future internet

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Towards Practical Applications in Modeling Blockchain System

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Abstract: Like multiservice networks, blockchain technology is currently experiencing significant development because of its decentralization and ability to organize secure, seamless, reliable data exchange and storage. Due to the significant demand for the technology, there is a need to analyze the impact of these technology processes on network characteristics to predict traffic behavior and ensure required quality indicators, as well as on the stability of public communication network elements when blockchain technology operates. Conducting a full-scale experiment is a time-consuming task that cannot always be accomplished, so in this paper, the authors propose considering approaches to modeling these systems and, as an example, propose to use a simulation system to assess the performance of the network and its elements.

Keywords: blockchain; distributed ledger; decentralized systems; simulation; analytical modeling

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Citation: Vladyko, A.; Spirkina, A.; Elagin, V. Towards Practical Applications in Modeling Blockchain System. *Future Internet* **2021**, *13*, 125. https://doi.org/10.3390/fi13050125

Academic Editor: Spyros Makridakis

Received: 22 April 2021
Accepted: 7 May 2021
Published: 12 May 2021

1. Introduction

Communication networks are now the basis for systems aimed at supporting the digitalization of the world community. Hence, it is necessary not only to ensure their sustainability but also to plan for their future development. The criteria of security, confidentiality, reliability, latency and data transmission for such systems are expected to be key and should be given special attention by the research community.

The promising blockchain technology can be used to solve the aforementioned problems by creating new forms of distributed architectures while being used to define the entire technological system behind the exchange of digital assets between participants in the same network without intermediaries [1].

Blockchain is a distributed database that consists of an updatable list of structured data and in which data storage and processing devices are distributed in a decentralized manner [2,3]. The main advantages of blockchain technology can be seen as the system's reliability, as any attempt to make unauthorized changes will result in the transaction being rejected due to inconsistency with previous copies and verification of added data by independent participants.

Today, researchers, developers suggest that blockchain technology, though new and controversial, could transform some of today's services. Blockchain's capabilities make it attractive to companies in various industries, with the financial, telecom, transportation, industrial and agribusiness sectors being prime candidates for blockchain adoption. A report by the US analysis company Transparency Market Research [4] indicates that the global blockchain market will be worth USD 20 billion by 2024, and the industry will grow at an annual rate of about 59%. Grand View Research conducted a similar study [5]. Comparison of perspectives proposed by companies is presented in Figure 1. Despite the significant difference in the final figures, many researchers believe that the market will grow and evolve rapidly, highlighting the integration needs of existing systems. At the beginning of 2021, we can conclude that the forecasting trend for the blockchain market is correct.

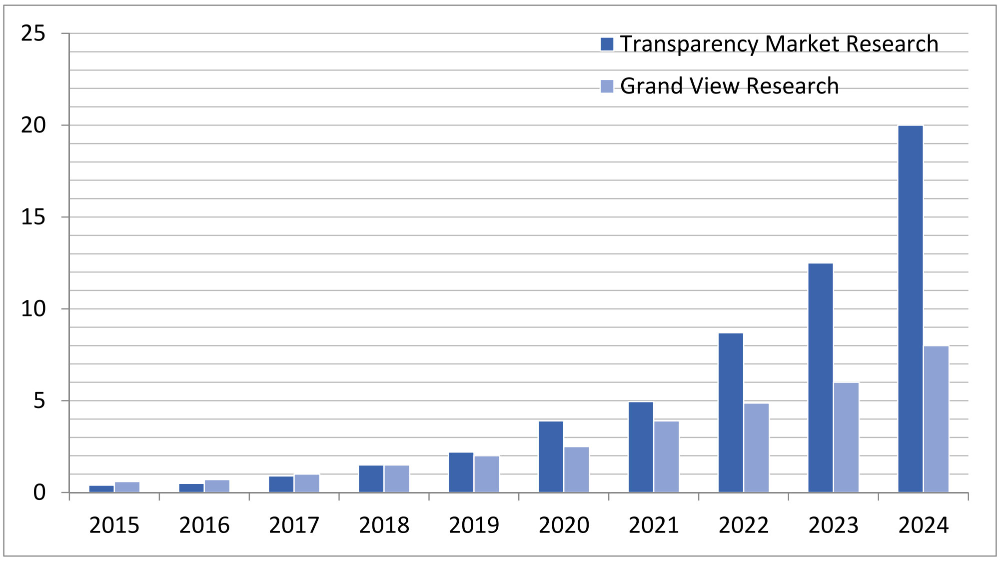

Figure 1. Blockchain market growth dynamics.

Blockchain created new forms of interaction, where network participants use a large network of untrusted participants for transactional data exchange without relying on a central hub [1]. However, it is important to note that this technology could have a significant impact on telecommunications.

Blockchain technology is a specialized information and communication technology with some specific features. Nodes, transactions and consensus algorithms are the key objects of the system that define the new capabilities. Depending on the algorithms and protocols for communication and data dissemination, different network effects may emerge.

The technology involves many nodes on the network to deal with the additional volume of service traffic and constant data exchange. This makes it necessary to consider its impact on the network and determine the current network infrastructure design for the new requirements, as the actual deployment phase may be adversely affected [3,6–8]. The current lack of unified tools for evaluating blockchain technology performance, but the number of blockchain applications in use has already reached a high level of quantification [7].

The work of blockchain technology can be divided into several stages:

1. Network discovery. The first time a node is connected to the network, it is booted and connected to the initial boot node to get a list of neighbor's nodes, synchronize and get the current version of the blockchain, subsequently disconnected;
2. Transaction creation and verification. All nodes in the network can initiate transactions to transfer digital assets to available peers in the network. The creation of a new transaction implies that certain conditions are fulfilled by the exchange participants, so the transaction specifies the amount and the addressee and may additionally specify the terms of the transaction. Once the transaction has been created, the sender signs it with their electronic key and sends it to the network. The transaction will be rejected if it is incorrectly generated, invalid or does not contain all the information required for execution, or if the user does not have sufficient funds to complete the transaction;
3. Mining. When a new transaction is received, the node initializes its addition to the block. The block is generated based on information about the past block received and the information collected. The miners try to find a solution; the block is checked, added to the registry and sent to the network to other nodes. If a solution is found by the second node, it is discarded to avoid branching;
4. Checking the block for correctness. Checking the block before adding it to the register implies that the previous block exists, that the data structure is intact, that the sender has sufficient funds, that the signature is correct, that the syntax is correct, that

the inputs and outputs are within acceptable values, that the transaction size is not higher than the maximum, that the transaction has not yet been processed. If confirmed, the chain is updated in the general ledger, and the transaction and user status are validated.

The development and popularization of this new technology introduce significant changes to network communication between devices. As mentioned in [8], blockchain generates additional traffic to update registries on all nodes involved, and an increased amount of service traffic appears when data are encrypted and markedly reduces the proportion of useful traffic. Preliminary calculations and modeling can help prepare the network for the required number of devices and calculate key parameters and interoperability opportunities.

Our main contributions can be summarized as follows:

1. We aim to create a simulation model of a communication network with a blockchain system awaiting the results of network delay simulation;
2. We are dedicated to providing analysis solutions for simulation and analytical modeling;
3. We include a comparison of simulation results with analytical solution results.

The rest of the paper is structured as follows: Section 2 presents similar and previous works. In Section 3, we summarize the main features of our proposal for modeling blockchain systems in a communication network and present the results of the modeling, and the results obtained are analyzed in Section 4. Finally, conclusions and future work are given in Section 5.

2. Related Works

Today, simulation and analytical modeling are standard tools for evaluating the behavior and performance of most blockchain-based solutions [9].

Modeling is used when conducting experiments with real objects/systems is inconvenient, impossible or too costly. The main difference between simulation and other methods of studying complex systems is the ability to optimize a system before it is implemented. Since many applications implement blockchain, which is difficult to deploy on test networks, modeling and simulation of systems is an important aspect for performance evaluation.

Models are traditionally divided into analytical and simulation models. An analytical model is based on a theory or hypothesis, describes a particular aspect of the system using mathematical expressions, and produces the final results of the study in formal relationships suitable for quantitative and qualitative analysis. This type of model is usually used to describe the fundamental properties of objects.

To date, the modeling of network processes in the field of blockchain solutions has been underdeveloped. However, researchers are already trying to identify mathematical models to describe blockchain technology processes and their dependencies. Table 1 compares the most significant analytical modeling solutions.

Simulation models are created using standard software using standard computer systems. An indisputable advantage of simulation modeling is the possibility of obtaining numerical solutions for those models that cannot be described by finite analytical expressions [8]. Of course, not all tasks can be solved using simulation modeling, for example, tasks that require too much computation due to limited resources of computing systems and finite time of operations.

Effective traffic forecasting models and methods are being developed to ensure the quality of services provided and the stability of communication network elements when using distributed registry technology.

Currently, there are several blockchain technology simulation solutions on the communication network that allow various tests to be carried out before making a final decision on implementation. Table 2 provides a comparison of the most relevant simulation solutions.

Table 1. Analytical modeling solutions for blockchain systems.

Research	Presented Solution	Tool/Technology	Parameters to be Considered and Characteristics to be Modeled
[10]	Modeling the process using multiple queues based on four phases (waiting for inclusion in the block; waiting for confirmation; waiting for service; servicing)	A state transition graph; Mass service theory; Markov processes	Simulation of block generation; State transition probabilities; Access delays
[11]	The mining organization model is defined by M/M/n/L. The queue capacity is set as TxB, the queue policy is first-come, first-served, and the discard rule is block after service, which means that only transactions of block size TxB remain in the dynamic memory of the mining nodes, while other transactions, even if they are processed, are in the memory pool	Mass service theory	Average number of transactions per block; Total mining capacity; Number of transactions per second
[12]	The M/M/1 model is used to model the blockchain memory pool, and the mining pool is modeled by the M/M/n model. There can only be one block in a mining pool at any one time. However, within a mining pool, processes can be divided into multiple tasks or threads for parallel processing by multiple mining nodes in the network.	Mass service theory	Average number of transactions per block; The speed at which transactions arrive; Average mining time per block; system/transaction throughput; waiting time in memory pool; The number of unconfirmed transactions in the entire system; Total number of transactions
[13]	The mining process is modeled using a queuing system, analyzing transaction confirmation times. The authors consider the M/G/1 model with batch service, in which a newly arrived transaction cannot reach the service facility even if the number of transactions in the service facility does not reach the maximum batch size. In this model, the dwell time of a transaction corresponds to its confirmation time.	Mass service theory	Average block generation time; Average number of transactions in the system
[14]	The system is considered using the M/G/1 model as an example. Data arrivals to nodes are modeled as a heterogeneous Poisson process, where the distribution of arrival rate to nodes is derived from an analytical model of the data delivery protocol.	Mass service theory	Block and transaction allocation time probabilities; Node response time; The likelihood of a branching chain; Duration of the period of the inconsistency of the register
[15]	Stochastic network models are proposed to capture the evolution and dynamics of the blockchain. A combination of analytical calculations and simulation experiments is used to investigate both steady-state and transient performance characteristics	Stochastic models	The effect of a block's propagation delay; Hashing power of nodes
[16]	Game theories are proposed for modeling to address common problems in the blockchain network, such as security, problems related to mining management, and issues related to the economics of the blockchain.	Game theory	Economic aspects
[17]	The system is examined using the M/G/∞ model as an example. Equivalence between two specific service disciplines is used to obtain the stationary distribution of the model.	Mass service theory	Distribution of busy periods; service delays
[18]	The theory of mass service in blockchain systems is developed, and system performance is evaluated. For this purpose, a Markov queuing system of packet service is developed with two different stages, which are suitable for explicitly expressing the process of mining in a pool of miners and constructing a new blockchain.	Mass service theory; Markov processes	Average number of transactions per queue, Average number of transactions per block; Average transaction confirmation time.

Table 2. Simulation solutions for blockchain systems.

The Solution	Description	Software Packages
Test networks	A test network of a particular system is used to test the performance or relevance of an application. Coin analyses that have no real value are used	Bitcoin Testnet Explorer [19]; Blockcypher [20]; Bitcoin Testnet Faucet [21]; Rinkeby network [22]; Ganachecli [23]; Ethereum Tester [24]; Truffle framework [25]; Remix ide [26]; IBM Blockchain platform [27]; Remme [28]; Cryptospaniards [29]
Demonstration of how the technology works	These solutions show how basic blockchain operations work, such as hashing, mining and distribution. It also provides information about the result of the procedure when certain parameters are changed	Blockchain demo [30];
Simulators for event management	With these solutions, users can explore the underlying characteristics and performance of the network, investigate interactions between nodes and compare different simulation scenarios. They serve as a fair comparison across platforms and provide a deeper understanding of different system design options. Applied to pretest to evaluate overall performance and with workloads to evaluate individual tier performance	Vibes [31]; Simblock [32]; Blocksim [33]; BlockLite [34]; Bitcoin simulator [35]; Blockbench [36]; Hyperledger Caliper [37]
Network section simulator	The solutions combine mathematical and logical aspects and reproduce the real behavior of the system using computer software	AnyLogic [38]; MATLAB [39]; NS3 [40]; GPSS World [41]

3. Modeling Blockchain Systems on a Communication Network

As modern networks provide a wide range of services, the transmission of each type of traffic requires some conditions to a number of service quality parameters, such as delay, loss, jitter and others. In this regard, there is a need for system modeling and parameter estimation, as the existing traffic models and traffic characteristics change as new applications are introduced. In the following, we propose considering the modeling of different system parts when transmitting user traffic.

Currently, user session traffic is referred to Poisson models [42], but in heterogeneous traffic, it is possible to observe self-similarity, estimated by the Hurst coefficient. The prevalence of non-Poisson traffic necessitates using G/G/v, G/D/v models to describe analytical methods [42,43].

It is worth noting, however, that the proof-of-work consensus mechanism involves nodes performing operations to solve a computational problem with extremely low probability. Thus, the nodes essentially perform Bernoulli tests at an enormous rate, each with an extremely low probability of success, meaning that successes roughly occur as a Poisson process [17].

In the proposed system, to describe the nature of third-party application data flows at the access layer, consider models with time intervals between packet requests formed according to the simplest distribution law commonly used in data communication network analysis and design (M_{NET}). The time interval between requests of blockchain applications, according to the solutions presented in Table 1, we refer to the Markovian (M_{BC}). According to the properties of such flows at the router, the total flow (M_{NET+BC}) converges to a simple flow with an intensity equal to the sum of the intensities of the original flows [44].

In this case, the law of service time distribution of such traffic is described by dependencies with the predominance of self-similarity, which occurs due to combining multiple isolated sources. To model the self-similar flow, various methods called the ONOF method are used, involving forming the flow of interest by combining flows from multiple sources [42]. Thus, due to the properties of pulsating traffic on the aggregation level equipment, the distribution of traffic service time obeys a law with "heavy tails" (Pareto, Weibull and lognormal distributions, etc.). Let us consider the Pareto distribution for traffic service time as the best fit in terms of characteristics. Hence, a simplified system model can be considered as $M_{NET+BC}/Pa/v$ and $M_{NET+BC}/Pa/1$ when considering and evaluating the performance of each device.

The Pareto distribution function is defined as follows:

$$F(t) = 1 - \left(\frac{M}{t}\right)^{a}, for\ t \geq M,\ t > 0,\ M > 0 \tag{1}$$

where:

M is the scale parameter;
a is the shape parameter.

Checking the aggregated original temporal sequence for self-similarity is an important task in the modeling of LSMS data. As defined in [45], self-similarity is preserved when the original temporal sequence is aggregated. In this case, the process is self-similar if:

$$\lim_{n \to \infty} R^{n}(k) = \frac{\sigma^2}{2}\left((k+1)^{2H} - 2k^{2H} + (k-1)^{2H}\right) \tag{2}$$

where:

$R^n\ (k)$ is the correlation function for the aggregated time series;
H is the Hurst parameter;
k is the time shift;
σ^2 is the sampling variance of the sequence.

However, if we consider a situation where the distribution law of service time for such traffic will be described by dependencies more complex to initialize, then it is worth moving to a model with a general distribution type—M/G/1. Then, according to [46], the average packet residence time in the system:

$$T = \rho + \rho^2 \frac{1 + C_B^2}{2(1-\rho)} \tag{3}$$

where:

ρ is the system utilization factor;
${C_B}^2$ is the normalized variance of the service time.

Average waiting time in the queue:

$$W = \frac{\lambda \varphi^2}{2(1-\rho)} \tag{4}$$

where:

λ is the average rate of receipt of an application
φ^2 is the second-order momentum of a random variable.

Most existing applications adhere to the nature of unicast, whereby traffic is directed from a single source to a single destination. Broadcasting is used to send a single stream of control commands and other service information to all subscribers on the network. However, due to the nature of the blockchain algorithm, there is a significant increase in multicast traffic when updating data in the registry, which duplicates information for different blockchain nodes.

When transmitted over a network, traffic is affected by network devices, processing policies in these network devices, quality of service mechanisms, congestion at nodes, operation of transport layer protocols, dynamic routing, load balancing, etc. Thus, flow characteristics can be significantly modified by network influences [47].

In data transmission networks, there are many queues to transmit, which interact with each other, merging with parts of other streams occurs, which affects and complicates the nature of the processes [47,48]. The result of aggregating random processes will also be a random process with modified characteristics.

In this regard, the interaction model—G/G/1 and G/G/n—can be arranged at the edge router. However, one way to estimate the probability-time characteristics of telecommunication nodes of an infocommunication network as a WAN under weak correlation is to solve the Lindley integral equations. Let us pay special attention to the final formula obtained in the derivation of the equation [46]. The expression of the integral waiting time function for any values of the argument will be:

$$W(y) = \int_{-\infty}^{y} W(y-u)c(u)du \tag{5}$$

Thus, the proposed model as a mass service network consists of coupled models characterized at the access level by M/M/1, at the primary hub level by M/G/1, and at the edge router level by G/G/1. Due to the complexity of self-similar processes, simulation methods are usually applied to calculate their analytical models [49].

The time for adding a transaction to the block and confirming it in general terms:

$$t_{BL} = \max_{i=k} t_{proc\ i} + \sum_m t_{delay\ m} + t_{MP} + t_m + t_{ver} \tag{6}$$

where:

k—the number of nodes initiating creating the transactions needed to form the block (depends on the number of transactions in the Memory Pool), varies with the number of connected active nodes;
$t_{proc\ i}$—the time taken for node i to send a transaction to the network, depends on the network card and network configuration;
m—the number of network devices the packet passes through during transmission, depends on network configuration;
$t_{delay\ m}$—the network latency introduced by devices when transmitting a packet—a problem that can create greater potential for forks and vulnerability to hostile attacks;
t_{MP}—dwell time of unconfirmed transactions in Memory Pool before being added to the block;
t_m—time to check the block and solve the computational problem by the miners, depends on the consensus algorithm;
t_{ver}—time taken to check the block and add it to the common chain (approximately a few milliseconds), depends on network configuration.

For the model presented, the transaction confirmation time will be represented as follows:

$$t_{BL} = \max_{i=k} t_{proc\ i} + \sum_m [\rho_m + {\rho_m}^2 \frac{1 + C_{Bm}^2}{2(1-\rho_m)}] + t_{MP} + t_m + t_{ver} \tag{7}$$

Analytical modeling of a blockchain network faces many challenges. For example, the variability in the number of connections between nodes affects the data distribution algorithm and introduces variability in the transmission rates of data arriving at the nodes [16].

To simulate the network delay ($t_{delay\ m}$), it is proposed to use the system the simulation system AnyLogic is proposed.

It is necessary to clarify some restrictions for the presented simulation model: the model aims to check the network characteristics when distributing blocks and does not include assessing the parameters of the throughput of transactions and the time for processing the block by miners. However, the scalability of the blockchain system depends on the underlying consensus, network synchronization, and architecture [50].

The system supports various approaches to simulation models, allows different aspects of the system to be modeled at different levels of detail, and has a graphical interface [49].

For the AnyLogic simulation model network presented by the authors, a simplified scaling of the system is assumed depending on the networks and parameters of interest. In this case, no separate virtual machines were used. In the current version, the characteristics were checked for devices between the access network and the border router, traffic from 100 blockchain devices belonging to the public network and using the characteristics of the PoW consensus algorithm was simulated on the access network, with the following indicators—the intensity of creating transactions according to the gamma distribution with variable parameters.

Figure 2 shows the AnyLogic model of a data network when blockchain technology is included.

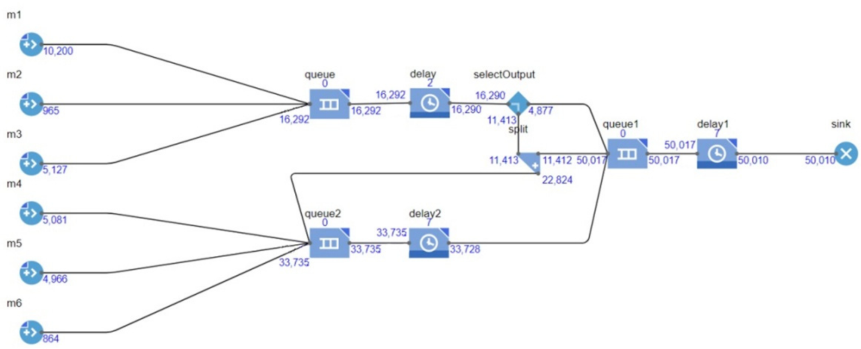

Figure 2. Simulation of a system with blockchain nodes.

Figure 3 shows the simulation of delay and queuing at the access node and aggregation node. Figure 4 shows the dependence of the proportion of packets at the end-to-end network delay of the system. Figure 4 shows the analytical and simulation model results for assessing network delay ($t_{delay\ m}$). It can be assumed that the results obtained are correct with acceptable measurement accuracy.

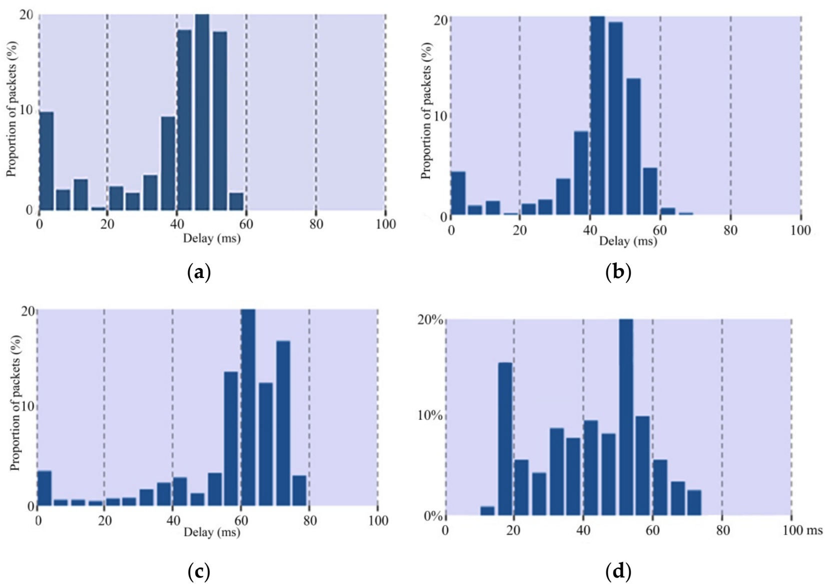

Figure 3. Simulation results of the blockchain node system: (**a**) Dependence of the proportion of packets on the waiting time for processing at the access node; (**b**) dependence of the proportion of packets on the delay at the access node; (**c**) dependence of the proportion of packets on the waiting time for processing at the aggregation node; (**d**) dependence of the proportion of packets on the delay at the aggregation node

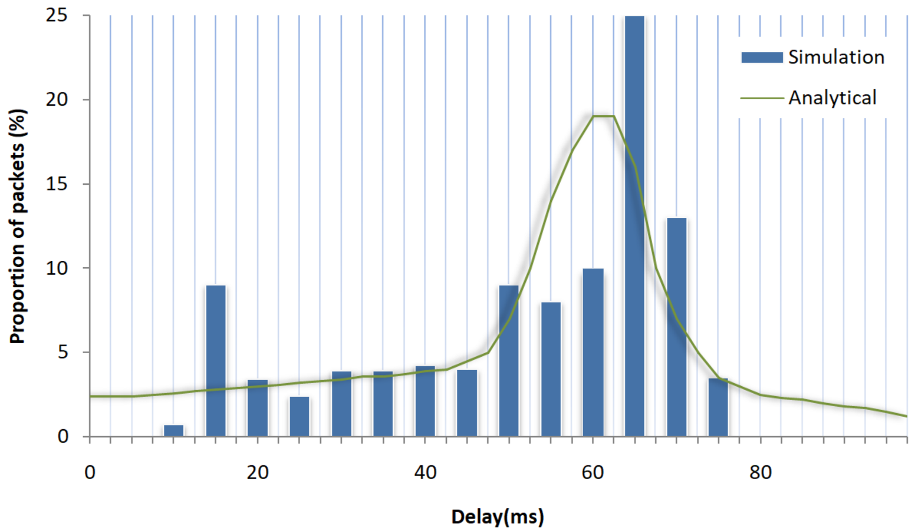

Figure 4. Dependence of the proportion of packets at the end-to-end network delay of the system.

4. Comparative Analysis of the Results

Figure 4 shows that the values obtained by simulation modeling take into account the peculiarities of the data in packet networks, but globally do not contradict the analytical conclusion obtained by equations 7. Network nodes introduce latency, but the main latency in confirming a transaction will depend on the time spent in the memory pool and on the computational task being performed by the miners. It is worth noting that network latency plays a key role in propagating a transaction and block through the network, so a significant latency will affect the queuing in the memory pool, which will affect the time to add a transaction to the block, and the confirmation of the mining task since a node should stop working on its blocks as soon as a new block is announced to save computational resources, but nodes may receive newly created blocks too late due to propagation delay and continue working on the already obsolete block. Therefore, in terms of efficient transaction processing and overall system performance, the network parameters of the nodes should be of key importance. The experiment also showed that the network's performance depends on the intensity of requests, and the node intensity and buffer size values can be varied for the correct operation of the blockchain technology presented.

It should be noted that modeling blockchain technology performance with AnyLogic is possible and convenient to analyze when various parameters change. However, for more accurate results and a more complete system response, more research into blockchain simulation is needed. The analysis of the models has shown the applicability of selected simulation systems for assessing the impact of blockchain technology on data networks.

5. Conclusions

Today, the volume of traffic generated by blockchain devices is less than that of services, such as video and data. However, because of the growing popularity of the technology, the potential number of blockchain devices may become so large that their traffic is comparable to that of traditional services. If blockchain technology traffic is co-served with delay- and loss-critical traffic, it can significantly impact the quality of service of traditional services traffic. In this paper, an overview of analytical and simulation modeling solutions focusing on mass service systems has been conducted and presented. Simulation comparison results are presented.

There are plans to extend the system indicators to obtain more accurate results with the AnyLogic system and to propose a methodology for calculating the network infrastructure based on the traffic characteristics and data obtained. A more detailed study of the dependencies associated with consensus, cryptographic primitives, is planned by the authors in future works.

Author Contributions: Conceptualization, A.V.; formal analysis, A.V.; funding acquisition, V.E.; investigation, A.S.; methodology, A.V. and V.E.; software, A.V.; supervision, A.V.; validation, V.E.; writing—original draft, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by RFBR, project number 19-37-90050/19 (Moscow, Russia).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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