CELLULAR INTERNET OF THINGS MODELING: THE LITERATURE REVIEW

DOI: 10.36724/2072-8735-2024-18-8-68-76

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Manuscript received 10 June 2024;
Accepted 17 July 2024

Keywords: *Internet of Things, resource allocation, telecommunication systems, cellular networks, mathematical modeling, LTE-M, NB-IoT, 3GPP, CIoT.*

This article presents a literature review on the Cellular Internet of Things (CIoT) and outlines how mathematical modeling can be used in the development of efficient solutions to model, analyze, and design CIoT networks. CIoT, by its nature, connects enormous device counts in cellular networks, thus facing challenges associated with scalability, latency, energy consumption, and security. Mathematical models, including Markov chains, queuing theory, and stochastic models, are considered important in simulating network behavior and predicting performance under varying conditions. Accordingly, different models are categorized with respect to their approaches and which specific aspects of CIoT they tackle. It is found that there is no comprehensive hybrid study in the previous literature that includes resource allocation and performance evaluation in burst access cases of mobile IoT devices with different traffic natures. Most previous studies focus on resource allocation in IoT networks, but they often ignore various QoS requirements, such as latency, for example. The review shows important directions, challenges, and gaps in recent research, pointing toward the necessity for more evolved and up-to-date models reflecting contemporary CIoT network complexities. This study would be a useful and efficient approach for researchers and designers of various CIoT models to assess the current state of CIoT modeling in the literature and identify future work opportunities as well.

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Для цитирования:
Давуд Таммам, Степанов М.С. Моделирование Сотового Интернета Вещей: обзор выполненных исследований // T-Comm: Телекоммуникации и транспорт. 2024. Том 18. №8. С. 68-76.

For citation:
Tammam Dawood, Stepanov M.S. (2024). Cellular Internet of Things Modeling: The Literature Review. *T-Comm*, vol. 18, no.8, pp. 68-76.

Introduction

The Internet of Things (IoT) is one of the most transformative technological advancements of the 21st century. Over the past decade, IoT has rapidly evolved, fundamentally altering the way people interact with the physical world by connecting everyday objects to the internet, enabling them to send and receive data. This connectivity allows for enhanced automation, improved efficiency, and the creation of smart environments in homes, cities, industries, and more. The IoT's impact spans numerous sectors, from healthcare and agriculture to manufacturing and urban development [1, 2].

IoT technologies optimize the management of traffic, reduce energy consumption, and increase public safety in smart cities. These also include self-adjusting brightness depending on pedestrian activity and the provision of connected traffic signals to improve transport flows. In health, IoT devices will help in real-time monitoring of patients remotely, thereby allowing timely interventions [3, 4].

The more sophisticated and widespread IoT applications become, the greater the need is for wide-area reliable connectivity. Cellular Internet of Things extends the capabilities of any automation system by using mobile networks like LTE and 5G to ensure that devices always stay connected and operational over long distances and in various environmental conditions. CIoT would therefore be very important in those applications that require mobility and real-time data transmission, such as fleet management, smart agriculture, and mobile health monitoring [5].

The importance of CIoT has been further increased with the forthcoming 5G. The 5G network possesses significantly lower latency, higher data rates, and increased capacity, which will introduce a new generation of IoT applications. On the other hand, it will enhance present-day applications. For instance, the autonomous vehicle will use 5G networks for communication among themselves and with the traffic infrastructure in real-time to ensure their safe and efficient operations [6]. CIoT devices can monitor soil conditions, climatic patterns, and crop health in agriculture, hence providing data-driven decisions to the farmer for increasing the yield and reducing wastage [7].

Two basic technologies specifically developed for IoT applications on cellular networks are LTE-M and NB-IoT. Since the data rate offered by LTE-M is higher and has more mobility, it is most appropriate for applications like asset tracking and remote monitoring. NB-IoT, being ultra-low power consumption and broad coverage, is the most suitable solution for applications such as smart metering and environmental monitoring. These two technologies help in ease of integration with existing LTE infrastructure, enabling increased cost-effectiveness and scalability of solutions [5]. Extended Coverage-GSM-Internet of Things (EC-GSM-IoT) and 5G NR Reduced Capability (NR-RedCap) are two evolving standards under the umbrella of CIoT that aim at the realization of extended coverage and reduced complexity while ensuring enhanced capabilities for specific use cases [8].

The role of mathematical models in CIoT is very important because the networks are dynamic in nature owing to device movements and changes in the network environment. They aid in ascertaining the complex interactions between the IoT devices and the network infrastructure, thereby making it possible to simulate a range of scenarios related to traffic loads, device densities, and mobility patterns. This simulation capability allows for the evaluation of some performance metrics, including latency, throughput, and energy consumption. In addition, these models provide insight into resource optimization, such as overall network efficiency and reliability for IoT. Only by making mathematical models of IoT systems can researchers capture their behavior, predict their performance under different conditions, and detect problems before they even happen [9-19]. It is specifically valuable for cellular IoT networks where a massive quantity of devices is necessarily on the move all the time, coupled with a very dynamic network environment and limited resources in terms of bandwidth, energy, and processing power [9-14]. With the optimal resource utilization assured, massive deployment of the devices can be permitted within these CIoT networks with guaranteed quality requirements.

The allocation of resources in LTE and 5G networks is dynamic, with the application of complex algorithms. These algorithms consider such parameters as the priority of IoT applications, the requirements for quality of service, and the current network load. The efficient allocation of resources minimizes delays, reduces energy consumption, and enhances the exploitation of existing resources [10, 12].

For example, smart cities can provide resource allocation algorithms that prioritize emergency responses over lower-priority applications. In the industrial IoT setting, they can help ensure that bandwidth for critical machine-to-machine connections is adequate to allow for their operations. Briefly, dynamic resource management is crucial to the stability and performance of IoT networks, particularly because the number of connected devices is growing rapidly.

The aim of this article is to review the most prominent research in the literature on modeling CIoT networks and outline the most critical parameters considered in their performance assessment. In addition, the strengths and weaknesses of each of those researches will be commented on to point out gaps and possible future research directions.

Cellular Internet of Things Modeling

The modeling of CIoT networks is crucial with the unique challenges introduced by the need for reliable and efficient communication in quite diverse and often resource-constrained environments. CIoT-related modeling aspects include ultra-fast wireless data aggregation (WDA) of ultra-densely deployed networks [20], strategies for energy harvesting and information transmission of energy-constrained IoT devices [21], the interplay of device-to-device communications and real-time monitoring systems in CIoT networks [22], accurate cellular traffic prediction [23], and so on.

Mathematical modeling plays a very important role in understanding and optimizing the performance of CIoT networks. The models developed are to analyze network behavior under different conditions, predict performance metrics such as throughput and latency, and thereafter develop resource allocation and traffic management algorithms. In the last decade, researchers have used various methodologies to approach the subject, from queuing theory and stochastic geometry to machine learning and game theory.

The model proposed in [24] relies on queuing theory to address the problem of joint servicing of unicast and multicast traffic with a special focus on prioritization of the various traffic types, keeping in view their diversified QoS requirements in 5G networks. The proposed model is of paramount importance for understanding the various types of traffic behavior in a network environment. It gives insight into the amount of resources occupied by the different types of traffic within different areas of the coverage zone. This is important information that is needed in the determination of the overall amount of resource involved in the 5G network. It calls for the need to prioritize the traffic types, more so in the context of 5G networks. On the other hand, there are some limitations:

- The created mathematical model is based on certain assumptions about traffic behavior and network conditions that may not be true in all real-world scenarios. This may limit the applicability of the results to diverse environments.
- The model does not take into consideration the resource requests from IoT devices and applications, which are of a special nature.
- The approach of dividing the coverage area into two distinct areas for analysis may oversimplify the complexities of real network environments, potentially overlooking interactions between different traffic types.
- The study primarily addresses unicast and multicast traffic, which may not encompass all types of traffic present in modern networks, such as broadcast or hybrid traffic scenarios.
- While the method for distributing radio resources is based on balancing performance indicators, the paper does not extensively discuss how variations in these indicators might affect overall network performance under different conditions.

In [25], three resource allocation strategies (Static, Dynamic, and Dynamic with Reservations) between NB-IoT devices and LTE users are discussed and analyzed (Fig. 1).

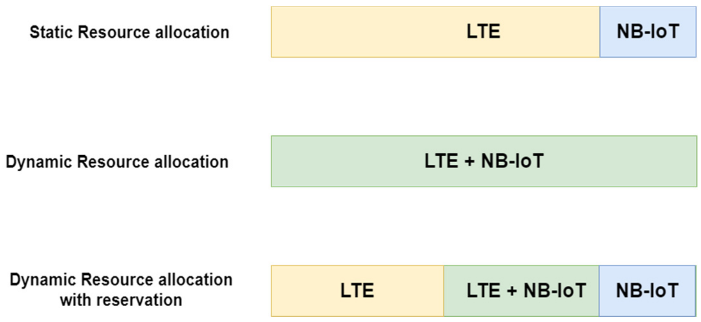

Fig. 1. Resource Allocation Strategies [25]

The study assessed the probability of blocking LTE sessions as the number of NB-IoT devices rises, as well as the probability of blocking NB-IoT sessions as the number of LTE users within the cell rises, across the three proposed resource allocation strategies. It was concluded that in the case of applying the static resource allocation strategy, the increasing load of a specific type of traffic does not affect the other type, but the level of the incoming load must be known accurately before starting the resource allocation process in order to determine the appropriate amount of resources for each type of traffic for obtaining better system throughput. In the case of dynamic resource allocation, the network throughput is higher, but increasing the number of devices of one type of traffic can increase the blocking rate of the other type (unguaranteed reliability). The dynamic allocation strategy with reservations allows for efficient use of network resources while maintaining reliability requirements for each type of traffic. In contrast, some characteristics of IoT traffic have not been considered by the authors, such as the case where IoT service requests arrive in groups or in bursts.

The authors of [25] continue their work on resource allocation in [26], where the study in the latter particularly focuses on the challenges of gathering heterogeneous data in IoT networks, especially the concurrent transmission of high-rate video streams from LTE-connected devices and low-rate sensory data from NB-IoT devices (Fig. 2). This focus is essential for modern IoT applications that require diverse data types. The paper employs a mixed service queuing system to model the performance of LTE and NB-IoT under varying traffic loads, allowing for the analysis of session drop probabilities and resource utilization. It also conducts a numerical study that evaluates different resource allocation strategies (static (fixed allocation), dynamic (fully shared resources), and dynamic with reservations (a mix of both)), ultimately advocating for dynamic resource sharing with reservations as the preferred solution.

This recommendation is based on its effectiveness in ensuring reliable data collection in large-scale IoT deployments while maintaining high resource utilization levels. The authors examine the performance of their model by taking into account the session drop probability for both NB-IoT and LTE sessions, as well as radio utilization. While the paper addresses QoS requirements, it may not fully account for the variability in QoS demands across different applications and scenarios. This could affect the model's ability to generalize across diverse IoT applications that have varying performance requirements, e.g., under conditions of burst arrivals. The parameters used in the numerical assessment are shown in Table 1.

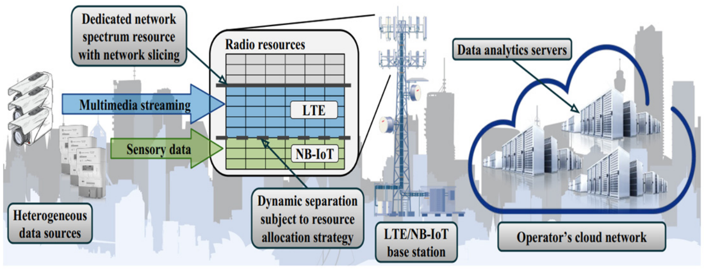

Fig. 2. Considered system design in [26]

Table 1

Parameters used in numerical analysis in [26]

Description	Value
Number of basic channels in one LTE cell	100
Number of basic channels in one Resource Block	4
Number of channels reserved for LTE	[0,…, 100]
Number of channels reserved for NB-IoT	[0,…, 100]
Number of channels for one LTE session	4
Number of channels for one NB-IoT session	1
Mean LTE session duration	10 s
Mean NB-IoT session traffic	100 Kbit
Session arrival rate per LTE device	1/min.
Session arrival rate per NB-IoT device	10/min.

In [27], a dynamic resource allocation scheme is proposed that allows for the sharing of physical resource blocks (PRBs) between multiple M2M devices or a single H2H (Human-to-Human) user, optimizing resource utilization. The resource allocation scheme is based on fixed bandwidth intervals, where traffic from Machine-Type Communication (MTC) devices is served according to the Processor Sharing (PS) discipline. This approach ensures that M2M communications are handled efficiently without monopolizing resources. However, the paper assumes certain characteristics for M2M traffic, such as minimum bandwidth requirements and data block sizes, while M2M applications can vary widely, and this generalization may not accurately reflect the diverse nature of M2M communications in real-world applications. In addition, while the paper provides performance measures such as blocking probabilities for H2H users, it does not comprehensively address other critical performance metrics, such as latency and throughput for M2M communications. The devices' mobility is also not taken into account.

A prioritization method proposed in [28] ensures the isolation of URLLC traffic from eMBB in industrial 5G NR deployments, using stochastic geometry and queuing theory for model formalization. While the paper claims to provide perfect isolation for URLLC traffic even in dynamically changing environments, the assumptions made regarding the nature of these changes may not fully capture real-world variability. The dynamic characteristics of eMBB traffic can be complex and unpredictable, which may affect the reliability of the proposed solutions in practice. This focus on eMBB and URLLC traffic may thus mask the impact of other types of traffic that could be constituted in the industrial environment, such as massive machine-type communications (mMTC). This limitation may affect the overall performance and strategies for resource allocation that are put forward in the paper.

The model proposed in [29] considers a single flow of customers with random resource requirements, and each customer competes for a limited number of resources available within a queuing system. Under these conditions, the behavior of such a system can be modeled by the stochastic process governing customer acceptance or loss, depending on the needs and availability of free resources. Efficient computation of the stationary probability distributions and resource metrics is key to assessing the M2M traffic characteristics over LTE networks; an algorithm for recurrent convolution is thus proposed. Coupled with sampling methodology for continuous resources, the developed algorithm analyzes the performance of an LTE network under M2M traffic conditions and gets insight into resource allocation strategies. The model presented in the paper contains a few key parameters that are essential in the analysis of M2M traffic over an LTE network. These parameters are explained as follows:

- Arrival Rate (λ): This is a parameter representing the rate by which customers, or in this case, M2M devices, arrive in the system. It is assumed to be Poisson-distributed, meaning that arrival times are random and independent in time.
- Number of Servers (N): The model includes N available servers to serve the arriving customers. One customer requires one server during the service period.
- Types of Resources (M): M types of resources have been considered that may be required by the customers. Here, for each type of resource, there may be a vector for the respective capacity. That means the resources have limited availability in the system.
- Resource Requirements (R): Each customer is associated with a resource requirement vector, which is a random variable (RV). It is independent of the arrival process, having a cumulative distribution function (CDF).
- Service Times: The service times for any customer are assumed to be exponentially distributed with parameter μ. That is, the time it takes to serve every customer is random, following an exponential distribution, which is quite frequent in queueing theory.
- Distance d: This is the random variable of distance from an M2M device to eNodeB. It becomes an important parameter in determining the achievable bit rate during data transmission.
- M2M Device Transmit Power (p): The transmit power of the M2M device is a random variable that determines the quality of communication and the achievable bit rate.
- Maximum Transmission Power ($p_{\max}$): This parameter defines the maximum transmission power a device is allowed to use. It puts a limit on the transmit power and is, thus, one of the parameters controlling the overall performance of a network.
- Uplink Bandwidth (B): The uplink bandwidth is another major parameter affecting the bit rate achievable for data transfer. It differs depending on the network configuration and specific service requirements.
- Guaranteed Bit Rate: The model considers guaranteed bit rate data transmission, which would be important in ensuring that during their communication, the M2M devices can meet all the requirements for their service.

These parameters, all together, bring out the behavior of the multiserver queuing system and turn out to be very essential in analyzing the performance of M2M traffic in an LTE network. The interactions among these parameters help in understanding the resource allocation and service dynamics within a network. However, the model has the following limitations:

- This analysis is oriented particularly to M2M traffic; therefore, the results may not be useful with other types of traffic in the LTE network. These unique features of the M2M communication may not generalize very well in other service types, such as human-centric communications.
- The model does not take into account different network conditions such as interference, device mobility, or variable channel conditions, which would affect the performance of M2M communications over real-world LTE networks.

The study in [30] presents the problems and solutions of the Random Access Channel (RACH) in LTE with a focus on massive M2M communications. The primary aim of the study is to analyze the RACH initiation procedure using a discrete Markov chain model. It presents a simulation model that estimates the influence of preamble collisions on the success of access connection initiation. This model is designed to evaluate the performance of the RACH under conditions of burst arrivals, which are common when many devices attempt to connect simultaneously, such as after a power outage. However, the study primarily concentrates on the Random Access Channel (RACH) initiation procedure. While this is a critical aspect of LTE performance, it may overlook other important factors affecting overall network performance, such as data transmission efficiency and quality of service during high traffic periods.

In [31], the authors propose a novel framework that analyzes the time-dependent behavior of 5G systems, particularly focusing on the transient dynamics following network-centric optimization. This framework incorporates insights from random walk and Markov chain theories to better understand how user mobility affects system performance. The research emphasizes the importance of energy-aware strategies, such as base station switching, to align network capacity with actual traffic demand. This approach not only reduces energy consumption but also enhances the sustainability of the network, demonstrating practical application of the theoretical findings. Although the paper discusses energy savings achieved through base station switching but does not provide a comprehensive analysis of how these savings may vary under different traffic conditions or user behaviors.

Previous studies have focused on resource allocation in IoT networks, but they often overlook the diverse QoS requirements, particularly regarding strict latency demands in multi-hop scenarios. Authors in [32] aim to fill this gap by proposing an optimization mechanism based on Age of Information (AoI) metrics to enhance packet delay performance in CIoT networks. They tackle the challenges of delivering reliable wireless access for massive IoT devices in cellular networks, highlighting the necessity for effective data transmission mechanisms to reduce packet delays. The expected number of devices and connections between Access Points (Aps) and the main base station (MBS) are calculated using the Poisson-Voronoi (PV) system. The paper introduces a queueing model that prioritizes data packets based on their AoI, allowing high-priority packets to access the channel without the listen-before-talk (LBT) requirement with the aim of efficiently managing limited resources while meeting the QoS requirements of delay-sensitive IoT applications. In contrast, the proposed model assumes uniform behavior among IoT devices and their packet transmission characteristics. This simplification may not capture the diverse nature of IoT devices, which can have varying capabilities and requirements, potentially resulting in inefficiencies in practical applications.

In [33], a new approach is introduced to enhance delay performance for both regular (permanently connected) and conventional stochastic traffic in NB-IoT deployments. The study constructs an analytical model to capture the random access procedures for these two traffic types over an application query interval. This model is calibrated using actual measurements from operational NB-IoT networks, providing a more accurate assessment of system performance. The research reveals that while the number of UEs generating regular traffic significantly impacts the average delay for both traffic types, conventional sporadic traffic has a minor negligible effect on the performance of regular traffic. However, the paper assumes an ideal network deployment by the telecom operator, without any user equipment (UE) in the cell experiencing very poor channel conditions. This assumption may not hold in real-world scenarios where varying channel conditions could significantly affect performance, potentially leading to inaccuracies in the model's predictions.

The authors of [34] explore the impact of heterogeneous mobility (user and device movement) on mission-critical machine-type communication (mcMTC) applications in three different scenarios (industrial automation "A", vehicular communication "B", and urban communication "C") shown in Fig. 3. Various mobility models are employed to assess the effects of device mobility on mcMTC performance, focusing on D2D links and drone small cells as mobile access points. The study concludes that while D2D and drone-assisted links enhance mcMTC performance at lower speeds, their benefits decrease significantly as speeds exceed 60 km/h and emphasizes the potential of heterogeneous multiconnectivity approaches to meet stringent industrial requirements while acknowledging the operational challenges posed by diverse equipment and higher operational costs. One of the major shortcomings of this research is that some parameters specific to IoT traffic were not taken into account.

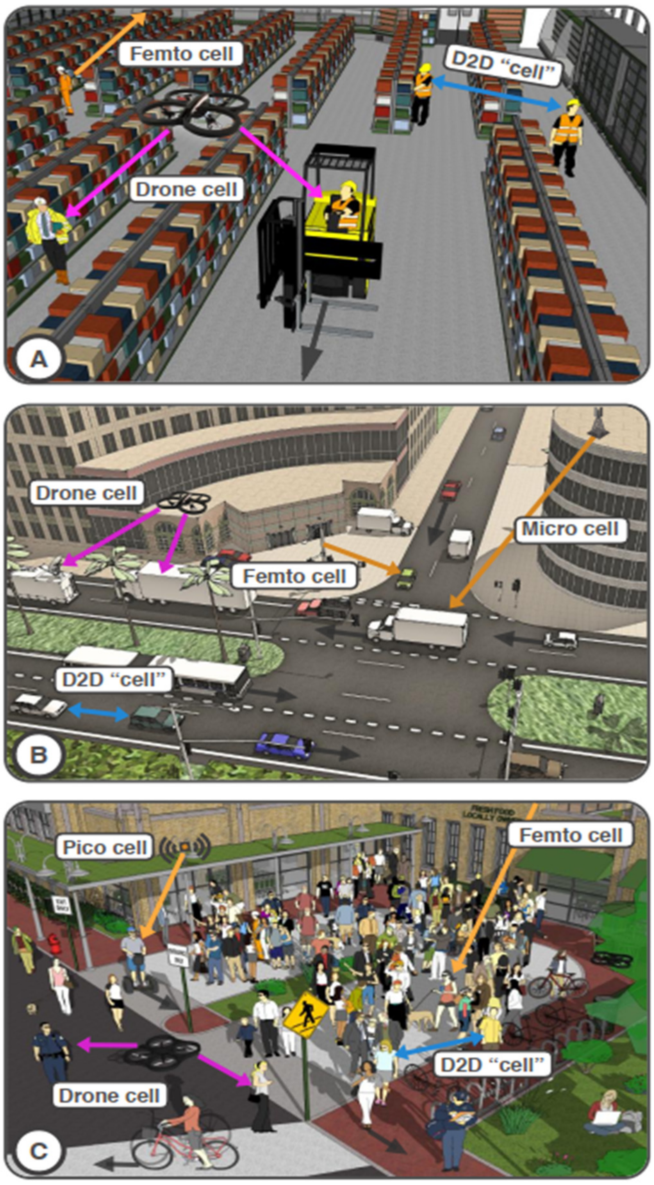

Fig. 3. Study cases in [34]

In [20], a novel analytical expression for the mean square error (MSE) in over-the-air computing (AirComp) within ultra-densely deployed cellular IoT networks is provided. This analytical approach addresses a gap in existing literature, which primarily relied on simulation-based analyses without a clear mathematical formulation of MSE. The effect of the access point (AP) access radius on AirComp performance is studied (Fig. 4), revealing that the choice of this radius significantly influences MSE.

The study identifies an optimal AP access radius that can reduce MSE by up to 12.7%, emphasizing the importance of this parameter in network design. It was observed that as the density of IoT devices increases, the AP can aggregate more data, reducing the MSE. Otherwise, the study focuses on the performance of AirComp with a single access point (AP). This limitation restricts the findings when considering scenarios with multiple APs, which are common in ultra-dense networks. The interactions between multiple APs and their effects on MSE and overall system performance are not addressed, which could be a significant oversight in understanding large-scale deployments.

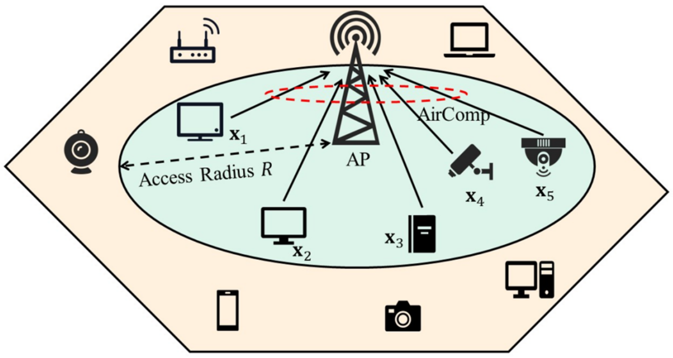

Fig. 4. CIoT network with AirComp [20]

Conclusions

We reviewed some of the related work in CIoT and highlighted how mathematical modeling can be exploited to come up with effective solutions for modeling, analysis, and designing of CIoT networks. The core for attaining maximum performance and efficiency in CIoT networks lies in efficient resource allocation, where usually limited resources like bandwidth, power, or computational capacity are to be utilized effectively. The current literature also reveals that, though there have been clear advances made in modeling different aspects of CIoT, there is a notable lack of comprehensive resource allocation models that can accommodate the exacting requirements of IoT devices and applications.

Future research should aim to develop advanced models that can integrate all these complexities into resource management in a more effective and adaptive manner. This includes how resources are to be allocated in real time, energy-efficient methods to be adopted, and security threats to be safeguarded at each stage of the allocation process. The results from the review conducted in this paper show the need for the development of more robust and adaptive resource allocation models to work in the dynamically changing environments of CIoT networks. By addressing these demands, researchers may considerably improve the performance and scalability of CIoT systems, hence contributing to the expansion of the IoT ecosystem.

In our future study, we plan to develop algorithms and mathematical models based on queueing theory and teletraffic theory for CIoT networks that aim to improve the process of resource planning and distribution between cellular subscribers and IoT devices to solve the problem of resource competition between these two types of users. We plan to discuss hybrid cases that have not been discussed in previous research, such as the case of group arrival of requests from mobile IoT devices with different traffic natures. Such scenarios are very common these days, as connected vehicles, mobile health, unmanned aerial vehicles (UAV), warehouse robots, etc. These models will take into account parameters such as the priority of IoT traffic, access rate, service time, offered link load, available bandwidth, quality of service requirements for each type of traffic, device mobility speed, and group access parameters for IoT requests such as the number of telemetry files in the incoming group and the size of each file. In addition, some QoS indicators (such as probability of lost requests, channel resource busy time, amount of occupied channel resources, etc.) will be adopted to evaluate the performance of such types of networks. These models can provide a reference to determine the resources required to serve each type of CIoT network traffic flow to achieve the desired quality of service in each use case.

This article is a call to action for the research community to focus on developing novel solutions that solve existing limits while anticipating future demands. The continual refining and growth of resource allocation models will be critical to realizing the full potential of CIoT and guaranteeing its success in a fast-changing technological world.

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МОДЕЛИРОВАНИЕ СОТОВОГО ИНТЕРНЕТА ВЕЩЕЙ: ОБЗОР ВЫПОЛНЕННЫХ ИССЛЕДОВАНИЙ

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Аннотация

В данной статье представлен обзор основных результатов в области моделирования систем Сотового Интернета Вещей (CIoT) и описано, как полученные подходы могут быть использованы для анализа и проектирования сетей межмашинного взаимодействия. Основной задачей технологий CIoT является объединение большого количество "умных" устройств посредством сотовых сетей. Следовательно, к главным проблемам, с которыми приходится сталкиваться при развертывании таких систем, можно отнести обеспечение масштабируемости, приемлемой величины задержки передачи данных, низкого энергопотребления и безопасности. Математические модели, основанные на цепях Маркова, теории очередей и т.д., широко используются для оценки характеристик сетей CIoT и прогнозирования их производительности в различных условиях. В статье рассмотрены различные модели CIoT, выделены их основные преимущества и недостатки. Результаты анализа показали, что на сегодняшний момент недостаточно внимания уделяется комплексным подходам, учитывающим распределение ресурсов и оценку производительности в случае передачи трафика с импульсным характером от мобильных IoT-устройств. Кроме того, среди недостатков большинства рассмотренных моделей можно выделить отсутствие учета некоторых важных показателей качества обслуживания, таких как величина задержки, Выводы, сделанные в обзоре, подчеркивают необходимость разработки более сложных моделей, отражающих основные технические особенности мобильных сетей, и определяют направление дальнейших исследований в данной области.

Ключевые слова: *Интернет Вещей, распределение ресурсов, телекоммуникационные системы, сотовые сети, математическое моделирование, LTE-M, NB-IoT, 3GPP, CIoT.*

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