SIR DISTRIBUTION IN D2D ENVIRONMENT WITH NON-STATIONARY MOBILITY OF USERS

Sergey Fedorov*, Yurii Orlov*†, Andrey Samuylov†‡, Dmitri Moltchanov†‡, Yuliya Gaidamaka†§, Konstantin Samouylov†§, Sergey Shorgin§

*Deparment of Kinetic Equations
Keldysh Institute of Applied Mathematics
Miusskaya Sq. 4, Moscow, 125047, Russian Federation
fyodor-on@mail.ru, ov3159f@yandex.ru

†Department of Applied Probability and Informatics
Peoples' Friendship University of Russia (RUDN University)
Miklukho-Maklaya St 6, Moscow, 117198, Russian Federation
ov3159f@yandex.ru, {samuylov_ak, molchanov_da, gaydamaka_yuv, samuylov_ke}@rudn.university

‡Department of Electronics and Communications Engineering
Tampere University of Technology
Korkeakoulunkatu 10, Tampere, 33720, Finland
{andrey.samuylov, dmitri.moltchanov}@tut.fi

§Institute of Informatics Problems, Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences
Vavilova st. 44-2, Moscow, 119333, Russian Federation
{gaydamaka_yuv, samuylov_ke}@rudn.university, sshorgin@ipiran.ru

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ABSTRACT

Fifth generation (5G) cellular systems are expected to rely on the set of advanced networking techniques to further enhance the spatial frequency reuse. Device-to-device (D2D) communications is one of them allowing users to establish opportunitic direct connections. The use of direct communications is primarily determined by the signal-to-interference ratio (SIR). However, depending on the users movement, the SIR of an ative connection is expected to drastically fluctuate. In this work we develop an analytical framework allowing to predict the channel quality between two moving entities in a filed of moving interfering stations. Assuming users movement driven by Fokker-Planck equation we obtain the empirical probability density function of SIR. The proposed methodology can be used to solve problems in the area of stochastic control of D2D communications in cellular networks.

INTRODUCTION

The need for higher capacity at the air interface in next generation mobile cellular systems calls for efficient ways of utilizing available frequency bands. Together with widening the bands itselves by moving upper in the frequency band to millimeter wave spectrum, one of the trends nowadays is developing of new techniques improving the use of available spectrum, e.g., increasing the base stations density via using the micro-, pico- and femto-cells, and enabling user devices to communicate directly with one another by establishing direct device-to-device (D2D) connections. The latter is the focus of this work.

The contemprorary cellular systems, such as GSM and LTE, are interference-limited in anture, implying that the link quality between two nodes highly depends on other nearby nodes using the same frequency, as their signal will literally interfere with the link of interest. As a result, the critical metric of interest for such systems characterizing the link quality is the signal-to-interference (SIR) ratio. A given level of SIR upper bounds the maximum capacity of a link. Furthermore, whenever SIR downcrosses some threshold it becomes impossible to maintain stable connection.

In this paper, we study the evolution of SIR for a pair of devices as a function of mobility, assuming that all the devices, including those of interest and interfering ones, are mobile. We formulate the framework that enables us to describe the analytical properties of SIR as a function of movement trajectories.

The proposed methodology not only forms the basis for analysis of statistical properties of SIR but potentially allows for stochastic control SIR functional. The future cellular system may contain advanced functionality of advising users to move in a certain derection to improve the channel quality. In this case, the framework offers the prossibility of functional modeling on the moving bodies trajectories. The case when the trajectories depend on the functional is of particular interest.

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GENERATING TRAJECTORIES OF NON-STATIONARY RANDOM WALKS

Consider a process with a non-stationary probability distribution function (pdf) and a given evolution equation. The method for generating a trajectory of the random process with thse properties has been proposed in (Bosov et al. 2014). In (Orlov 2014, Orlov and Fedorov 2016) it has been extended to generating an trajectories, whose pdf is evolving according to a given kinetic equation. The software tool for generating an ensemble of random non-stationary trajectories and performing their statistical analysis has been introduced in (Orlov and Fedorov 2016, Fedorov and Orlov, 2016). Below, we describe the key points of the developed methodology.

Let pdf $f(x,t)$ be defined by a kinetic equation. Consider the Fokker-Plank equation,

$$\frac{\partial f}{\partial t}+\frac{\partial}{\partial x}(u(x,t)f)-\frac{\lambda(t)}{2}\frac{\partial^2 f}{\partial x^2}=0. \quad (1)$$

This equation can be solved numerically for a given initial condition,

$$f(x,t)|_{t=0}=\rho(x).$$

The solution of (1) is based on the time horizon T. For the sake of simplicity, choose a unit time step. At each time instant $t=1,2,\ldots,T$ a random number is generated from the cumulative distribution function (CDF)

$$F(x,t)=\int_0^x f(y,t)dy. \quad (2)$$

When the solution of (1) is represented as a histogram $f_j(t)$, where j is the number of class intervals, the continuous strictly monotonic CDF has the form

$$F(x,t)=(nx-j)\cdot f_{j+1}(t)+\sum_{k=1}^{j} f_k(t), \quad (3)$$

for $x\in[(j-1)/n;\, j/n]$, $j=1,..,n$.

The algorithm for generating a sequence of random numbers, forming a feasible trajectory of the time series for a predetermined time interval is as follows. First, generate a series of random numbers, $\{y_k\}$, of length T having uniform distribution in $[0,1]$. The series with CDF $F(x,t)$ is obtained by combining the numerical inverse transform method with sliding window of length T, that is,

$$y_k=F_N(x_k,k). \quad (4)$$

Generating a set of samples, we obtain the set of trajectories that can be considered as an ensemble of solutions of the kinetic equation.

STATISTICAL ANALYSIS OF FUNCTIONAL ON THE ENSEMBLE OF TRAJECTORIES

Consider SIR functional defined as a function of the distance between the moving points. The positions of these points form an ensemble of trajectories of a random process. Let x_i^α be a position of point i in a certain region of a three-dimensional space, where the superscript α labels (x,y,z) coordinates . The number of points in the system is $N+2$. Let also r_{ij} be the distance between the points, calculated in the Cartesian coordinate system as

$$r_{ij}^2=\sum_{\alpha=1}^{3}(x_i^\alpha-x_j^\alpha)^2. \quad (5)$$

Let $\varphi_{ij}=\varphi(r_{ij})$ be an arbitrary transformation function of distance between two points i and j. Consider the SIR functional (Hesham ElSawy et al. 2014, Samuylov et al. 2015, Gaidamaka et al. 2016) between a pair of points, for example 1 and 2, where 1 stands for the receiver of interest, and 2 is the corresponding transmitter,

$$S(\mathbf{r}_1,\mathbf{r}_2)=\frac{\varphi_{12}}{\sum_{j=3}^{N+2}\varphi_{1j}}. \quad (6)$$

Here $\mathbf{r}_i$ is the vector of i point coordinates.

The sum in the denominator of (6) can replaced by the product of N means of the transformation function,

$$U(\mathbf{r}_1)=\int_V \varphi(|\mathbf{r}_1-\mathbf{r}'|)\rho(\mathbf{r}')d\mathbf{r}', \quad (7)\text{rr}$$

where $\rho(\mathbf{r}')$ is the pdf of the spatial distribution of the remaining N points in area V. For convenience, denote $\mathbf{r}=\mathbf{r}_{12}$ and $r=|\mathbf{r}|$. Then SIR in (6) can be written as

$$S=S(r)=\frac{\varphi(r)}{NU(r)}. \quad (8)$$

Consider only those $\rho(r)$, for which (8) is monotonous. In this case, the pdf of S is written as

$$g(S)=[S^{-1}(r)]'\rho(S^{-1}(r)). \quad (9)$$

Assume that φ is monotonous and bounded, e.g.,

$$\varphi(r)=1/(r^2+a^2),\ a>0. \quad (10)$$

Let V be a three-dimensional unit sphere, and points be uniformly distyributed in V. Then, (8) is monotonous. In this case, $U(r)$ in (8) is obtained in closed from,

$$U(r)= \\ =\frac{3a}{r}\left(arctg\frac{r}{a}+\frac{1}{2}\left(arctg\frac{1-r}{a}-arctg\frac{1+r}{a}\right)\right)- \\ -\frac{3}{4r}\ln\left(\frac{(1-r)^2+a^2}{(1+r)^2+a^2}\right). \quad (11)$$

Non-monotonous link distances $\rho(\mathbf{r}')$ may lead to non-monotonous behaviour of (8). This happens when the movement of points in V is not stationary and, thus, does not result in stationary distribution of points in V. In this case, we should analyze the dynamic change of (8) when density $\rho(\mathbf{r}')$ varies in time. In practice, we assume that the distribution of points changes over time according to the kinetic equation (1) with respect to pdf $f(r,t)$. Specific samples of points forming trajectories

of non-stationary random walk process are obtained using (4) based on the solution of kinetic equation on a given time horizon.
The average interference at r is determined by

$$U(r,t)=\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)f(\mathbf{r}',t)d\mathbf{r}' . \qquad (12)$$

The communication between these transmitter and receiver of interest shall now be studied directly using (12). We emphasize that (1) is written with respect to the pdf of the increments of coordinates, so that the trajectory of the i-th point is the trajectory of the total random increment $x_i(t)$. This allows to easily specify an arbitrary random trajectory for the functional *S*.
The average value of the SIR is given by,

$$s(t)=\frac{1}{N}\int \frac{\varphi(r)}{U(r,t)} f(r,t)dr . \qquad (13)$$

Below, we obtain time-series with arbitrary (in general) non-stationary distribution function.

EVOLUTION EQUATION FOR AVERAGE SIR

The evolution equation for mean SIR in (13) is given by

$$N\frac{ds}{dt}=\int_V \frac{\varphi(r)}{U(r,t)}\frac{\partial f(r,t)}{\partial t}d^3r - \int_V \frac{\varphi(r)}{U^2(r,t)}\frac{\partial U(r,t)}{\partial t} f(r,t)d^3r . \qquad (14)$$

We assume that the pdf is zero at the boundary of *V*. The second term in the right part of (14) after substituting the derivative for $\frac{\partial f}{\partial t}$ from (1) and taking into account the expression (12) is represented in the form

$$-\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)}\frac{\partial U(\mathbf{r},t)}{\partial t} f(\mathbf{r},t)d\mathbf{r} =$$

$$=-\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)}\left(\frac{\partial}{\partial t}\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)f(\mathbf{r}',t)d\mathbf{r}'\right) f(\mathbf{r},t)d\mathbf{r} =$$

$$=-\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)}\left(\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)\frac{\partial}{\partial t} f(\mathbf{r}',t)d\mathbf{r}'\right) f(\mathbf{r},t)d\mathbf{r} =$$

$$=-\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)}\left(\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)\cdot \right.$$

$$\left.\cdot\left(-div_{\mathbf{r}'}(\mathbf{u}(\mathbf{r}',t)f(\mathbf{r}',t))+\frac{\lambda(t)}{2}\Delta_{\mathbf{r}'}f(\mathbf{r}',t)\right)d\mathbf{r}'\right) f(\mathbf{r},t)d\mathbf{r}.$$

After integration by parts with taking into account that the boundary probability flow is equal to zero, the first internal integral in the last expression has the form

$$\int_V\left(\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)\left(div_{\mathbf{r}'}(\mathbf{u}(\mathbf{r}',t)f(\mathbf{r}',t))\right)d\mathbf{r}'\right)\cdot$$

$$\cdot\frac{\varphi(r)}{U^2(\mathbf{r},t)} f(\mathbf{r},t)d\mathbf{r} =$$

$$=-\int_V\left(\int_V f(\mathbf{r}',t)\mathbf{u}(\mathbf{r}',t)grad_{\mathbf{r}'}\varphi(|\mathbf{r}-\mathbf{r}'|)d\mathbf{r}'\right)\cdot$$

$$\cdot\frac{\varphi(r)}{U^2(\mathbf{r},t)} f(\mathbf{r},t)d\mathbf{r} =$$

$$=\int_V\left(\int_V f(\mathbf{r}',t)\mathbf{u}(\mathbf{r}',t)grad_{\mathbf{r}}\varphi(|\mathbf{r}-\mathbf{r}'|)d\mathbf{r}'\right)\cdot$$

$$\cdot\frac{\varphi(r)}{U^2(\mathbf{r},t)} f(\mathbf{r},t)d\mathbf{r} =$$

$$=\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)} div_{\mathbf{r}}\left(\int_V f(\mathbf{r}',t)\mathbf{u}(\mathbf{r}',t)\varphi(|\mathbf{r}-\mathbf{r}'|)d\mathbf{r}'\right) f(\mathbf{r},t)d\mathbf{r} =$$

$$=\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)} f(\mathbf{r},t)div_{\mathbf{r}}J(\mathbf{r},t)d\mathbf{r},$$

where

$$\mathbf{J}(\mathbf{r},t)=\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)\mathbf{u}(\mathbf{r}',t)f(\mathbf{r}',t)d^3r' .$$

We assume, that all integrals uniformly converge by $\mathbf{r}$ and *t*, which means that the negative signs can be taken out. In the same way we get

$$-\frac{\lambda(t)}{2}\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)}\left(\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)\left(\Delta_{\mathbf{r}'}f(\mathbf{r}',t)\right)d\mathbf{r}'\right) f(\mathbf{r},t)d\mathbf{r} =$$

$$=-\frac{\lambda(t)}{2}\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)} f(\mathbf{r},t)\Delta_{\mathbf{r}}\left(\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)f(\mathbf{r}',t)d\mathbf{r}'\right)d\mathbf{r} =$$

$$=-\frac{\lambda(t)}{2}\int_V \frac{\varphi(r)}{U^2(\mathbf{r},t)} f(\mathbf{r},t)\Delta_{\mathbf{r}}U(\mathbf{r},t)d\mathbf{r},$$

so that finally we have

$$\frac{\partial U}{\partial t}=\frac{\lambda}{2}\Delta U - div\mathbf{J}, \qquad \mathbf{J}=\int_V \varphi(|\mathbf{r}-\mathbf{r}'|)\mathbf{u}(\mathbf{r}',t)f(\mathbf{r}',t)d^3r' . \qquad (15)$$

This means that the mean interference changes over time in the same way as its pdf, i.e., according to the diffusion equation with the same ratio as in (1).
Next, applying (1) to the first term in (14) we get

$$\int_V \frac{\varphi(r)}{U(r,t)}\frac{\partial f(r,t)}{\partial t}d^3r =$$

$$=-\int_V \frac{\varphi(r)}{U(r,t)} div(\mathbf{u}f)d^3r+\frac{\lambda}{2}\int_V \frac{\varphi(r)}{U(r,t)}\Delta f d^3r .$$

After integrating by parts we obtain

$$\int_V \frac{\varphi}{U}\frac{\partial f}{\partial t}d^3r=\int_V f\cdot\left(\mathbf{u}\nabla+\frac{\lambda}{2}\Delta\right)\left(\frac{\varphi}{U}\right)d^3r .$$

As a result, (14) takes the following form

$$N\frac{ds}{dt}=\int_V\left(\left(\mathbf{u}\nabla+\frac{\lambda}{2}\Delta\right)\left(\frac{\varphi}{U}\right)\right)f(r,t)d^3r - \int_V \frac{\varphi}{U^2}\left(\frac{\lambda}{2}\Delta U - div\mathbf{J}\right)f(r,t)d^3r . \qquad (16)$$

The latter equation is non-linear with respect to the density of the ensemble of sample trajectories and cannot be solved in closed-form. However, the structure of (16) scheds the light on various properties of SIR. The term $\mathbf{u}\nabla(\varphi/U)$ represents the influence of drift in the Fokker-Planck equation (1) on variance of SIR, and the term $(\varphi/U^2)div\mathbf{J}$ affects the mean SIR $U(r,t)$. These terms have different signes, so the total transport effect of the drift $\mathbf{u}\nabla(\varphi/U)+(\varphi/U^2)div\mathbf{J}$ after integration with density $f(r,t)$ is negligible in some situations, that can be reffered to as "zero SIR flow". This phenomenon is observed when the scalar product of drift and radius-vector $\mathbf{ur}$ is zero. In this case, SIR variance is due to diffusion effect only. However, in practice, such ideal situations are rarely observed. The reason is that for realistic environments such as malls, stadiums, etc., there is always a non-zero time-dependent drift, corresponding to, e.g., lunch breaks, other intermissions, when human flow changes. In this cases numerical simulations are of special importance.

SIMULATION OF THE SIR DISTRIBUTION

In this section we provide a numerical illustrations, showing the dependence of SIR on mobility parameters. In our statistical experiment we generate a set of time series, for which the sampling density in the window of T=1000 steps evolves on the horizon T from red curve to green curve. This evolution is depicted on Fig. 1. The red curve is the initial pdf in (1) and the green curve is its position after 1000 time steps for given drift $u(x,t)$ and diffusion $\lambda(t)$ functions. The pdfs have similar shape, but the quantitative difference is greater than the average difference between finite stationary samples of the same length. This difference is attributed to the effects of non-stationarity.

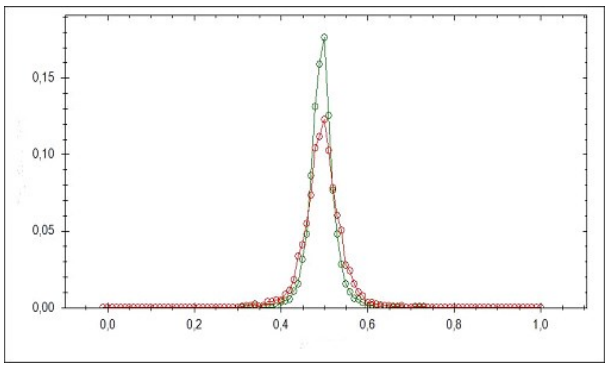

Fig. 1. Initial and final pdfs of coordinates increments.

Further, following the method of modeling of random trajectories in (4), we generated 1000 samples for each of the three dimensions in a cube with a side of 10 and perfectly reflecting boundaries. The resulting set of trajectories is interpreted as the movement path of points for witch we compute the SIR, using the function $\varphi(r)=1/(r^2+a^2)$. with $a=0{,}02$. A non-zero parameter a in this formula corresponds to the minimum distance between communicating nodes.

The SIR time series for this model are shown in Fig. 2. Here, horizontal axis represents the modeling time. As one may observe, approximately 80% of SIR values, presented on the vertical axis, are less than 0.2. At the same time, occasionally, there are extremely large outliners corresponding to extremely good spatial locations of nodes.

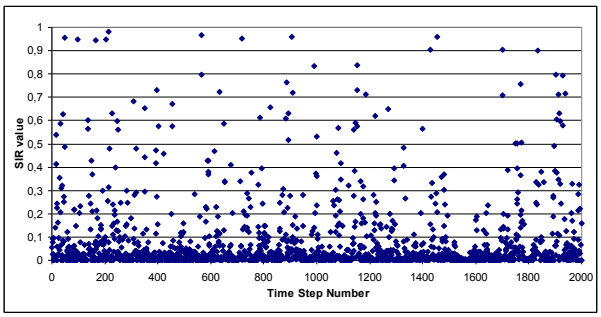

Fig. 2. SIR time series simulation.

Fig. 3 shows theSIR pdf for different values of diffusion and zero drift. For the sake of visualization, we show only the values that are less than 0.8. As parameter λ increases, the sample pdf of SIR shifts upwards, which means a shift toward lower values of SIR.

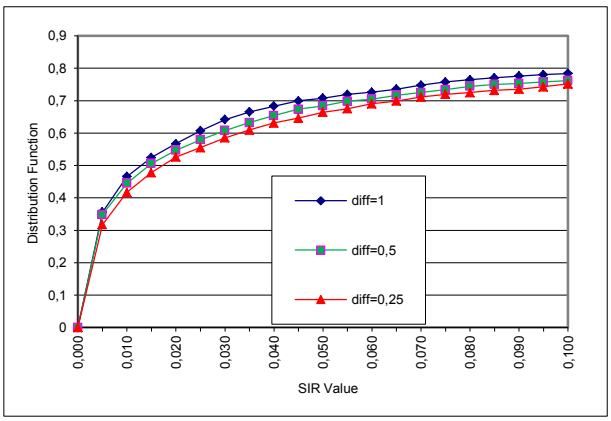

Fig. 3. SIR distribution as a function of the diffusion parameter $\lambda/2$ and zero drift speed.

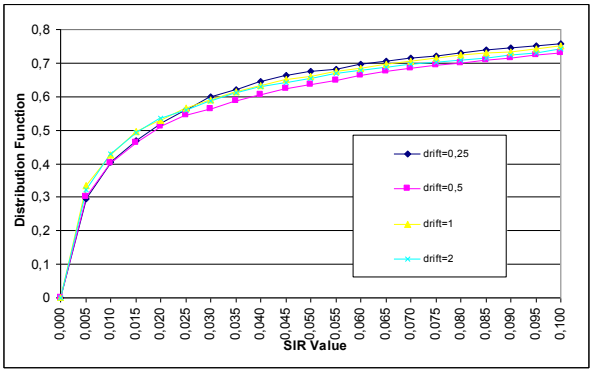

Fig. 4. The SIR distribution as a function of drift with zero diffusion.

Varying the drift speed shows another effect, illustrated in Fig. 4. One may observe the periodic dependence of sample pdf on the drift speed.

CONCLUSION

In this paper we have analyzed interference and SIR for D2D deployment as a function of random movement of nodes. We have first demonstrated that these metrics can be obtained in closed-form when the underlying mobility of users is a stationary. Further, assuming non-stationary movement of users, we have obtained kinetic equation representation of SIR showing that it cannot be solved in closed-form.

To obtain SIR properties we have debeloped a numerical simulsation methodology. In the provided numerical example we had shown that non-stationarty results in fundamentally different distributions of SIR compared to the stationary case. The resulting pdf is highly sensitive to the drift and diffusion coefficient that are used to represent the motion of users.

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AUTHOR BIOGRAPHIES

SERGEY L. FEDOROV was born in Moscow, Russia and went to the Moscow Institute of Physics and Technology, where he studied computer science and mathematical modeling. He worked for a three years in Dorodnitsyn Computing Centre of RAS and after that three years in Keldysh Institute of Applied Mathematics of RAS. His specialty is the mathematical modeling, and numerical methods in the field of simulation of non-stationary stochastic processes, images recognition and kinetic equations investigation. His e-mail address is: fyodor-on@mail.ru

YURII N. ORLOV was born in Mytischy, Moscow region, Russia and at 1987 finished the Moscow Institute of Physics and Technology, where he studied statistical physics and kinetic theory. After post-graduation at the Keldysh Institute of Applied Mathematics he obtained the Cand.Sc. degree in 1992 and doctor degree on mathematical physics in 2007. His interests area belongs to non-stationary stochastic processes and time-series. His e-mail address is: ov3159f@yandex.ru.

ANDREY SAMUYLOV received the Ms.C. in Applied Mathematics and Cand.Sc. in Physics and Mathematics from the RUDN University, Russia, in 2012 and 2015, respectively. Since 2015 he is working at Tampere University of Technology as a researcher, working on performance analysis of various 5G wireless networks technologies. His research interests include P2P networks performance analysis, performance evaluation of wireless networks with enabled D2D communications, and mmWave band communications. His e-mail address is: andrey.samuylov@tut.fi.

DMITRI MOLTCHANOV received the M.Sc. and Cand.Sc. degrees from the St. Petersburg State University of Telecommunications, Russia, in 2000 and 2002, respectively, and the Ph.D. degree from the Tampere University of Technology in 2006. He is a Senior Research Scientist with the Department of Electronics and Communications Engineering, Tampere University of Technology, Finland. He has authored over 100 publications. His research interests include performance evaluation and optimization issues of wired and wireless IP networks, Internet traffic dynamics, quality of user experience of real-time applications, and mmWave/terahertz communications systems. He serves as a TPC member in a number of international conferences. His e-mail address is: dmitri.moltchanov@tut.fi.

YULIYA GAIDAMAKA received the Ph.D. in Mathematics from the Peoples' Friendship University of Russia in 2001. Since then, she has been an associate professor in the university's Department of Applied Probability and Informatics. She is the author of more than 50 scientific and conference papers. Her current research focuses on performance analysis of 4G/5G

networks including M2M- and D2D communications, queuing theory, and mathematical modeling of communication networks. Her e-mail address is gaydamaka_yuv@rudn.university.

KONSTANTIN SAMOUYLOV received his Ph.D. degree from the Moscow State University and Doctor of Sciences degree from the Moscow Technical University of Communications and Informatics. In 1996 he became the head of the Telecommunication Systems Department of RUDN University, Russia, and later, in 2014, he became the head of Department of Applied Informatics and Probability Theory. During the last two decades, Konstantin Samouylov has been conducting research projects for the Helsinki and Lappeenranta Universities of Technology, Moscow Central Science Research Telecommunication Institute, several Institutes of Russian Academy of Sciences and a number of Russian network operators. His current research interests are performance analysis of 4G networks (LTE, WiMAX), signalling network (SIP) planning, and cloud computing. He has written more than 150 scientific and technical papers and 5 books. His e-mail address is: samuylov_ke@rudn.university.

SERGEY YA. SHORGIN received the Doctor of Sciences degree in Physics and Mathematics in 1997. Since 2003, he is a professor, and since 2015 he is a Deputy Director of Federal Research Center "Computer Science and Control", Russian Academy of Sciences. He is the author of more than 100 scientific and conference papers and coauthor of three monographs. His research interests include probability theory, modeling complex systems, actuarial and financial mathematics. His email address is: sshorgin@ipiran.ru.