Discrete & Continuous Models
& Applied Computational Science
ISSN 2658-7149 (Online), 2658-4670 (Print)

2024, 32 (4) 362–369
http://journals.rudn.ru/miph

Research article

UDC 519.872:519.217
PACS 02.50.Ey, 02.50.Fz
DOI: 10.22363/2658-4670-2024-32-4-362-369

EDN: DRHDFU

Two-queue polling system as a model of an integrated access and backhaul network node in half-duplex mode

Dmitry I. Nikolaev[1], Vitalii A. Beschastnyi[1], Yuliya V. Gaidamaka[1,2]

[1] RUDN University, 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation

[2] Institute of Informatics Problems, 44 Vavilova St, bldg 2, Moscow 119333, Russian Federation

(received: September 3, 2024; revised: September 25, 2024; accepted: September 28, 2024)

Abstract. Integrated Access and Backhaul (IAB) technology facilitates the establishment of a compact network by utilizing repeater nodes rather than fully equipped base stations, which subsequently minimizes the expenses associated with the transition towards next-generation networks. The majority of studies focusing on IAB networks rely on simulation tools and the creation of discrete-time models. This paper introduces a mathematical model for the boundary node in an IAB network functioning in half-duplex mode. The proposed model is structured as a polling service system with a dual-queue setup, represented as a random process in continuous time, and is examined through the lens of queueing theory, integral transforms, and generating functions (GF). As a result, analytical expressions were obtained for the GF, marginal distribution, as well as the mean and variance of the number of requests in the queues, which correspond to packets pending transmission by the relay node via access and backhaul channels.

Key words and phrases: polling, queuing system, integrated access and backhaul, half-duplex

For citation: Nikolaev, D. I., Beschastnyi, V. A., Gaidamaka, Y. V. Two-queue polling system as a model of an integrated access and backhaul network node in half-duplex mode. *Discrete and Continuous Models and Applied Computational Science* **32** (4), 362–369. doi: 10.22363/2658-4670-2024-32-4-362-369. edn: DRHDFU (2024).

1. Introduction

To simplify and reduce the cost of deploying dense 5G networks, standardizing organizations have proposed various technologies, one of which is Integrated Access and Backhaul (IAB) [1]. This technology enables telecom operators to seamlessly transition to 5G-compliant networks by utilizing cost-effective relay nodes that implement wireless relay instead of fully-equipped base stations. By implementing a network with IAB technology, consisting of backbone and relay nodes, operators can meet the limitations of 5G standards and have the flexibility to upgrade relay nodes with access to the backbone network in the future, ultimately enhancing the quality of service for users.

Integrated Access and Backhaul is one of the approved objectives of the 17th Release of the 3GPP (3rd Generation Partnership Project) [2]. In IAB, a small number of backbone base stations (BSs) are connected to the existing fibre-optic network infrastructure. The remaining BSs transmit backhaul traffic over wireless channels [3].

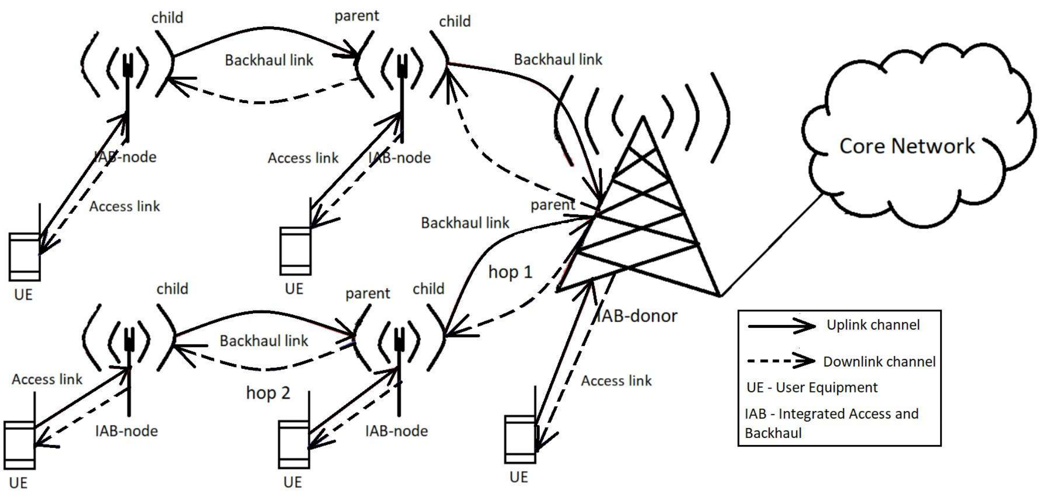

Figure 1. IAB network fragment in the form of a spanning tree

In comparison to LTE-Advanced, IAB is a more advanced solution that supports multi-hop, dynamic resource multiplexing, and plug-and-play design, significantly reducing the complexity of network deployment. Given the aforementioned benefits of IAB technology, the design of an efficient and high-performance 5G/6G network incorporating this technology has become a pressing research topic. As such, further exploration and utilization of IAB within the context of 5G/6G networks holds immense potential for enhancing network capabilities and improving overall user experience [4].

The IAB technology, along with its characteristics and operational mechanisms, has been investigated from multiple perspectives. Research efforts have addressed challenges such as routing in multi-hop networks [5, 6], the selection of optimal network topology [7], and efficient resource allocation [8]. In addition, advanced beamforming techniques have been explored [9], while the development of data channel management policies for latency control [10] and the establishment of network stability conditions that maximize throughput have also been studied [11, 12]. Furthermore, frequency reuse using graph coloring methods has been investigated [13]. Moreover, one study constructs a mathematical model of the IAB edge node as a Markov process and analyzes packet transmission delays [14], while another work develops a simulation model of the IAB edge node [15]. Complementary research includes the construction of mathematical models for IAB networks incorporating blockage effects [16], mean and the formulation of queuing system models to represent the number of users at an IAB node [17].

Figure 1 shows an example of the IAB network topology in the form of a spanning tree, with the IAB-donor reference base station (BS) located at the root vertex. The remaining IAB nodes in the network are branch vertices and leaf vertices. The focus of this study is on the IAB boundary node, which corresponds to the leaf vertex in the tree. The subject of the study is the packet flow that passes through this node.

Due to the separation of downlink and uplink channels, a mathematical model has been proposed in the form of a polling service system [18–23]. Data packets will be associated with requests, and the IAB boundary node will correspond to a server. Downlink traffic from the parent node to the current node and from the current node to user equipments (UEs) will be directed to queue Q_1 for receiving and servicing requests. Uplink traffic from UEs to the current node and from the current node to the parent node will correspond for receiving and servicing requests in queue Q_2 (see Table 1).

Table 1

The correspondence between the objects and processes of the technical system and the queueing system

Technical system	IAB-node	Data packets	Downlink from the parent node	Uplink to the current node	Downlink from the current node	Uplink to the parent node
Queueing system	Server	Requests	Receipt of requests in the queue Q_1	Receipt of requests in the queue Q_2	Servicing of requests in the queue Q_1	Servicing of requests in the queue Q_2

Considering the limitations imposed by the half-duplex data transmission mode, we can divide the operation of the IAB boundary node into phases shown in Table 2. For simplicity, let's combine the first two phases of request receipt into one. We then arrive at a polling service system with two queues, where requests are received during the switching of devices at the end of each service cycle. That is, the switching time between queues within the service cycle is zero, and applications are received exclusively during the above-described period. The characteristics of this model will be studied in the next section.

Table 2

Phases of operation of the IAB network boundary node

	Q_1	Q_2
Downlink from the parent node	+	0
Uplink to the current node	0	+
Downlink from the current node	–	0
Uplink to the parent node	0	–

2. Mathematical model

We will now delve deeper into the details of the $M_2|GI_2|1$ polling service system that was introduced in the preceding section. In order to study the system, we must make the assumption that it is operating in a stationary mode. Within this context, we will use X_i^j to denote the number of requests in the queue Q_j at any given time Q_i, $i,\ j = 1,\ 2$ [24].

Additionally, we make use of the notation $A_i(t)$ to represent the number of requests received in the i-th queue during time t. It is important to note that our system consists of 2 Poisson input flows, each with their own parameter, denoted by λ_i. Furthermore, the service time for a given request in queue Q_i is denoted as b_{ik}, with k representing the k-th request. It is also stated that these service times are independent and equally distributed with a cumulative distribution function (CDF) of $B_i(t)$.

Moving on to the half-duplex aspect of the system, we introduce the random variable s_0, which represents the switching time of the server. Its distribution is given by the CDF $S(t)$, and it has raw moments of arbitrary order $s_0^{(n)} = \int_0^\infty t^n \, \mathrm{d}(S(t))$, with $n \geq 1$. Finally, we arrive at the expressions for

X_i^j for our system, which can be written as follows:

$$X_i^j = \begin{cases} 0, & j < i, \\ A_j(s_0), & j \geq i, \end{cases} \quad \Leftrightarrow \quad X_i^j = \begin{cases} 0, & (j=1) \wedge (i=2), \\ A_1(s_0), & (j=1) \wedge (i=1), \\ A_2(s_0), & j=2. \end{cases} \tag{1}$$

For these values, we have $p_i(n_1, n_2)$ — the probability distribution that at any moment of servicing the i-th queue Q_i j-th queue Q_j contains n_j applications, $n_j \geq 0$, $i, j = 1, 2$.

The generating functions (GFs) of random variables $(X_i^1, X_i^2, \dots, X_i^K)$, $i = 1, \dots, K$ are expressed according to the following lemma.

Lemma 1. *GF of random variables* (X_i^1, X_i^2), $i = 1, 2$ *have the following form*

$$P_i(\mathbf{z}) = P_i(z_1, z_2) = \tilde{S}\left(\sum_{j=i}^{2}(\lambda_j(1 - z_j))\right), \quad i = 1, 2, \tag{2}$$

where $\tilde{S}(w)$*—Laplace-Stieltjes Transform (LST) of RV* $s_0 \sim S(t)$.

Substituting the value of **1** into the variable **z** in the derivatives of (2), we obtain the values of the mean and variance of the number of requests in the queues.

Theorem 1. *For a polling system* $M_2|GI_2|1$ *with state-dependent input flows and switching time* s_0 *distributed according to the CDF* $S(t)$, *the mean* $\overline{N}_i(j)$ *and the variance* $\mathrm{Var}\left(X_i^j\right)$ *of the number of requests in queue* Q_j *at the time of servicing queue* Q_i, $i, j = 1, 2$, *are expressed by the following formulas:*

$$\overline{N}_i(j) = \begin{cases} 0, & j < i, \\ \overline{s_0}\lambda_j, & j \geq i, \end{cases} \quad \mathrm{Var}\left(X_i^j\right) = \begin{cases} 0, & j < i, \\ s_0^{(2)}\lambda_j^2 + \overline{s_0}\lambda_j(1 - \overline{s_0}\lambda_j), & j \geq i, \end{cases} \tag{3}$$

If the switching time is exponentially distributed with parameter s ($S(t) = 1 - e^{-st}$, $t \geq 0$), *then formulas*(3) *are transformed to the form* (4).

$$\overline{N}_i(j) = \begin{cases} 0, & j < i, \\ \dfrac{\lambda_j}{s}, & j \geq i, \end{cases} \quad \mathrm{Var}\left(X_i^j\right) = \begin{cases} 0, & j < i, \\ \dfrac{\lambda_j^2}{s^2} + \dfrac{\lambda_j}{s}, & j \geq i, \end{cases} \tag{4}$$

where $\mathrm{Var}(\cdot)$ — *Variance of RV.*

Substituting the value of **0** into the variable **z** in the derivatives of (2), we obtain the probability distribution of number of requests in queues.

Theorem 2. *For a polling system* $M_2|GI_2|1$ *with state-dependent input flows and switching time* s_0 *distributed according to the exponential law* $S(t) = 1 - e^{-st}$, $t \geq 0$, *the distributions of the number of requests in queue* Q_j *at the moment of servicing queue* Q_i, $i, j = 1, 2$, *are expressed by the following formulas:*

$$p_i(n_1, n_2) = \begin{cases} 0, & (n_1 \geq 1) \wedge (i = 2), \\ \dfrac{s\lambda_2^{n_2}}{(s + \lambda_2)^{n_2+1}}, & (n_1 = 0) \wedge (i = 2), \\ \dfrac{s\lambda_1^{n_1}\lambda_2^{n_2}(n_1 + n_2)!}{(n_1)!(n_2)!(s + \lambda_1 + \lambda_2)^{n_1+n_2+1}}, & i = 1, \end{cases} \tag{5}$$

where $n_k = 0, \dots, \infty$ — *the number of requests in queue* Q_k, $k = 1, 2$.

3. Conclusion

In the transition to the next generation of networks, integrated access and backhaul (IAB) technology is considered a key technology. However, due to limitations imposed by the half-duplex mode of data transmission, it is necessary to build adequate models of how IAB networks operate.

In this paper, a model of the boundary node of an IAB network in the form of a queueing polling system was constructed. We also derived analytical expressions for the generating functions, marginal distribution, raw, and central moments of the number of requests (packets) in queues.

These results allow us to estimate the probability and conditions of overloads at the IAB boundary node. For future research, we plan to build and analyze an energy-efficient model of the entire IAB network. This will be done for both the topology presented in this paper and for more complex topologies where there are multiple routes from the reference base station to user devices.

Author Contributions: Conceptualization, Dmitry I. Nikolaev and Yuliya V. Gaidamaka; methodology, Yuliya V. Gaidamaka; validation, Dmitry I. Nikolaev, Vitalii A. Beschastnyi, Yuliya V. Gaidamaka ; formal analysis, Dmitry I. Nikolaev; investigation, Dmitry I. Nikolaev; resources, Vitalii A. Beschastnyi and Yuliya V. Gaidamaka; writing—original draft preparation, Dmitry I. Nikolaev; writing—review and editing, Dmitry I. Nikolaev, Vitalii A. Beschastnyi, Yuliya V. Gaidamaka; supervision, Yuliya V. Gaidamaka; project administration, Vitalii A. Beschastnyi and Yuliya V. Gaidamaka; funding acquisition, Vitalii A. Beschastnyi All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The reported study was funded by RSF, project number 23-79-01140, https://rscf.ru/en/project/23-79-01140/.

Data Availability Statement: Data sharing is not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. *3GPP: Study on Integrated Access and Backhaul. Technical report (TR) 38.874 v16.0.0 (2018)*
2. *3GPP: Integrated Access and Backhaul (IAB) radio transmission and reception. Technical Specification (TS) 38.174 v17.2.0 (2022)*
3. Polese, M., Giordani, M., Zugno, T., Roy, A., Goyal, S., Castor, D. & Zorzi, M. Integrated Access and Backhaul in 5G mmWave Networks: Potential and Challenges. *IEEE Communications Magazine* **58,** 62–68. doi:10.1109/MCOM.001.1900346 (Mar. 2020).
4. Sadovaya, Y., Molchanov, D., Mao, W., Orhan, O., Yeh, S.-p., Nikopour, H., Talwur, S. & Andreev, S. Integrated access and backhaul in millimeter-wave cellular: Benefits and challenges. *IEEE Communications Magazine* **60,** 81–86 (2022).
5. Gomez-Cuba, F. & Zorzi, M. Optimal link scheduling in millimeter wave multi-hop networks with MU-MIMO radios. *IEEE Transactions on Wireless Communications* **19,** 1839–1854 (2020).
6. Alghafari, H. & Sayad Haghighi, M. Decentralized Joint Resource Allocation and Path Selection in Multi-hop Integrated Access Backhaul 5G Networks. *Computer Networks,* 108837. doi:10.1016/j.comnet.2022.108837 (Feb. 2022).
7. Madapatha, C. *et al.* On topology optimization and routing in integrated access and backhaul networks: A genetic algorithm based approach. *IEEE Open Journal of the Communications Society* **2,** 2273–2291 (2021).

8. Tafintsev, N., Moltchanov, D., Yeh, S.-p., Nikopour, H., Mao, W., Orhan, O., Talwar, S., Valkama, M. & Andreev, S. *Joint Path Selection and Resource Allocation in Multi-Hop mmWave-based IAB Systems* in *ICC 2023 - IEEE International Conference on Communications* (2023), 4194–4199. doi:10.1109/ICC45041.2023.10279180.
9. Jayasinghe, P., Tölli, A., Kaleva, J. & Latva-Aho, M. Traffic Aware Beamformer Design for Flexible TDD-Based Integrated Access and Backhaul. *IEEE Access* **8,** 205534–205549. doi:10.1109/ACCESS.2020.3037814 (2020).
10. Yarkina, N., Moltchanov, D. & Koucheryavy, Y. Counter Waves Link Activation Policy for Latency Control in In-Band IAB Systems. *IEEE Communications Letters* **27,** 3108–3112. doi:10.1109/LCOMM.2023.3313233 (2023).
11. Neely, M. *Stochastic Network Optimization with Application to Communication and Queueing Systems* doi:10.2200/S00271ED1V01Y201006CNT007 (2010).
12. Tassiulas, L. & Ephremides, A. Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks. *IEEE Transactions on Automatic Control* **37,** 1936–1948. doi:10.1109/9.182479 (1992).
13. Silard, M., Fabian, P., Papadopoulos, G. Z. & Savelli, P. *Frequency Reuse in IAB-based 5G Networks using Graph Coloring Methods* in *2022 Global Information Infrastructure and Networking Symposium (GIIS)* (Argostoli, Greece, 2022), 104–110. doi:10.1109/GIIS56506.2022.9937005.
14. Nikolaev, D. & Gaidamaka, Y. *Leaf Node Polling Model Analysis in an Integrated Access and Backhaul Network* in *Information Technologies and Mathematical Modelling. Queueing Theory and Applications* (eds Dudin, A., Nazarov, A. & Moiseev, A.) (Springer Nature Switzerland, Cham, 2024), 106–117. doi:10.1007/978-3-031-65385-8_8.
15. Feoktistov, V., Nikolaev, D., Gaidamaka, Y. & Samouylov, K. *Analysis of Probabilistic Characteristics in the Integrated Access and Backhaul System* in *Distributed Computer and Communication Networks: Control, Computation, Communications* (eds Vishnevskiy, V. M., Samouylov, K. E. & Kozyrev, D. V.) (Springer Nature Switzerland, Cham, 2024), 277–290. doi:10.1007/978-3-031-50482-2_22.
16. Khayrov, E. & Koucheryavy, Y. Packet Level Performance of 5G NR System Under Blockage and Micromobility Impairments. *IEEE Access* **11,** 90383–90395. doi:10.1109/ACCESS.2023.3307021 (2023).
17. Salimzyanov, R. & Moiseev, A. *Local balance equation for the probability distribution of the number of customers in the IAB network* in *SUITMM, Omsk* (2023), 284–289.
18. Rykov, V. On analysis of periodic polling systems. *Autom. Remote Control* **70,** 997–1018. doi:10.1134/S0005117909060071 (2009).
19. Takagi, H. *Analysis of polling systems* p. 175. 175 pp. (MIT Press, 1986).
20. Takagi, H. & Kleinrock, L. *A tutorial on the analysis of polling systems* p. 172. 172 pp. (UCLA Computer Science Department, 1985).
21. Takagi, H. Mean message waiting times in symmetric multiqueue systems with cyclic service. *Performance Evaluation* **5,** 271–277 (1985).
22. Zaripova, E. *Metody analiza pokazateley effektivnosti telekommunikatsionnoy seti serverov protokola ustanovleniya sessiy [Methods of analyzing the efficiency indicators of the telecommunication network of session establishment protocol servers]* p. 18. PhD thesis (RUDN, Moscow, 2015), 18.
23. Ge, J., Bao, L., Ding, H. & Ding, X. *Performance Analysis of the First-order Characteristics of Two-level Priority Polling System Based on Parallel Gated and Exhaustive Services Mode* in *2021 IEEE 4th International Conference on Electronic Information and Communication Technology (ICEICT)* (2021), 10–13. doi:10.1109/ICEICT53123.2021.9531122.
24. Vishnevsky, V. & Semenova, O. *Sistemy pollinga: Teoriya i primenenie v shirokopolosnykh besprovodnykh setyakh [Polling systems. Theory and applications for broadband wireless networks]* p. 312. 312 pp. (Tekhnosfera, Moscow, 2012).

Information about the authors

Dmitry I. Nikolaev—Master's degree student of Department of Probability Theory and Cybersecurity of RUDN University (e-mail: nikolaev-di@rudn.ru, phone: +7 (919) 964-08-44, ORCID: 0009-0001-5885-8566, ResearcherID: LEM-8084-2024, Scopus Author ID: 58971412800)

Vitalii A. Beschastnyi—Candidate of Physical and Mathematical Sciences, assistant professor of Department of Probability Theory and Cybersecurity of RUDN University (e-mail: beschastnyy-va@rudn.ru, ORCID: 0000-0003-1373-4014, ResearcherID: AAH-7080-2019, Scopus Author ID: 57192573001)

Yuliya V. Gaidamaka—Doctor of Physical and Mathematical Sciences, full professor of Department of Probability Theory and Cybersecurity of RUDN University; Senior Researcher of Institute of Informatics Problems of Federal Research Center "Computer Science and Control" Russian Academy of Sciences (e-mail: gaydamaka-yuv@rudn.ru, ORCID: 0000-0003-2655-4805, ResearcherID: E-5620-2014, Scopus Author ID: 35106984800)

УДК 519.872:519.217
PACS 02.50.Ey, 02.50.Fz
DOI: 10.22363/2658-4670-2024-32-4-362-369 EDN: DRHDFU

Система поллинга с двумя очередями как модель узла сети интегрированного доступа и транзита в полудуплексном режиме

Д. И. Николаев[1], В. А. Бесчастный[1], Ю. В. Гайдамака[1, 2]

[1] Российский университет дружбы народов, ул. Миклухо-Маклая, д. 6, Москва, 117198, Российская Федерация

[2] Институт проблем информатики, Федеральный исследовательский центр «Информатика и управление» РАН, ул. Вавилова, д. 44, корп. 2, Москва, 119333, Российская Федерация

Аннотация. Технология интегрированного доступа и транзита (Integrated Access and Backhaul, IAB) позволяет создать компактную сеть за счёт использования узлов ретрансляторов вместо полностью оборудованных базовых станций, что впоследствии минимизирует расходы, связанные с переходом к сетям следующего поколения. Большая часть работ, посвящённых сетям IAB, опираются на инструменты имитационного моделирования и создание моделей, функционирующих в дискретном времени. В данной работе представлена математическая модель граничного узла в сети IAB с полудуплексным режимом передачи данных. Предлагаемая модель конструируется как система поллинга с двумя очередями в непрерывном времени и анализируется с помощью аппарата теории массового обслуживания, интегральных преобразований и производящих функций (ПФ). В результате получены аналитические выражения для ПФ, вероятностных распределений, а также средних и дисперсий числа заявок в очередях, которые соответствуют пакетам, ожидающим своей передачи на ретрансляционном узле по каналам доступа и транзита.

Ключевые слова: поллинг, система массового обслуживания, интегрированный доступ и транзит, полудуплекс