигнал/шум на терминальной станции вследствие поломки на поезде. Представлены результаты теоретического математического расчета увеличения эффективной площади покрытия радиосети от использования mesh-технологии. Также приводятся результаты моделирования mesh-сети на железной дороге и представлены зависимости вероятности установления связи от таких факторов, как: количество поездов на железнодорожной линии, количество и радиус действия базовых станций, радиус действия терминальных станций, емкость сети и ограничение по количеству ретрансляций, и др. Для случая использования mesh-сети в качестве бэкап-опции при полном покрытии базовыми станциями железнодорожной линии приведены результаты моделирования времени установления связи через ретрансляторы в зоне выхода из строя базовой станции. Приводится сравнение возможностей, предоставляемых mesh-сетями первого порядка (с одной ретрансляцией между терминальной и базовой станциями) и более емких (второго и более высоких порядков по количеству допустимых ретрансляций). В качестве стандарта радиосвязи для моделирования mesh-сети рассмотрено применение DMR (Digital Mobile Radio), как перспективного для железнодорожной связи, требующего небольшого количества базовых станций.

Ключевые слова: Московская железнодорожная сеть, Московские диаметры, GSM-R, DMR, TETRA, железнодорожная mesh сеть, DMR mesh сеть.

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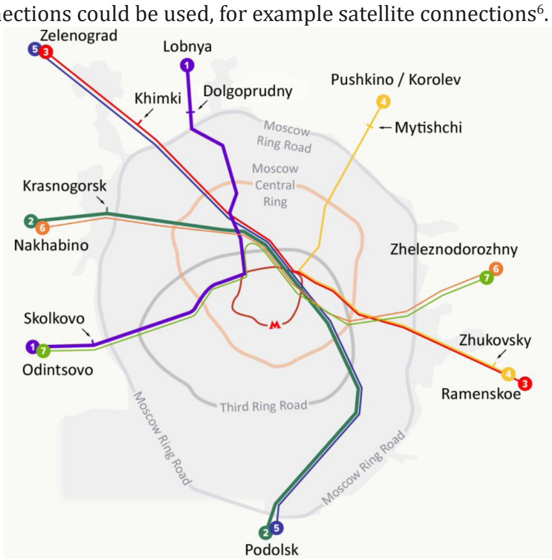
Introduction

Nowadays modern railway systems require special communication and signaling network along the train path. The onboard equipment collects data from train automation and telemechanics (GAT) and exchanges information with the central processing complex (CSC) [16]. Existing railway radio communication systems require migration to digital standards. The currently used GSM-R mobile communication standard is out-of-date and is expected to be discontinued by 2030[1] [17]. The promising modern digital radio standard DMR (Digital Mobile Radio)[2] has advantages in comparison with GSM-R, LTE and 5G[3], and is equals or exceeds the TETRA digital radio standard (depending on the frequencies used) in the base stations coverage area[4]. The DMR Level 3 specifications (Tier III – professional / industrial equipment) satisfy the requirements for maintaining the voice communication between the operator and the central complex, and have sufficient bandwidth for the transmission of GAT data. A feature of the DMR standard is the economic availability of equipment. In practice, DMR is considered as communications standard in the association of urban and suburban railway communications of the Moscow agglomeration, in the so-called Moscow diameters[5] (see Figure 1).

For communication in less densely populated regions of Russia, long-range (in comparison with GSM 2-5 generations) digital radio connections could be used, for example satellite connections[6].

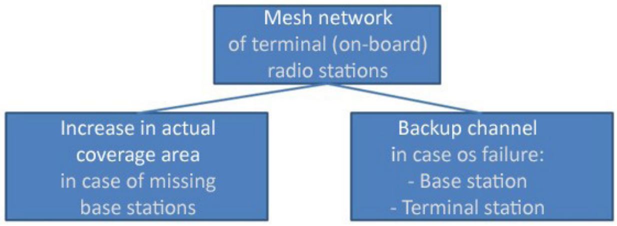


F i g. 1. Moscow railways and projected central diameters [3]

Further in this article, usage of the digital DMR radio standard or analog with a station coverage area of 10 km or more capable of supporting the terminal (on-board) radio station speed up to 500 km/h will be proposed. The communication distance between the terminal stations is assumed to be several times lower than the communication distance between the base and the terminal stations.

These parameters of digital radio system for voice and data transmission allow implementing mesh network based on fixed base stations with a large coverage area, and a set of moving terminal stations act as repeater for each other. Mesh network provides online connection out of the base stations coverage with a certain probability. This probability is a benefit in functional area of the radio system due to the mesh networks usage. On the other hand, if the railway line has 100% connection coverage directly to the base stations, then using the mesh network will restore the signal in case of base station problems (Figure 2):

- One base station failure. In this area there will be trains connecting to neighboring base stations via mesh network repeaters.
- The drop in radio power of the terminal station on a train or the occasional stop/deceleration of the train far from the base station. Trains moving in the same and opposite directions (with the normal terminal station power) will provide the communication of the broken train with the CSC.



F i g. 2. Goals of using mesh network

If the railway radio communication and signaling network is built on the basis of the DMR standard, the mesh network implementation will require a small costs increase. First of all, it is based on usage of already installed terminal stations as the repeaters. Compared with the additional base stations installations, the use of terminal repeaters is economically reasonable because of the following reasons:

- Terminal stations are easier in support, since does not require the technician's visit on a place. The train itself arrives at the

[1] EIRENE Functional Requirements Specification, Version 8.0.0. GSM-R Functional Group. UIC CODE 950. Version: 0.0.2. International Union of Railways, Paris, France, 2015. [Electronic recourse]. Available at: https://uic.org/IMG/pdf/frs-8.0.0_uic_950_0.0.2_final.pdf (accessed 12.01.2019). (In Eng.)

[2] DMR - New Radio Standard. Radioprofessional [Electronic recourse]. Available at: http://www.radioprofessional.info/dmr_new.php (accessed 12.01.2019). (In Russ.)

[3] Mottier D. How 5G technologies could benefit to the railway sector: challenges and opportunities. Mitsubishi Electric R&D Centre Europe - France. 2016. [Electronic recourse]. Available at: https://docbox.etsi.org/Workshop/2016/201611_managing_rail_mobile_comms/s03_attractiveness_future_other_techno/benefits_5g_techno_railway_sector_mottier_merce.pdf (accessed 12.01.2019). (In Eng.)

[4] Marengon R. A TETRA and DMR Comparison. MissionCritical Communications, RadioResource International. April 01, 2010. [Electronic recourse]. Available at: https://www.rrmediagroup.com/Features/FeaturesDetails/FID/174 (accessed 12.01.2019). (In Eng.); A comparison of TETRA and GSM-R for railway communications. Sepura, 2017. [Electronic recourse]. Available at: http://fplreflib.findlay.co.uk/images/pdf/tetratoday/A-comparison-of-TETRA.pdf (accessed 12.01.2019). (In Eng.); Teltronic Tetra Solutions for railway signaling applications. White papers. Teltronic, Zaragoza Spain. [Electronic recourse]. Available at: https://www.teltronic.es/wp-content/uploads/2017/06/BD170317_eng_ed2.0_White-Paper_TETRA-for-Railway-Signaling.pdf (accessed 12.01.2019). (In Eng.)

[5] All Moscow Metro lines now feature MT_FREE Wi-Fi network. Moscow Mayor official website. 30 April 2017. [Electronic recourse]. Available at: https://www.mos.ru/en/news/item/23445073 (accessed 12.01.2019). (In Eng.)

[6] Morris I. Russia's MTS: There Is No 5G Business Case. Light Reading. 3 Dec. 2017. [Electronic recourse]. Available at: http://www.lightreading.com/mobile/5g/russias-mts-there-is-no-5g-business-case/d/d-id/731347 (accessed 12.01.2019). (In Eng.)

depot – the service can be produced there serially.

- Terminal stations are installed on trains and do not require engineering and protective structures (towers, etc.)
- According to the requirements of the railway system, a 100%-coverage by the radio signal of the entire train path can be provided. In this case, the mesh network has a high economic potential as a backup technology compared to base stations duplication. In the case of an occasional train stop or the signal-to-noise ratio fall at the terminal station, mesh network will allow the most rapid receipt of a signal from the broken train away from the base stations of the system and the absence of other means of communication.

First and second level mesh network

Mobile terminal radio station located on train could connect with either base radio station directly (if located inside the coverage area of network base station) or with usage of mobile repeater (mobile terminal radio station that has connection to base directly or also using repeaters); it's a basement of considered mesh network. In case of possibility of only one repeater in the network route because of some limits or network structure features, terminal radio station with actual network connection has to be located inside base station coverage area or inside the coverage area of the mobile station placed there. This mesh network could be named "first-level mesh network". The coverage are of mobile radio station is lesser then area of base station, so mobile station used as repeater should be located near the edge of base coverage area virtually extending that. Main parameters:

B – base station coverage distance, *km.* Connection probability inside that assumed to be 100%.

b – mobile terminal (on-board) repeater station coverage distance, *km* ($b<B$). If repeater is inside the base station coverage area inside this distance connection probability assumed to be 100%. If not, connection possibility is assumed to be 0%.

L – length of the model railway, *km*

N – number of trains that could be used as repeaters in mesh network, *pc.*

If the train trying to connect the network, is outside the edge of base coverage area B in distance x, following conditions should be correct to connect through repeater located in distance i from the base (see Figure 3):

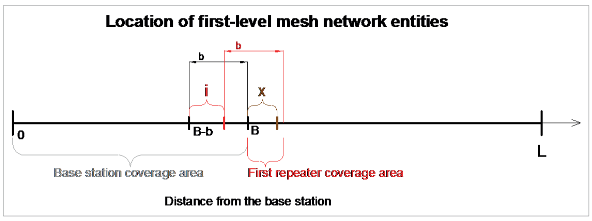


Fig. 3. The location of the base station edge B, repeater i, train x

$$\begin{cases} i<B \\ B+x<i+b \end{cases}.$$ (1) – repeater i is inside B area (2) – train x is inside i area

or:

$$B+x-b<i<B. \qquad \text{(A)}$$

Acceptable values for $x>0$ for conditions (A) are $x\in(0,b)$:

$$B+x-b<B \Rightarrow x<b$$

Probability of random $i\in(0,L)$. to be under (A) demands:

$$p_i(x)=\frac{1}{L}\int_{B+x-b}^{B} di=\frac{i}{L}\Big|_{B+x-b}^{B}=\frac{1}{L}\left[B-(B+x-b)\right]=\frac{1}{L}(b-x)$$

Probability for random i to be in contradiction with (A):

obability for all N random repeaters to be in contradiction with (A):

$$\overline{P_1}(x)=\left(\overline{p_i}(x)\right)^N=\left(1-\frac{b-x}{L}\right)^N$$

obability for at least one of N random repeaters to be under (A) demands:

$$P_1(x)=1-\overline{P_1}(x)=1-\left(1-\frac{b-x}{L}\right)^N.$$

Figure 5 shows the theoretical dependence for the probability of establishing a connection using a 1 repeater on position relative to base station edge and computer simulation of this parameter.

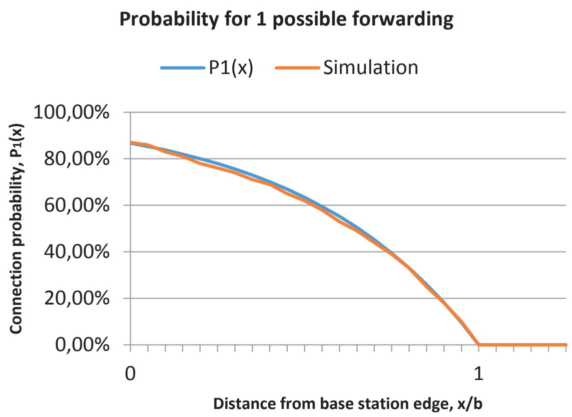


Fig. 4. Dependence for the connection probability with 1 repeater $P_1(x)$ on x (for b=10, L=500, N=100): theoretical and computer simulation

Figure 5 shows virtual base station area coverage extension because of usage first-level mesh network. Connection probability at the edges (outside base station area) is lesser 100% and depends on potential repeaters positions.

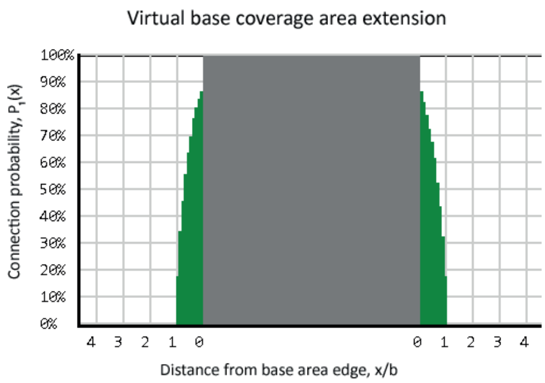


Fig. 5. Virtual base station coverage extension. Computer simulation for *b=10 km, L=500 km, N=100 pc, B=40 km* (*M=5000* cycles)

Summary probability with conditions (A) at least one of N random i with random $x \in (0, b)$. (if $x>b$ connection probability is 0, because of impossibility of achievement (A)):

$$P_1 = \frac{1}{L}\left(B + \int_{x=0}^{b} P_1(x)\,dx\right) = \frac{1}{L}\left(B + b - \int_{x=0}^{b} \overline{P_1}(x)\,dx\right)$$

Defining an additional parameter λ:

$$\lambda = \int_0^b \left(1 - \frac{b}{L} + \frac{x}{L}\right)^N dx \underset{y=1-\frac{b}{L}+\frac{x}{L}}{=} L \int_{1-\frac{b}{L}}^{1} y^N dy = \frac{L}{N+1} y^{N+1} \Big|_{1-\frac{b}{L}}^{1} = \frac{L}{N+1}\left(1 - \left(1 - \frac{b}{L}\right)^{N+1}\right) = \lambda$$

.Summary connection probability on the path L using 1 repeater:

$$P_1 = \frac{B + b - \lambda}{L} = \frac{B+b}{L} - \frac{1}{N+1}\left(1 - \left(1 - \frac{b}{L}\right)^{N+1}\right).$$

For the second-level mesh network (where up to 2 repeaters in network route could be used) 0, 1 or 2 repeaters could exist between the trains that want to connect the base station. In this case for the train in distance x from the base coverage area edge B (i.e. direct connection to the base station is impossible) for 1 or 2 retransmissions allowed connection probability can be calculated similarly to first-level mesh network:

$$P_{1,2}(x) = \begin{cases} 1 - \left(1 - \frac{b-x}{L}\right)^N \left(1 - \frac{x^2}{2L^2}\right)^{\frac{N(N-1)}{2}}, for x \in (0; b) \\ 1 - \left(1 - \frac{(2b-x)^2}{2L^2}\right)^{\frac{N(N-1)}{2}}, for x \in (b; 2b) \\ 0, e \end{cases}$$

ure 6 shows connection probability dependence on x position of a train for parameters *b=10 km, L=500 km, N=100 pc.* Blue line shows theoretical result and red line shows computer simulation.

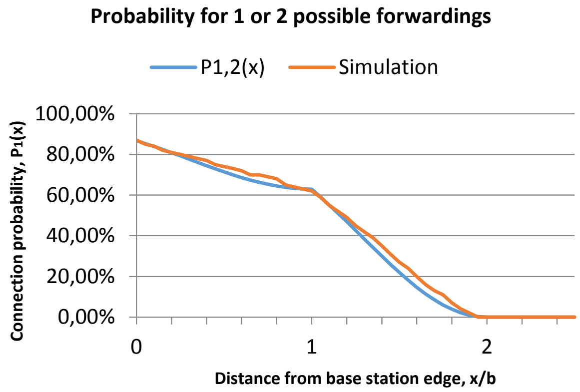


Fig. 6. Connection probability dependence for 2 and lesser retransmissions $P_{1,2}(x)$ on train position x from base coverage area for *b=10 km, L=500 km, N=100 pc*

Figure 6 shows that possibility to realize second retransmission increases the probability of establishing a connection in comparison with limiting to only one retransmission. Also second-level mesh network provide high connection probability (0-60%) on the distance more than one terminal station coverage area b from base edge (with example parameter values). Increasing number of possible retransmissions (3 and more) also increases virtual base coverage area extension; or decreases offline time in case of base station failure time for fully covered railway (that mean that mesh network will act as a backup option for the railway communication system).

Computer simulation

The estimation of the change in quality of network communication due to some mesh network methods can be performed by numerical computing for models with varying degrees of proximity to the real situation.

Basic model.

Similar to the theoretical approach, the basic model estimate the connection probability at each point of path with random positions of the repeater trains. For this purpose, the presence of a network connection at each point with a random distribution of repeaters is checked certain number of times, forming a statistical distribution.

Initial parameters for the model: the route length (*L, km*), number of trains with terminal stations on the route (*N, pc*), base station coverage distance (*B, km*), repeater coverage distance (*b, km*), the array of base positions (*{bases}*) and indirect: dimensioned analysis step (*Δx*) and number of cycles (*M*).

Total communication probability on the railway is defined as the ratio of the number of points with connection to the base (directly or using repeaters) to the total number of possible coordinate values (*L*) for randomly generated train repeaters positions. The procedure is performed a predetermined number of times for statistical results: average connection possibility on the path (*P*) and probability dependence on coordinate (*P(x)*).

Basic model 1. Two base stations

Model demonstrated basic possibilities for extending the influence of base stations distance.

Initial parameter values: the route length *L = 500 km*, base station coverage distance *B = 40 km*, repeater coverage distance *b = 10 km*, number of train repeaters *N = 120 pc*, base positions: {*167 km, 333 km*}, cycles number M=5000, analysis step *Δx = 1 km*.

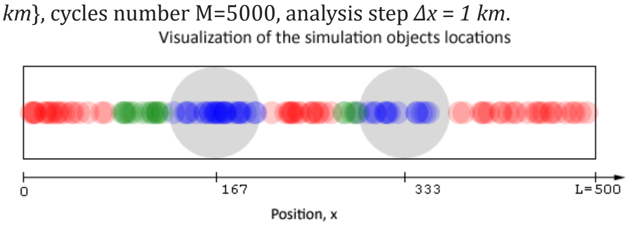


Fig. 7. One of model generated random train allocations. Gray circles are bases, blue – trains inside the base coverage (direct connections), green – with network access through repeaters, red circles – offline trains

Analysis results:

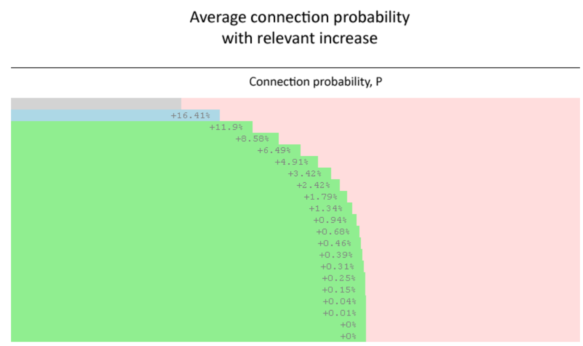
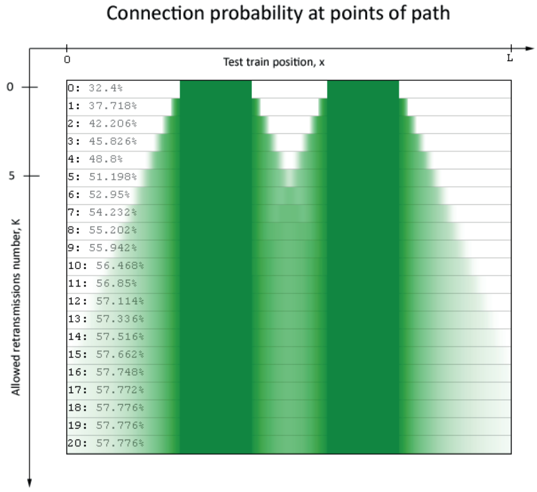


Fig. 8. Model analysis result visualization: total connection probability (*P*) depending on allowed number of retransmissions (*K, pc*). For each *K* (black bold) communication probability (black) and increase (gray) relevant to *K*-1 retransmissions are indicated.

Figure 8 demonstrates that for determined parameter values even first-level mesh network gives relevant connection probability increase 16%. The biggest win is achieved by 18-level mesh network and is more than 25%.



F i g. 9. Model analysis result visualization: total probability of connection established (*P, %*) depending on allowed number of retransmissions (*K, pc*). The intensity of the color corresponds to the probability of connection. For each *K* (black), the connection probability is shown (gray).

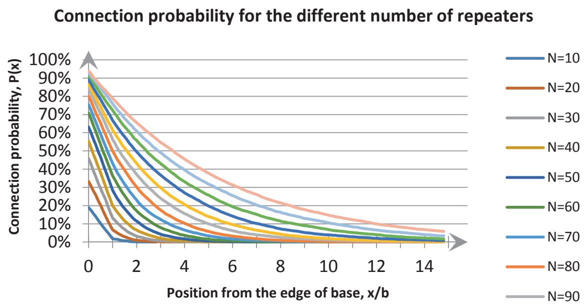
The contribution to the efficiency of communication decreases with the growth of the required number of retransmissions (the main contribution is made by 1 and 2 retransmissions), however this contribution still remains significant.

Thus, for parameter values specified in the model (a relatively large number of repeater trains on the line, not too close and not too far base stations), the initial low probability of establishing communication is greatly enhanced by using the mesh network.

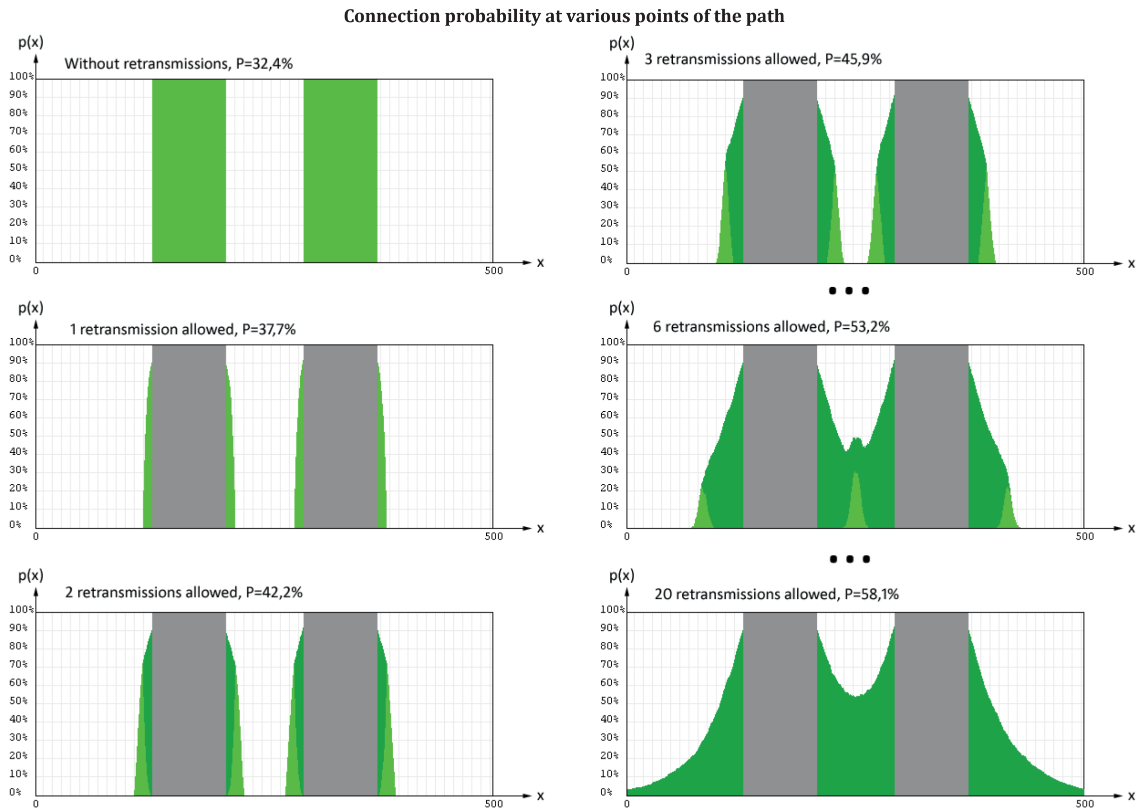
Parameter values variations

The effectiveness of the mesh network strongly depends on the initial parameters: the base station coverage distance *B*, the density of the location of the base stations on the path, the repeaters coverage distance *b* and the number of repeaters *N* on the railway.

The analysis of the model allows to explore and to evaluate some rules of such dependences (performed for the above parameters, except for the variable).



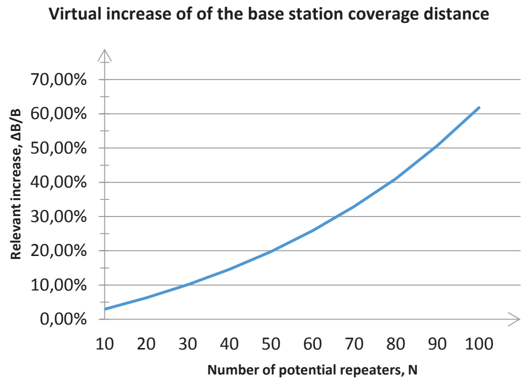
F i g. 11. Model parameter values variation analysis visualization: connection probability at each points (*P(x)*, %) for a different number of evenly distributed repeaters *N, pc*



F i g. 10. Model analysis result visualization: connection probability for each point of path (*P(x)*) depending on allowed retransmissions number (*K*). Height corresponds to connection probability; light green shows contribution to result by K-level mesh above (K-1)-level mesh network.

Efficiency of mesh network features rapidly increases with the increase in the number of repeaters N (but the growth rate slows down with this increase), especially at small distances from the base station. Therefore, the more the number of trains, the higher the expediency of using them as repeaters.

But even with a small number of repeaters, mesh network gives an increase in efficiency. The quantity characteristic of this can be an "virtual increase" of the base station coverage distance – the difference between the real diameter of the base station and the one that would be necessary to provide the probability of communication with the same level as retransmission system:



F i g. 12. Virtual the base station coverage distance increase (the coefficient of increase in the coverage distance of the base station, leading to the same change in the total probability of communication along the entire path)

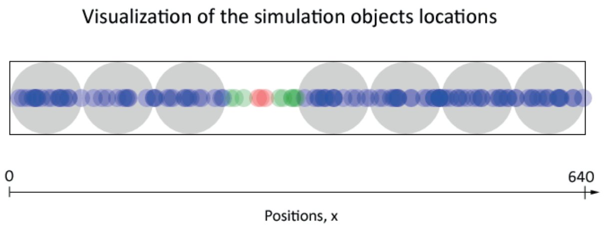
Even with the moderate number of repeaters (less than *30*) retransmission system leads to the same result of the final probability of communication along the entire path, as if the range of base stations increased by 4-10% (or the number of base stations increased by the corresponding number).

Relative increase of connection probability using the repeaters decreases with base stations number increase. Each base station acts as a reference for the retransmission chain, but simultaneously increases the initial value for direct connection to the base station, creating a higher base for estimating the relative increment. In addition, if the bases are located close to each other, only part of the space potentially improved by retransmissions will be included in their effectiveness: the rest positions will be in direct connection with the base station.

Basic model 2. Missing base/failure of the base station.

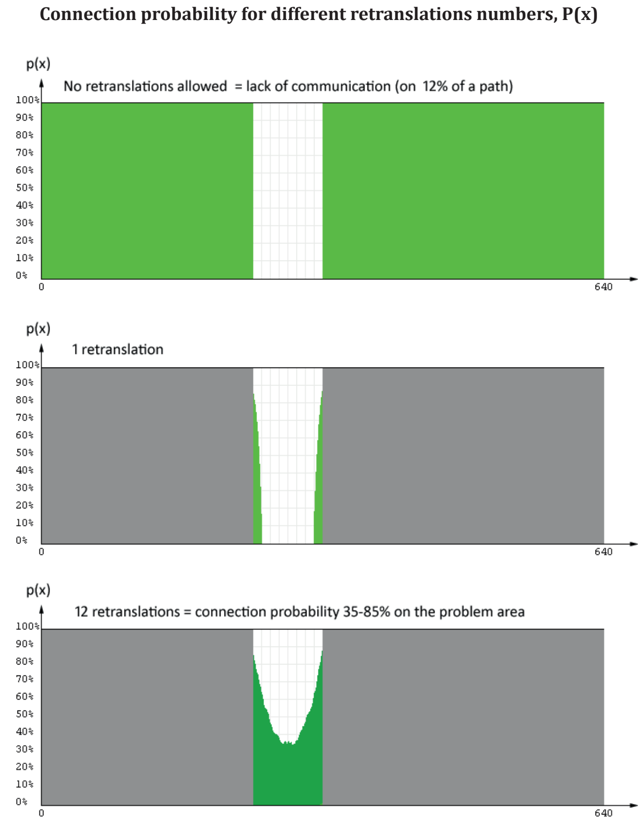
The model demonstrates main possibilities of establishing connection when one base station fails.

Initial parameter values: the route length $L = 640$ *km*, base station coverage distance $B = 40$ *km*, repeater coverage distance $b = 10$ *km*, number of train repeaters $N = 120$ *pc*, base positions: {*40, 120, 200, 360, 440, 520, 600 km*}, cycles number M=5000, analysis step $\Delta x = 1$ *km*.



F i g. 13. One of model generated random train allocations. Gray circles are bases, blue – trains inside the base coverage (direct connections), green – with network access through repeaters, red circles – offline trains.

Analysis results:



F i g. 14. Model analysis result visualization: connection probability at each path point ($P(x)$): without retransmissions, with 1 retransmission allowed and with an unlimited number of allowable retransmissions

In defined model conditions retransmission system on the "problem" area provides at least 35% of the probability of establishing a connection (on average – in 51.6% cases). That means that the connection is partially restored on site: on average half the time the train in the zone of the missed base station network will be online. Surely, this does not replace the guaranteed availability of connection (since it relies on random positions of trains), but the mesh network system can act as a backup communication system in the event of a failure of the base station.

More realistic model

The simulation model with trains moving along the railway between stations provides an analysis of their radio communication with the base stations (directly or via repeaters) at various times. These trains move according to a timetable based on a real one (making stops of different duration at intermediate stations), and all types of trains are taken into account: long-distance trains that pass way in whole or in part, as well as suburban electric trains. The analysis is performed in 24 hours.

The basic analysis of realistic model is carried out similarly to the basic model, but the distribution of repeaters is no longer randomly, but corresponds to the schedule embedded in the simulation for each time point of the considered interval. Additionally, for each train, the time it was online using mesh network system and direct connection with the base station time is compared.

This model based on the main Oktyabrskaya railway system route (Moscow-St. Petersburg) with a length of 650 km as an example.

The coordinates of the base stations (their distance from the end points) are selected in accordance with the really existing large railway stations.
The initial parameters: the analyzed length is $L = 650$ *km*, the base station coverage distance is $B = 40$ *km*, the coverage distance of the repeater is $b = 10$ *km*, the coordinates of the base stations are $\{0, 167, 209, 331, 532, 650$ *km*$\}$, the number of simulation cycles $M = 5000$, distance computation step: *1 km*, time step is: *1 min*.

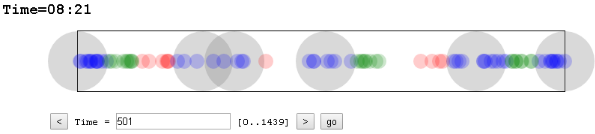


Fig. 15. Model visualization example. The black border corresponds to the railway (*0 .. L=650 km*). Gray circles are bases, blue – trains inside the base coverage (direct connections), green – with network access through repeaters, red circles – offline trains

Train schedule.
The actual schedule for one of the days (01/09/2018) was chosen as the initial data of train dispositions. From public sources, model schedule was created for all passenger trains passing at least part of the way. The control points are station arrival and departure times for each train. Between the stations trains assumed to move uniformly within the model, that is, at a constant speed (including the passage of intermediate stations without stop).

Train	Moscow *0 km*	Tver *167 km*		V.Volochek *286 km*		Bologoe M *331 km*		Uglovka *381 km*	
	dep.	arr.	dep.	arr.	dep.	arr.	dep.	arr.	dep.
116C	0:10	2:05	2:07	3:20	3:22	3:54	3:55		
020U Megapolis	0:20	2:13	2:15						
016A «Arctic»	0:41	2:29	2:31	3:43	3:45	4:15	4:40		
060*G «Volga»	0:44	2:37	2:39	4:23	4:25				
030A	1:15	3:01	3:03	4:14	4:16	4:47	4:48	5:26	5:27
128A	1:25								
062A	1:53	3:42	3:44			5:20	5:32		

Fig. 16. Example part of model used train schedule with the stations (and their positions), arrival and departure time for each train, that acts as a repeater

Several types of trains on the railway, acting as repeaters were considered (only a part of them are on the way at the same time):

- long-distance trains running the full path from start to finish – 94 pc (average amount on the railway is about 28 pieces at the same time);
- long-distance trains passing only part of the way – 41 pc (average amount on the railway is about 10 pieces at a time);
- electric trains (local trains) – 312 pc (average amount on the railway is about 18 pieces at a time).
- Further by default results for all types of trains are given.

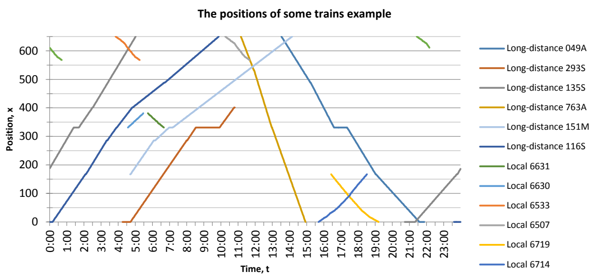


Fig. 17. Model positions in time visualization for some typical trains: full-path long-distance trains, part-path long-distance trains and regional local trains (in different directions; some of them with long-term staying on intermediate stations)

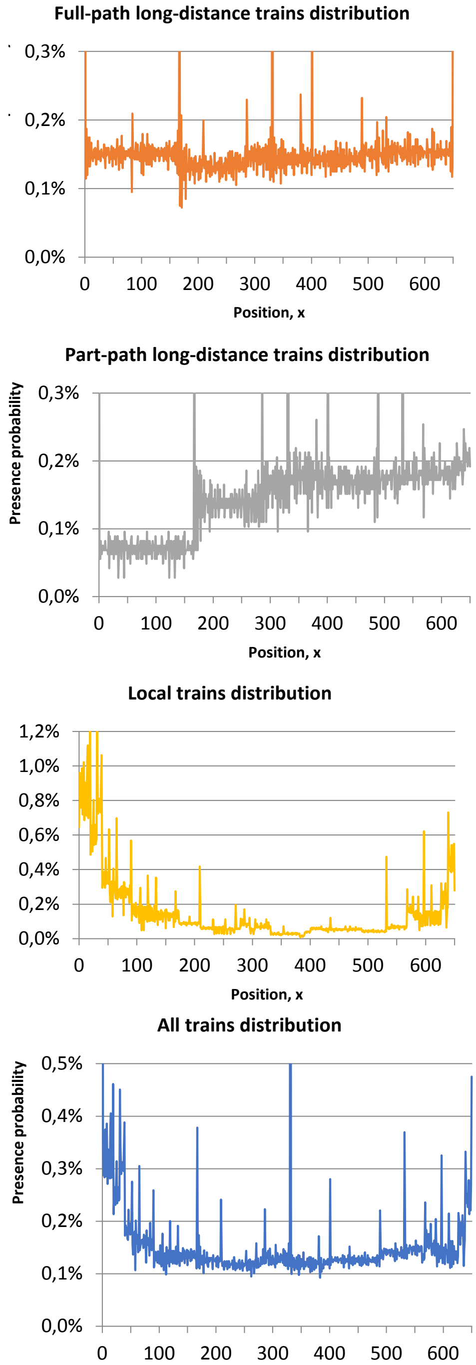
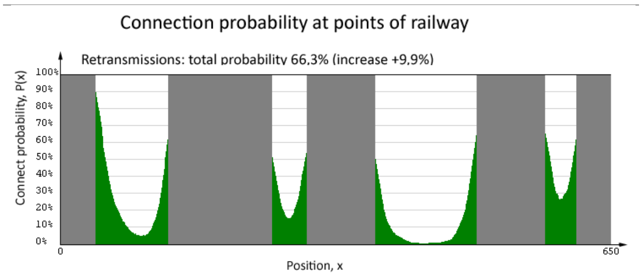
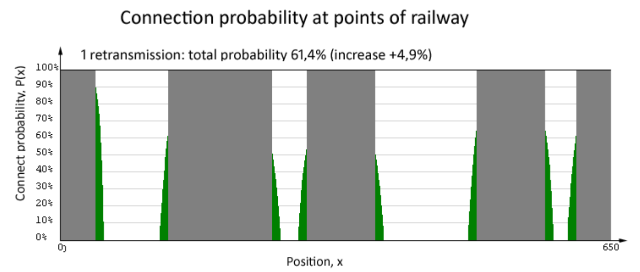


Fig. 18. Trains distribution: probability to find a train of a certain type at random time at all positions

The Figure 19 shows that realistic distributions contain peaks of probability (corresponding to the stations on which the trains are staying for a long time; that fact reduces the efficiency of retransmissions). But also their distribution differs from the uniform: only long-distance trains running all the way from the initial to the final point are relatively close to a equable distribution.
So, the conclusions of the basic models are limited and applicable to reality only qualitatively. Obviously further refinement of the motion models (for example, including to train schedule intermediate stations on which the trains do not stop, and therefore the corresponding data are not available for public access) will allow a more qualitative analysis for the situation closer to the real.
Analysis results:



F i g. 19. Probability of the connection establishment (averaged over time) for each point of the way. Gray indicates direct communication with the base station; green – through the retransmissions chain.

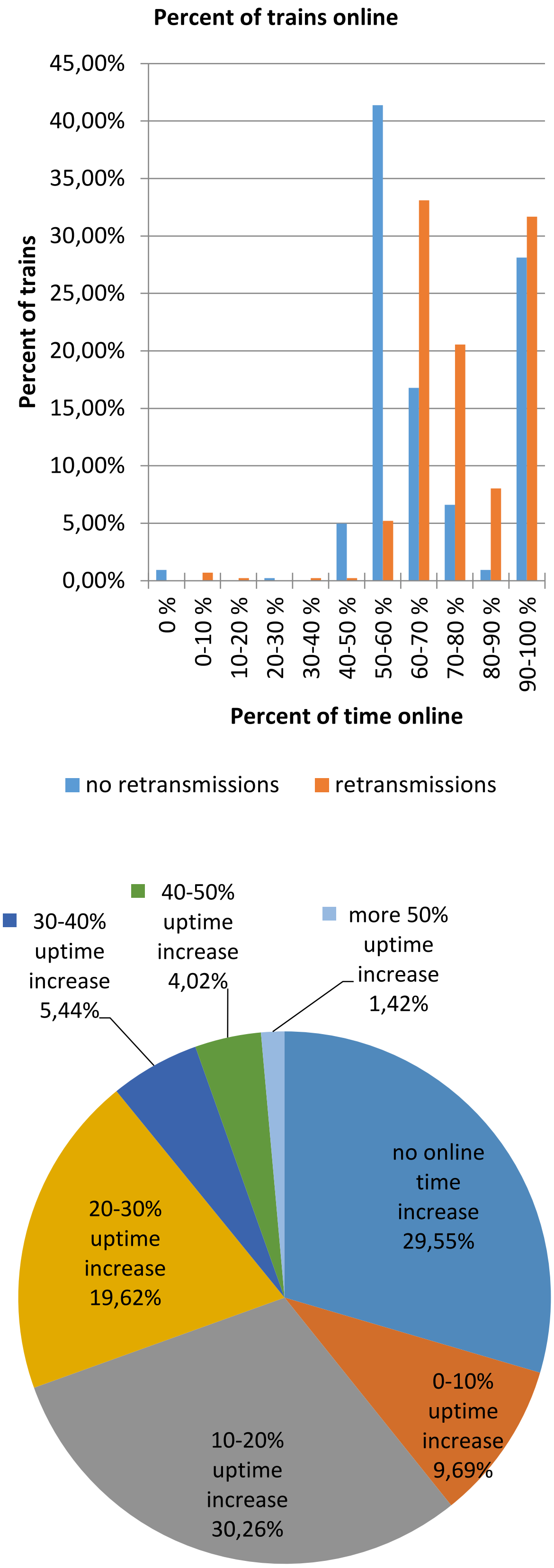


F i g. 20. Probability of the connection establishment (averaged over time) for each point of the way. Gray indicates direct communication with the base station; green – through 1 retransmission

Realistic model results comparable with basic models: the increase in the connection probability on the path due to retransmission system is approximately 10% (of which about half is provided by 1 retransmission).
The presence of defined moving trains and the timetable for their movement in the model makes possible to estimate an important parameter: the additional time that the train is on (potential) communication with base stations due to retransmissions and compare it with such time without them.
Within the model, the average online time increase for all trains is 14.8% due to mesh network, while:

- for 30% trains there is no increase;
- for 30% trains online time increased by 10-20%;
- for 20% more trains - 20-30%;
- for 10% more trains - by 10%.

Thus, mesh network features can give a significant increase in the time at which many trains on the railway are online in the network.



F i g. 21. Efficiency of retransmissions: increasing the proportion of time online

Model limitations:

- One-dimensional linear motion.
  The model considers the only one variable coordinate of the repeater on a straight line path, and also considers linear changing of it (the reference railway is really quite straightforward on a large scale, but generally speaking, the railways are two-dimensional at least and could have even three dimensions when passing a terrain with a large difference in altitude). In some cases, taking into account the nonlinearity of the path could force to increase/decrease results, since the movement along the straight line corresponds to the maximum rapid removal and earlier exit from the base station coverage, but also does not take into account the additional different disturbances.
- Simplified trajectories of the trains: even movement (no change in speed except stations) and deterministic (without occasional deviations from the schedule).
- Not taken into account obstacles and interference, as well as the direction diagram of the signal source (that leads to indeterminate actual boundaries of the coverage area of the stations, determined by an acceptable signal-to-noise ratio).
- The really used equipment of base stations and repeaters and their practical coverage distance and other characteristics are not discussed.
- The location of the base stations is largely arbitrary (even in realistic model), since the purpose is to demonstrate the principal opportunities for improving communication by retransmitting mesh networks. In particular, it is possible to provide a complete network connection on the railway, when only the reserve channel function remains for retransmissions.

Possible further modifications.

For a deeper exploring of the mesh network capabilities for railways, or to analyze the practical possibilities for certain cases, further model changes are possible in order to improve accuracy:

- More detailed train schedule (intermediate stations without stay, other control points).
- Accounting for irregularities in the movement (random deviations from the schedule).
- Random deviations of the coverage distances of base stations and repeaters (or probability distribution depending on remoteness).

Also important possibility is to transfer packages offline: via repeaters, which are not currently in communication, but are waiting for it in the near future. This may be relevant for the transmission of GAT data, for example, in the areas of failure of the network infrastructure.

Conclusions.

The presented theoretical and simulation-based results allow predicting efficiency increase for railway radio communication network due to the implementation of the mesh network features.

Mesh network allow restoring communication in the areas of the base station failure or in the case when a train suddenly stops out of direct connection with the base station for any reason. In this case, the neighboring repeater-train will help to establish the connection of the train with the CSC.

Also mesh network significantly increases the functional coverage of base stations (from 10% and higher), wherein the additional costs of implementing a mesh network features may be minimal (depending on the digital radio standard used).

Mesh network could become a way to solve some typical problems of data transmission of GAT related to linear or ring circuits.

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