Modeling Coexistence of Unicast and Multicast Communications in 5G New Radio Systems

Andrey Samuylov*†, Vitalii Beschastnyi*, Dmitri Moltchanov†, Darya Ostrikova*, Yuliya Gaidamaka*‡, Vsevolod Shorgin‡

*Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation

{samuylov-ak@rudn.ru, beschastnyy-va, ostrikova-dyu, gaydamaka-yuv}@rudn.ru,

† Tampere University, Laboratory of Electronics and Communications Engineering, Kalevantie 4, Tampere, 33100, Finland

dmitri.moltchanov@tuni.fi

‡ Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences (FRC CSC RAS), 44-2 Vavilov St, Moscow, 119333, Russian Federation

vshorgin@ipiran.ru

***Abstract*—Multicasting is widely used in conventional wired and wireless networks as it allows to significantly improve resource utilization in presence of users interested in the same content. However, the support of this type of service in prospective 5G New Radio (NR) systems has received only little attention so far. In this paper, merging the tools of queuing theory and stochastic geometry we develop a model of 5G NR base station (BS) serving a mixture of unicast and multicast traffic. We validate our model against computer simulations using multicast/unicast session drop probabilities and system resource utilization as metrics of interest. Our numerical results illustrate that the presence of multicast type of traffic severely compromises performance of unicast sessions. Furthermore, this effect is amplified when the inter-site distance (ISD) between BSs increases. Thus, in order to satisfy prescribed performance guarantees in terms of unicast and multicast session drop probabilities, explicit resource reservation mechanism at NR BS might be required.**

***Index Terms*—mmWave, unicast, multicast, resource queue, simulation.**

I. Introduction

3GPP New Radio (NR) radio access technology currently being standardized by 3rd Generation Partnership Project (3GPP) [1] is expected to play a key role in 5G systems. NR systems operating in millimeter wave (mmWave) frequency band promise multi-gigabit rates and reduced latency at the air interface compared to LTE systems [1]. As vendors and network operators perform first field trials of this upcoming technology [2], the research community concentrates their efforts on performance analysis of advanced capabilities, use cases and services for 5G NR systems [3], [4].

In addition to extraordinary promises, 5G NR systems bring a set of new unique challenges to systems designers including much higher propagation losses compared to microwave communications, blockage of propagation paths by small dynamic objects in the channel, the need for efficient electronic beamstreering mechanisms, etc [5]. In real-life outdoor deployments 5G NR systems mostly suffer from mobile obstacles such as humans and cars, which are often termed "blockers" [6].

Depending on the propagation environment and the distance to NR base station (BS), a user equipment (UE) experiencing such type of blockage may either enter outage conditions or lower its modulation and coding scheme such that block error probability at the air interface is satisfied [7]. To target outage situations 3GPP has recently proposed multi-connectivity operation, where several simultaneously active links for adjacent NR BSs are maintained and the connection is transferred between them in case of blockage events [8]. When no outage conditions are experiences by UE, the service may continue at the current BS. However, to support the required rate at the air interface more physical resources are needed. When this surplus of resources is not available an ongoing session is dropped or its rate needs to be reduced [3], [9].

Performance of NR BS service unicast type of traffic has been deeply investigated so far using the tools of stochastic geometry and queuing theory, see, e.g., [4], [10]. Surprisingly, the support of multicast session in these systems has received only little attention so far. Particularly, the authors in [11]–[13], [15] proposed optimization algorithms to support multicasting in NR systems assuming that NR BS serves multicast traffic only. The only study, where the mixture of unicast and multicast traffic is addressed is due to Samuylov et al. [14], where the authors consider coexistence of a single multicast and single unicast service at NR BS. The authors developed a simple analytical model for a mixture of unicast and multicast service. Among other conclusions they demonstrated that there exists an inherent trade-off between performance metrics provided to unicast and multicast sessions and the number of antenna elements needed at the NR BS.

In this paper, we continue efforts in [14] and consider a 5G NR BS deployment serving mixture of unicast and multicast sessions. First, we use the tools of stochastic geometry and 3GPP propagation model to characterize the amount of resources requested by UE. Then, we formalize and solve a queuing model with random resource requirements and external process of line-of-sight (LoS) blockage events and two types of traffic with different resource allocation strategies representing those of unicast and multicast traffic. The main contributions of our study are: (i) the presence of multicast type of traffic severely compromises unicast session performance in terms of session drop probability and (ii) the negative effect of multicast traffic is amplified by the increased inter-site distance (ISD) between NR BSs. Thus, to satisfy the prescribed drop probabilities of unicast and multicast traffic, explicit resource reservation mechanism at NR BSs might be needed.

The rest of the paper is organized as follows. First, in Section II we introduce the system model of NR BS serving unicast and multicast traffic. The modeling framework is developed in Section III. Numerical results are presented in Section IV. Conclusions are drawn in the last section.

II. System Model

We consider a 5G NR Base Station (BS) deployment simultaneously serving process point-to-point (unicast) and point-to-multipoint (multicast) sessions, see Fig. 1. Each BS has a circularly-shaped coverage area of radius R estimated using the mmWave propagation model and the set of MCS [7]. Users are assumed to be randomly distributed according to Poisson Point Process (PPP) with parameter ρ. So the intensity of user requests for service, both unicast and multicast, is Poisson process with parameter $\Lambda = \lambda\rho\pi R^2$, where λ is the parameter of exponentially distributed intervals between two consecutive requests from a single user and ρ is the density of users. To process a user request BS allocates radio frequency resource of the size that is generally a random variable and determined by the UE location.

Following [16], the mmWave path loss L_{dB} for LoS and nLoS conditions is given by:

$$L_{dB}(x) = \begin{cases} 32.4 + 21\log(x) + 20\log f_c, \text{non-blocked}, \\ 47.4 + 21\log(x) + 20\log f_c, \text{blocked}, \end{cases}$$

where f_c is operational frequency measured in GHz, and x is the distance between BS and UE. From these equations we derive maximum distances d^E_{nLoS} and d^E_{nLoS} at which a UE can establish a session in LoS and nLoS states respectively by setting value of L_{dB} threshold as the worst possible Signal-to-Noise Ratio (SNR).

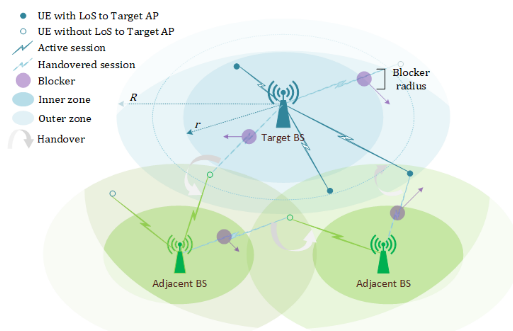

Fig. 1. System model communication scenario.

Our model accounts for LoS blockage by human bodies. We define two zones, inner zone with radius $r = d^E_{nLoS}$ and outer zone with radius R. In the zone inner zone specified by d^E_{nLoS}, once LoS between UE and BS gets blocked, the session can still be maintained by allocating greater amount of resources to compensate for degraded channel quality. However, if the system has insufficient amount of resources it is dropped. In the outer zone, specified by d^E_{nLoS} and R UE is in outage conditions when LoS is blocked. To provide continuous service we assume multiconnectivity option, that is, each UE maintains active links with two NR BS. If UE experiences outage conditions, the session can be handed over to another NR BS. As UE is always served at BS with better channel quality, after handover it will demand greater amount of resource than it was previously allocated by the origin BS. On re-establishment of LoS towards origin BS, the session is handed over back with the former demand. However, at this moment it may appear that origin BS does not have available resource to resume session, in this case the session proceeds its service at adjacent BS until the required amount of resource at origin BS is released. In a similar way, sessions originated in adjacent BS may be handed over to the considered BS demanding more resource than origin sessions.

A request for establishing a unicast session is denied (session drop) if the amount of available resource is not enough for maintaining a new session. Another metric of interest is the session service interruption probability that may occur in case of LoS blockage when additional portion of resource is not available. A request for establishing a multicast session inside inner zone is denied only if on the request arrival there are no multicast sessions with the same or greater demand for resource being served and the amount of available resource is not enough to establish a new session of that type. When a blocker occludes LoS between BS and UE located in the outer zone unicast and multicast sessions are handed over to nearby BS, which resource is assumed to be unlimited meaning that such handover is always possible. As soon as LoS is back, the session proceeds being served by nearby BS until origin BS has available resource, sufficient to resume session, after that the session is immediately handed over back.

III. System Performance Analysis

In subsection III-A, based on the introduced system model, we formalize a queuing framework. Then, in subsection III-B we present our system-level simulation tool based on discrete-event modeling technique.

A. Queuing System Formalization

In this section we consider a resource queue with limited amount of resource C to describe the service process for the user requests [18], [20], [21] illustrated in Fig. 2. We differentiate three types of arriving flows: a flow of requests from inner zone with intensity Λ^r, a flow of requests from outer zone with intensity Λ^R, and a flow of requests for handover from adjacent BSs with intensity Λ^H, $\Lambda = \Lambda^r + \Lambda^R + \Lambda^H$.

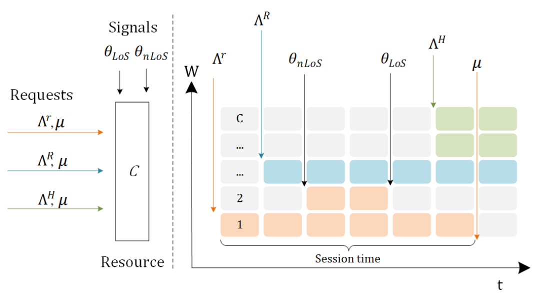

Fig. 2. Queuing Model Scheme.

We assume arrival flows to follow Poisson processes with parameters $\Lambda^r = \lambda^{r,U} + \lambda^{r,M}$, $\Lambda^R = \lambda^{R,U} + \lambda^{R,M}$, and $\Lambda^H = \lambda^{H,U} + \lambda^{H,M}$ correspondingly, where U and M determine the request type (unicast and multicast), while r, R and H the origin locations of UEs (in the inner zone, in the outer zone and in the adjacent BS). The service duration of sessions originated in target BS service area are exponentially distributed with parameters μ^U and μ^M for unicast and multicast sessions and do not depend on location of UE. Similarly, duration of stay for sessions handed over from adjacent BS is exponentially distributed with parameter θ_{nLoS}. Main notations used in this paper are presented in Table I.

Several sessions form a multicast group with demand equal to the greatest demand among sessions in the group. Besides, the first multicast request that forms the group defines service time for this group, thus, all the sessions from the group are terminated at the moment of service completion for the initiating session [22], [23].

Movement of blockers can be modeled with two exponentially distributed random variables with parameters θ_{LoS} and θ_{nLoS} that represent blockage duration (nLoS state intensity) and time intervals between blockages (LoS state intensity) [3]. In Fig. 3 we present a scenario

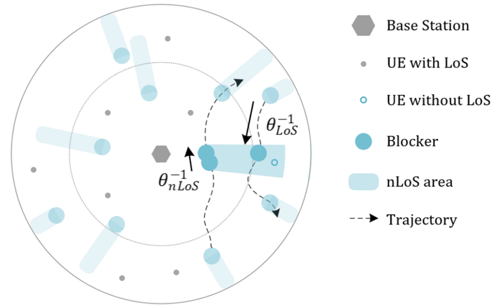

Fig. 3. LoS blockage model.

for our LoS blockage model, where an obstacle blocks the LoS between the BS and UE during the time interval defined by θ_{nLoS} parameter. As the LoS is resumed it takes another time interval defined by θ_{LoS} parameter before a session is blocked by another blocker.

We also put the following simplifying assumptions:

1) session always starts its serving in LoS condition;
2) arrival intensity of handover sessions is calculated as $\lambda^{H,t} = \lambda^{R,t}\frac{\theta_{nLoS}}{(\theta_{LoS}+\theta_{nLoS})}$, where $t \in \{U, M\}$;
3) ongoing handover sessions at target BS cannot be blocked.

B. System-Level Simulation Tool

To study the above-proposed queuing system we have developed a dedicated system level simulation (SLS) tool that is based on discrete-event modeling approach [17]. This approach allows us for flexible modeling of system and gives the opportunity to analyze different movement models and scenarios. To calculate the amount of requested resources we have used NR MCS schemes provided in [7]. The pseudo code of event processing procedure is provided in Algorithm 1.

To obtain numerical results a large-scale simulation campaign has been carried out. As all the involved processes in out simulations are wide sense stationary in nature while the capacity of the serving system is limited the system has a steady-state conditions. The beginning of steady-state period is detected using exponentially-weighted moving average technique with smoothing parameter set to 0.05. We gathered data during the stead-state period only by sampling each 10-s observation and then applying the batch means technique to remove the effect of residual correlation [17]. According to it, each obtained sample is divided into batches each having 1000 observations. The mean of each batch is statistically independent from means of other batches and, thus, the sample of means can be processed using standard statistical methods. In what follows, we demonstrate only point estimates of the metrics of interest. The reason is that, in each experiment we gather sufficient amount of batches for confidence limits to not deviate from the point estimates by more than 1% with the level of significance set to $\alpha = 0.05$.

Algorithm 1 Simulation Algorithm for Standalone Cell with mixture of unicast and multicast traffic

Input: C, r, R, $\mathbf{b}$, $\rho^{U/M}$, $\lambda^{U/M}$, $\mu^{U/M}$, T_{end}
Output: B_U, B_M, $UTIL$
Initialization :
Generate coordinates for $N^U \sim Pois(\lambda^U \rho^U \pi R^2)$ and $N^M \sim Pois(\lambda^M \rho^M \pi R^2)$ UEs
for $n = 1$ to $N^U + N^M$ **do**
  Generate events for the first arrivals and sessions termination
end for
for $time = 0$ to T_{end} **do**
  Dispatch event
  if new request of t type **then**
    Generate event for the next arrival of t-session and its termination
    if remaining resource is sufficient **then**
      Establish session, $S_t = S_t + 1$
      Allocate resource b^t_{LoS} if needed
    else
      Deny request, $B_t = B_t + 1$
    end if
  end if
  if ongoing session of t-type LoS blocking **then**
    if remaining resource is sufficient **then**
      Proceed the session service
      Allocate additional resource $b^t_{nLoS} - b^t_{LoS}$ if needed
    else
      Drop session, $B_t = B_t + 1$
    end if
  end if
  if ongoing session of t-type LoS unblocking **then**
    Proceed the session service
    Release resource $b^t_{nLoS} - b^t_{LoS}$ if possible
  end if
  if session of t-type service termination **then**
    Release resource $b^t_{nLoS/LoS}$ if possible
  end if
  $UTIL = UTIL + C_{occupied} * (time - l_t)$
  $l_t = time$
end for
$B_U = B_U / S_U$
$B_M = B_M / S_M$
$UTIL = (UTIL / T_{end}) \cdot 100$
return B_U, B_M, $UTIL$

IV. Numerical Analysis

In this section, we numerically analyze NR BS operation under a mixture of unicast and multicast traffic load. Below we first concentrate on unicast and multicast session drop probabilities and mean NR BS resource utilization for a fixed ISD and then consider the effect of ISD on these metrics in detail. The default system parameters [14], [19] are summarized in Table I. The traffic profile complies with the global traffic forecast for 2024 [24], while service characteristics are taken from [25].

TABLE I
INPUT DATA

Notation	Description	Values
f_c	Operational frequency	28 GHz
W	Bandwidth	1 GHz
s_A	Service unit	1.44 MHz
r_B	Blocker radius	0.4 m
P_T	Transmit power	0.2 W
γ	Path loss exponent	2.1
G_T	BS antenna gain	2.58 dBi
R	Outer zone radius	400-800 m
r	Inner zone radius	199 m
d_{ISD}	Inter site distance	600-1000 m
v	Service Data Rate	5-50 Mbps
$\rho^U + \rho^M$	Density of UEs	0.1 units/m^2
λ^{-1}	Session mean inter-arrival time	200-2000 s
μ^{-1}	Mean service time	1-90 s
θ^{-1}_{nLoS}	Mean blockage time	2.94 s

Let us first consider the user- and system-centric performance metrics for fixed ISD. Particularly, Fig. 4 illustrates the unicast and multicast session drop probabilities for two defined zones as a function of unicast traffic share $\frac{\rho^U}{\rho^U + \rho^M}$ for a fixed ISD of 600 m and arrival rate of 1 session per second. As one may observe, the multicast session drop probability increases exponentially as unicast traffic share increases. However, the corresponding increase in multicast session drop probability is much slower than exponential and remains bounded even when unicast traffic share approaches unity. The rationale behind this trend is that in presence of multicast traffic NB BR operate with implicit resource reservation mechanism providing priority for multicast session. Particularly, even for high values of unicast traffic share there is non-zero probability that upon arrival of multicast session there is already at least one multicast session in the system.

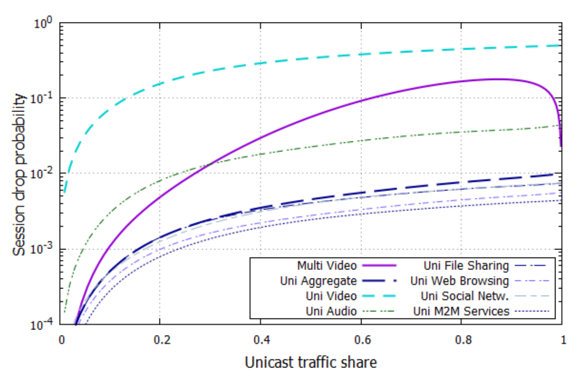

Fig. 4. Session drop probabilities for fixed ISD.

Recalling the resource reservation mechanism for multicast session, we observe that the multicast session drop probability shall increase much slower than exponential, as we observe in Fig. 4. We specifically note that this behavior is inherent for both inner and outer zones.

The mean percentage of NR BS system resource utilization for different types of traffic is shown in Fig. 5 as a function of unicast traffic share for a fixed ISD of 600 m and arrival rate of 1 session per second.

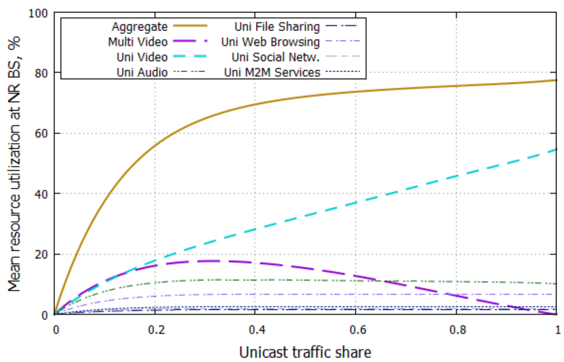

Fig. 5. The mean NR BS resource utilization for fixed ISD.

Logically, the aggregated NR BS resource utilization increases as the unicast traffic share increase. The reason is that due to multicast resource reservation mechanism the overall NR BS offered load decreases when the unicast traffic share increases. The fraction of unicast traffic in the aggregated traffic at NR BS increases linearly when unicast traffic share increases. However, the fraction of multicast traffic in overall resource utilization peaks when the unicast traffic share is approximately 0.3. The reason is that further increase in the unicast traffic share lowers the intensity of multicast session arrivals to the system.

Fig. 6 illustrates session drop probabilities for unicast and multicast services as function of the mean blocking probability, i.e., the mean share of time when a session experiences nLoS state.

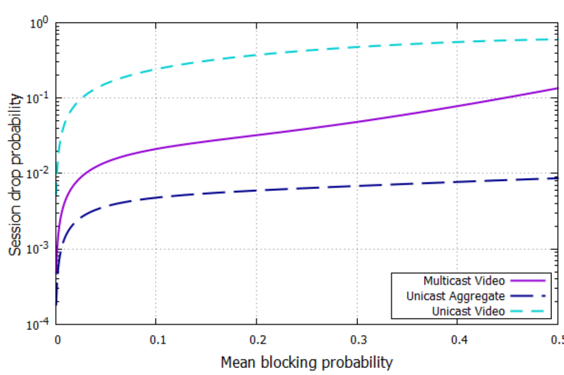

Fig. 6. Session drop probabilities for fixed ISD.

As one may observe, multicast sessions are more resistant to the channel quality. The reason is again the specifics of the multicast service process as the amount of resources requested by multiple multicast sessions is comparable to that of a single unicast session.

Having analyzed the response of the system to fixed ISD we now proceed assessing metrics of interest for different distances between NR BSs. Particularly, Fig. 7 illustrates the unicast session drop probabilities for different ISD, sessions arrival rates in range from 1 to 4 sessions per second. As one may observe, for all the considered values of ISD, the unicast session drop probability increases as unicast traffic share gets higher.

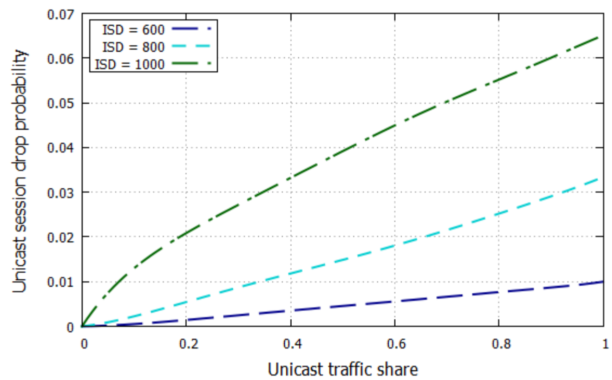

Fig. 7. Unicast session drop probability as a function of ISD.

The multicast session drop probability for different values of ISD are illustrated in Fig. 8, where the unicast traffic shares scales from zero to unity over OX axis. First, comparing Fig. 7 and Fig. 8, one may observe that for all considered ISDs the unicast session drop probabilities are much lower compared to multicast session drop probabilities. This implies that when serving a mixture of unicast and multicast traffic the performance of the latter is severely compromised.

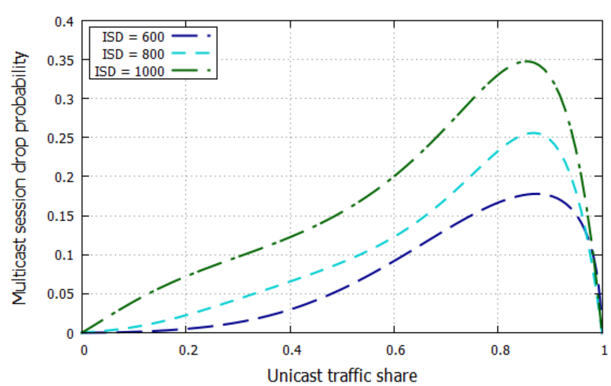

Fig. 8. Multicast session drop probability as a function of ISD.

It is also important to note that similarly to unicast traffic the worst performance for multicast traffic is observed for higher values of ISD.

V. Conclusion

Motivated by the needs to support multicast traffic in forthcoming millimeter wave NR systems, in this paper, we have formalized a system model of cellular NR BS deployment serving mixture of unicast and multicast type of traffic and accounting for millimeter wave propagation effects and NR system specifics. To analyze the proposed system model we have developed a system-level simulation tool capable of delivering user- and system-centric metrics of interest.

Our numerical results revealed that the service performance of NR BS systems is severely affected by presence of multicast type of traffic. Particularly, multicast type of traffic induces an implicit resource reservation into NR BS service process providing priority to multicast sessions.

Our future plans include formalization of analytical framework that will allow to derive user- and system-centric performance metrics in closed-from such that they can be further used in performance optimization of practical NR BS deployments.

Acknowledgment

The publication has been prepared with the support of the "RUDN University Program 5-100" and funded by RFBR according to the research projects No. 17-07-00845, 18-37-00380. This work has been developed within the framework of the COST Action CA15104, Inclusive Radio Communication Networks for 5G and beyond (IRACON).

References

[1] IEEE Standard: 802.11ad-2012: Enhancements for Very High Throughput in the 60 GHz Band, https://ieeexplore.ieee.org/document/6392842/.

[2] Qualcomm, "mmWave 5G NR prototype demo video." [Online] https://www.qualcomm.com/videos/mmwave-5g-nr-prototype-demo-video, May 2018.

[3] R. Kovalchukov, D. Moltchanov, V. Begishev, A. Samuylov, S. Andreev, Y. Koucheryavy, and K. Samouylov. "Improved session continuity in 5G NR with joint use of multi-connectivity and guard bandwidth," in 2018 IEEE Global Communications Conference (GLOBECOM), pp. 1–7, 2018.

[4] V. Petrov, M. A. Lema, M. Gapeyenko, K. Antonakoglou, D. Moltchanov, F. Sardis, A. Samuylov, S. Andreev, Y. Koucheryavy, and M. Dohler, "Achieving End-to-End Reliability of Mission-Critical Traffic in Softwarized 5G Networks," IEEE Journal on Selected Areas in Communications, vol. 36, no. 3, pp. 485–501, 2018.

[5] M. Shafi, A.F. Molisch, P.J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, G. Wunder. 5G: A tutorial overview of standards, trials, challenges, deployment, and practice. IEEE Journal on Selected Areas in Communications, Vol.: 35, No. 6, pp. 1201–1221, June 2017.

[6] M. Gapeyenko, A. Samuylov, M. Gerasimenko, D. Moltchanov, S.A. Singh, M. Riza, E. Aryafar, N. Himayat, S. Andreev, Ye. Koucheryavy. On the Temporal Effects of Mobile Blockers in Urban Millimeter-Wave Cellular Scenarios, 2017.

[7] 3GPP, "NR: Physical channels and modulation (Release 15)", 3GPP TR 38.211, December 2017.

[8] 3GPP, "NR: Multi-connectivity; Overall description (Release 15)", 3GPP TS 37.34 V15.2.0, June 2018.

[9] D. Moltchanov, A. Samuylov, V. Petrov, M. Gapeyenko, N. Himayat, S. Andreev, Sergey, Ye. Koucheryavy. Improving session continuity with bandwidth reservation in mmwave communications // IEEE Wireless Communications Letters, Vol. 8, No. 1, pp. 05–108, 2019.

[10] V. Petrov, D. Solomitckii, A. Samuylov, M.A. Lema, M. Gapeyenko, D. Moltchanov, S. Andreev, V. Naumov, K. Samouylov, M. Dohler. Dynamic Multi-connectivity Performance in Ultra-dense Urban mmWave Deployments // IEEE Journal on Selected Areas in Communications. Vol. 35, No. 9, pp. 2038–2055, 2017.

[11] W. Kim, T. Song, S. Pack, "Rate adaptation for directional multicast in IEEE 802.11 Ad Networks," in Consumer Electronics // IEEE International Conference, pp. 364–365, IEEE, 2012.

[12] H. Park, S. Park, T. Song, and S. Pack, "An incremental multicast grouping scheme for mmWave networks with directional antennas," IEEE Comm. Letters, vol. 17, no. 3, pp. 616–619, 2013.

[13] W. Feng, Y. Li, Y. Niu, L. Su, and D. Jin, "Multicast spatial reuse scheduling over millimeter-wave networks," in Wireless Communications and Mobile Computing Conference (IWCMC), pp. 317–322, IEEE, 2017.

[14] A. Samuylov, D. Moltchanov, A. Krupko, R. Kovalchukov, F. Moskaleva, Yu. Gaidamaka. "Performance Analysis of Mixture of Unicast and Multicast Sessions in 5G NR Systems" // 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT – 2018). Moscow, Russia, 2018.

[15] A. Biason and M. Zorzi. Multicast via Point to Multipoint Transmissions in Directional 5G mmWave Communications // IEEE Communications Magazine, February 2019.

[16] 3GPP, "5G; Study on channel model for frequencies from 0.5 to 100 GHz (Release 14)", 3GPP TR 38.901, May 2017.

[17] M. Mezzavilla, M. Zhang, M. Polese, R. Ford, S. Dutta, S. Rangan, M. Zorzi. End-to-End Simulation of 5G mmWave Networks // IEEE Comm. Surveys & Tutorials (Vol.: 20, Issue: 3), 2018.

[18] V. Naumov, K. Samouylov. Analysis of multi-resource loss system with state-dependent arrival and service rates (2017) Probability in the Engineering and Informational Sciences, 31 (4), pp. 413–419.

[19] V.Y. Borodakiy, K.E. Samouylov, I.A. Gudkova, E.V. Markova. Analyzing Mean Bit Rate of Multicast Video Conference in LTE Network with Adaptive Radio Admission Control Scheme (2016) Journal of Mathematical Sciences, 218 (3), pp. 257–268.

[20] K. Samouylov, V. Naumov, E. Sopin, I. Gudkova, S. Shorgin. Sojourn time analysis for processor sharing loss system with unreliable server (2016) Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 9845 LNCS, pp. 284–297.

[21] I. Gudkova, K. Samouylov, I. Buturlin, V. Borodakiy, M. Gerasimenko, O. Galinina, S. Andreev. Analyzing impacts of coexistence between M2M and H2H Communication on 3GPP LTE System (2014) Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 8458, pp. 162–174.

[22] G. Basharin, Y. Gaidamaka, and K. Samouylov, "Mathematical theory of teletraffic and its application to the analysis of multiservice communication of next generation networks," Automatic Control and Computer Sciences, vol. 47, pp. 62–69, 2013.

[23] K. Samouylov and Y. Gaidamaka, "Analysis of loss systems with overlapping resource requirements," Statistical Papers, vol. 59, no. 4, pp. 1463–1470, 2018.

[24] Ericsson Mobility Report [Online] https://www.ericsson.com/assets/local/mobility-report/documents/2019/ericsson-mobility-report-june-2019.pdf, June 2019.

[25] Sina Khatibi. Radio Resource Management Strategies in Virtual Networks // PhD, 196 p., University of Lisbon, 2016.