The Concept of Efficient Utilization of the Uplink Frequency Resource of a Smart Factory 5G Cluster by IIoT Devices

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Abstract

The article investigates the functioning process of a smart factory 5G cluster, where both human operators and Industrial Internet of Things (IIoT) devices contend for monopolistic use of the uplink frequency resource, based on the defined Quality of Service (QoS) policy. To analytically formalize this process, the authors have developed a Markovian model. This model reflects both the inherent characteristics of the studied process and the mechanism of adaptive power control, which considers the type of traffic being served by the base station at any given moment. In formulating the model, the authors take into account the spatial geometry of the end devices within the coverage area of the base station, segmented into concentric zones with threshold values for communication quality characteristics. Additionally, the model considers the scenario where the base station transitions into uplink-autonomous mode if it is unable to provide a guaranteed speed for servicing new incoming requests from IIoT devices. To calculate the parameters of the model, a computationally efficient information technology is formulated. Within the framework of the created model, a qualitative metric is proposed, capable of characterizing the evolution of the studied process instance through a set of indicators such as the probability of realizing uplink-autonomous mode, the probability of interruption of IIoT device servicing due to the activation of uplink-autonomous mode, and the average number of devices being serviced in the smart factory 5G cluster during the implementation of uplink-autonomous mode.

Keywords

5G cluster, Smart factory, IIoT traffic, Frequency resource control, Markovian model, Qualitative metric.

1. Introduction

The implementation of Industry 4.0 in organizing smart manufacturing significantly complicates the design stage. Numerous standardized nuances have to be taken into account. Without this, the launch of a smart factory into operation in developed countries is simply not feasible. The communication technologies are the linking element of all components of the smart infrastructure [1, 2]. The most flexible and parametrically responsive to the challenges of Industry 4.0 is the 5G platform [3, 4], the permissible frequency spectrum for the application of which is strictly regulated, finite, and overloaded. This overload phenomenon is characteristic of smart factories with thousands of IIoT devices generating intensive uplink traffic. Under such conditions, achieving effective control of communication resource utilization by simply organizing "vertical" virtual network segments using Network Slicing [5, 6] technology is no longer sufficient. Attention should be paid to the issue of "horizontal" control. The latter involves reasoned QoS policy-based organization of alternating service periods for different types of traffic based on their source within the allocated frequency range. This article proposes an original analytically substantiated response to this relevant scientific and applied issue.

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Among the plethora of network technologies, the one most closely aligned with the aforementioned concept of "horizontal control" is Licensed Shared Access Control (LSAC) technology. An examination of the literature revealed a substantial number of papers dedicated to simulating LSAC [7-9]. For instance, within [10, 11], theoretical discussions regarding various scenarios of network resource management were presented, albeit without the inclusion of analytical models. The studies in [8, 9, 12] outlined a mechanism for allocating the frequency spectrum among multiple tenants of licensed bands through a collaborative auction. This approach facilitated unrestricted access to the shared spectrum for diverse licensees without affiliations. However, no analytical model was put forth in these works either.

In [13], the implementation of LSAC has been suggested for enhancing inter-cell interference coordination by intelligently assigning licensed spectrum to both central and peripheral areas of cells within a mobile network operator, resulting in significant interference reduction. Within [14], the utilization of both dedicated and shared spectrum for in-building small cells has been explored. Furthermore, the challenges associated with operating indoor wireless systems using shared spectrum, in contrast to dedicated spectrum, have been highlighted, emphasizing the importance of interference coordination due to the extensive deployment of small cells in indoor wireless setups. In [15], the analysis of co-channel interference in indoor systems arising from the sharing of satellite spectrum with indoor small cells has been conducted. A study initiative for 5G mobile systems to support Non-Terrestrial Networks, such as satellite systems, has recently been launched by the 3GPP [16]. Additionally, the Federal Communications Commission has proposed spectrum sharing between small cells of mobile systems and satellite systems at 3.5 GHz [9].

The analytical aspect of this issue has been inadequately explored [11, 17], and to derive a model solution, cognitive radio technology was employed. This technology facilitated dynamic spectrum access. The assessment of the model was conducted through analytical and simulation techniques. It is noteworthy that the performance metrics of the analytical models were examined under stationary conditions. On the other hand, non-stationary conditions were considered for the simulation models [18, 19]. Nevertheless, the models analyzed under non-stationary conditions did not incorporate the influence of the periods during which the frequency band operates or remains inactive over time. Non-stationary methods could assess the time dependency and its effects on performance metrics. In recent years, such models have also received significant attention [17, 20].

Taking into account the identified limitations characteristic of the aforementioned closely related studies, let's formulate the object, subject, aim, and tasks of our research.

The object of the research is the functioning process of a 5G smart factory cluster, the monopolistic use of uplink frequency resources of which (concerning the defined QoS policy) is claimed by both human operators and IIoT devices.

The subject of the research comprises elements of probability theory, Markovian chains, and functional analysis.

The aim of the research is to analytically justify the concept of efficient utilization of the uplink frequency resource of a smart factory 5G cluster by IIoT devices.

The research tasks include:

- Parameterization of the research object;
- Formalization of the Markovian model of sequential servicing of standardized uplink traffic by the smart factory 5G cluster's base station under conditions of limited frequency resources.
- Formalization of quality metric indicators for evaluating an instance of a smart factory 5G cluster oriented towards monopolistic use of uplink frequency resources, particularly by IIoT devices.
- Analysis of empirical results obtained during the demonstration of the proposed mathematical framework's functionality.

2. Models and methods

2.1. Research Statement

The focus of our research is a smart factory 5G cluster with a coverage zone limited by a circle of diameter $2R$ centred at the location of the base station. Let's assume that within the vicinity of the 5G cluster, IIoT devices are uniformly distributed and attempt to transfer information messages to the base station with intensity η. The duration of transmitting an information message by an IIoT device is a stochastic parameter, exponentially distributed with intensity θ. We assume that the quality characteristics of the communication channel between the IIoT device and the base station are mostly determined by the distance between these entities. In this context, let's divide the coverage area of the 5G cluster into zones z in the form of concentric circles with radii $z R/Z$, where z is the index of the respective concentric circle, $z=\overline{1,Z}$; and Z is the total number of allocated concentric zones. Next, let's assume that the quality characteristics of the communication (primarily its speed) for all IIoT devices located within the same concentric zone are the same. We'll introduce auxiliary variables: the index $x=Z-z$ and the distance $\delta_l\left(x\right)=xR/Z$, $0\le l\le R$. Considering that the magnitude $\delta\left(x\right)$ is stochastic, let's define its density and distribution function as $f_{\delta_l(x)}\left(l\right)=2l/R^2$ and $F_{\delta_l(x)}\left(l\right)=\left(l/R\right)^2$, respectively. In this case, we will define the distribution series for the variable x as $s_d=\left(2Z-2d-1\right)/Z^2$, $d=\overline{1,Z}$.

Let's suppose that the investigated scenario of operation for the smart factory 5G cluster entails that the singular volume of frequency resource ω can be monopolistically utilized at a certain moment either by a human operator or by IIoT devices, but considering the priorities defined in the QoS policy. In this context, the duration of time when the frequency resource is monopolistically used by IIoT devices will be characterized by a stochastic variable ϕ, distributed exponentially. Similarly, the duration of time when the frequency resource is monopolistically used by a human operator (not IIoT devices) will be characterized by a stochastic variable φ, also distributed exponentially.

Let's consider that during the usage of the frequency resource ω by IIoT devices to support information transfer, power p_ϕ is utilized. Consequently, the power employed for servicing information traffic of a human operator within the frequency resource f amounts to p_φ. Therefore, the uplink traffic speed for any end device in the investigated 5G cluster is a function of its type and its distance from the base station: $v\left(p_{\{\phi,\varphi\}},\delta_l\left(x\right)\right)$. Based on Shannon's theorem, we define parameter $v\left(p_{\{\phi,\varphi\}},\delta_l\left(x\right)\right)$ as

$$v\left(p_{\{\phi,\varphi\}},\delta_l\left(x\right)\right)=\omega\ln\left(1+\frac{\Psi p_{\{\phi,\varphi\}}}{L\left(xR/Z\right)^{\psi}}\right), \tag{1}$$

where Ψ, ψ are constants and the exponent of signal decay, respectively; L represents the noise level.

According to QoS, if the uplink connection speed that the base station can offer in response to an incoming request from an IIoT device is lower than the guaranteed speed v_0, then the base station switches to an autonomous mode regarding new uplink requests (hereinafter referred to as uplink-autonomous mode), during which all incoming requests from end devices directed to it are lost.

Let's note that we defined the speed s through expression (1), from which it follows that when $x=0$ speed $v\to\infty$. To maintain the adequacy of the model represented by expression (1) to the investigated process, we introduce the limitation $\delta_l\left(x=1\right)=l_0$, $l_0=R/Z$. Furthermore, in terms of the model (1), if the end device is located at a distance l_0 from the base station, then its connection speed potentially can reach the design maximum $v_{\{\phi,\varphi\}}^{\max}=v\left(p_{\{\varphi,\varphi\}},l_0\right)$. Within the introduced nomenclature of parameters in the formalization of the model (1) and considering the implementation of QoS in the investigated 5G cluster, we characterize the maximum number of end devices whose uplink transfer can be supported by the base station as expression $N_{\{\phi,\varphi\}}=\left\lfloor v_{\{\phi,\varphi\}}^{\max}/v_0\right\rfloor$.

2.2. The concept of efficient utilization of the uplink frequency resource of a smart factory 5G cluster by IIoT devices

Let's formalize analytically the concept of effective utilization of the uplink frequency resource of a smart factory 5G cluster with a focus on servicing IIoT device traffic.

Let there be $\delta\left(t\right)$ IIoT devices located within the coverage area of the 5G cluster, where for each i-th device, a parameter x is set: $x_i\left(t\right)$. The utilization state of the uplink frequency resource of the 5G cluster at a time $t\geq 0$ is characterized by the function $\xi\left(t\right)$. The introduced stochastic parameters are sufficient to describe the operation process of the uplink frequency resource of the 5G cluster $Y=\left\{\delta\left(t\right),x_1\left(t\right),\ldots,x_{\delta(t)}\left(t\right),\xi\left(t\right),t\geq 0\right\}$ directly in terms of the state space

$$\mathrm{Z}=\Big\{\left(0,\{\phi,\varphi\}\right),\left(n,d_1,\ldots,d_n,\{\phi,\varphi\}\right),d_i=\overline{1,Z},i=\overline{1,n},n=1,2,\ldots:$$

$$\sum_{i=1}^{n}v_0\Big/\left(\omega\ln\left(1+\Psi p_{\{\phi,\varphi\}}\Big/\left(L\left(Rd_i/Z\right)^{\psi}\right)\right)\right)\leq 1\Big\},$$

where n denotes the number of active IIoT devices.

If we investigate the utilization state of the frequency resource of the 5G cluster without focusing on each IIoT device separately, we can transition to a generalized form of representing the stochastic process Y, namely: $Y=\left\{\delta\left(t\right),\xi\left(t\right),t\geq 0\right\}$ over the space $\mathrm{Z}_{\varphi}=\left\{\left(n,\{\phi,\varphi\}:n=\overline{0,N_{\{\phi,\varphi\}}}\right)\right\}$.

Next, let's consider that when the base station transitions to the uplink-autonomous mode, residual information traffic continues to be serviced with a power level p_{ϕ}, resulting in the interruption of active sessions with $n-N_{\phi}$ end devices (considering that $n>N_{\phi}$), where N_{ϕ} is a constant determining the maximum number of information exchange sessions that the base station can support while in uplink-autonomous mode. When the base station exits this mode, power in the amount of p_{φ} is again directed to support information traffic in the investigated 5G cluster.

Let's introduce a parameter $Q_{\{\phi,\varphi\}}\left(n\right)$, which characterizes the probability that the input request from the $n+1$-th end device will be accepted given that the base station is already servicing information traffic from n end devices. In terms of the stochastic process (1), this probability can be analytically expressed as

$$Q_{\{\phi,\varphi\}}\left(0\right)=F_{\delta_l(x)}\left(R,\left(\frac{\Psi p_{\{\phi,\varphi\}}}{L\left(\exp\left(v_0/\omega\right)-1\right)}\right)^{\frac{1}{\psi}}\right), \tag{2}$$

$$Q_{\{\phi,\varphi\}}(n)=\frac{\Phi\left(\left(1-\alpha_{n+1,\{\phi,\varphi\}}\right)\big/\beta_{n+1,\{\phi,\varphi\}}\right)}{\Phi\left(\left(1-\alpha_{n,\{\phi,\varphi\}}\right)\big/\beta_{n,\{\phi,\varphi\}}\right)}, \tag{3}$$

where

$$\Phi(n)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{n}\exp\left(-\frac{t^2}{2}\right)dt,$$

$$\alpha_{n,\{\phi,\varphi\}}=nv_0\mathrm{E}\left[1\big/v\left(l,p_{\{\phi,\varphi\}}\right)\right],$$

$$\beta^2_{n,\{\phi,\varphi\}}=nv_0^2\left(\mathrm{E}\left[\frac{1}{v^2\left(l,p_{\{\phi,\varphi\}}\right)}\right]-\mathrm{E}^2\left[\left[\frac{1}{v\left(l,p_{\{\phi,\varphi\}}\right)}\right]\right]\right),$$

$$\mathrm{E}\left[\frac{1}{v\left(l,p_{\{\phi,\varphi\}}\right)}\right]=\frac{F_{\delta_l(x)}(l_0)}{v^{\max}_{\{\phi,\varphi\}}}+\int_{l_0}^{R}\frac{f_{\delta_l(x)}(l)}{\omega\ln\left(1+\left(\Psi p_{\{\phi,\varphi\}}\right)\big/\left(Ll^{\psi}\right)\right)}dl,$$

$$\mathrm{E}\left[\frac{1}{v^2\left(l,p_{\{\phi,\varphi\}}\right)}\right]=\frac{F_{\delta_l(x)}(l_0)}{\left(v^{\max}_{\{\phi,\varphi\}}\right)^2}+\int_{l_0}^{R}\frac{f_{\delta_l(x)}(l)}{\omega^2\ln^2\left(1+\left(\Psi p_{\{\phi,\varphi\}}\right)\big/\left(Ll^{\psi}\right)\right)}dl\cdot$$

The specificity of the evolution of the stochastic process $Y=\{\delta(t),\xi(t),t\geq 0\}$ allows us to classify it into the class of Markovian processes. This enables us to move from conditional probabilities (2), and (3) to stationary probabilities $q(n,\{\phi,\varphi\})$, $(n,\{\phi,\varphi\})\in \mathrm{Z}_{\varphi}$. Let's formulate a computationally efficient information technology for their calculation:

1. We calculate the values of the unnormalized probabilities $q'(n,\{\phi,\varphi\})$ using the expressions

$$q'(0,\phi)=1,$$

$$q'(0,\varphi)=y,$$

$$q'(n,\{\phi,\varphi\})=\gamma_{n,\{\phi,\varphi\}}+\sigma_{n,\{\phi,\varphi\}}y,\ n>0,$$

where $y=\dfrac{\gamma_{N_\varphi,\varphi}\left(N_\varphi\theta+\tau_\phi\right)+\eta\gamma_{N_\varphi-1,\varphi}Q_\varphi\left(N_\varphi-1\right)}{\eta\sigma_{N_\varphi-1,\varphi}\left(N_\varphi-1\right)-\sigma_{N_\varphi,\varphi}\left(N_\varphi\theta+\tau_\phi\right)}$; N_φ is the maximum number of end devices whose requests can be serviced in the 5G cluster if the base station of the latter is not in uplink-autonomous mode; τ_ϕ is the average duration of the frequency resource availability period for end devices.

2. We calculate the coefficients $\gamma_{n,\{\phi,\varphi\}}$, $\sigma_{n,\{\phi,\varphi\}}$ using the following recurrent expressions:

$$\gamma_{0,\phi}=\gamma_{0,\varphi}=\sigma_{0,\phi}=0,\ \sigma_{0,\varphi}=1;$$

$$\gamma_{1,\phi}=\left(\eta Q_\phi(0)+\tau_\varphi\right)/\theta,\ \sigma_{1,\phi}=-\tau_\phi/\theta,\ \gamma_{1,\varphi}=-\tau_\varphi/\theta,\ \sigma_{1,\varphi}=\left(\eta Q_\varphi(0)+\tau_\phi\right)/\theta;$$

$$\gamma_{n,\phi}=\gamma_{n-1,\phi}\left(\eta Q_\phi(n-1)+\theta(n-1)+\tau_\varphi\right)/(n\theta)-$$
$$-\gamma_{n-2,\phi}\left(\eta Q_\phi(n-2)\right)/(n\theta)-\gamma_{n-1,\varphi}\left(\tau_\phi\right)/(n\theta)\forall n=\overline{2,N_\phi},$$

$$\sigma_{n,\phi}=\sigma_{n-1,\phi}\left(\eta Q_\phi(n-1)+\theta(n-1)+\tau_\varphi\right)/(n\theta)-$$
$$-\sigma_{n-2,\phi}\left(\eta Q_\phi(n-2)\right)/(n\theta)-\sigma_{n-1,\varphi}\left(\tau_\phi\right)/(n\theta)\forall n=\overline{2,N_\phi},$$

$$\gamma_{n,\varphi}=\gamma_{n-1,\varphi}\left(\eta Q_\varphi(n-1)+\theta(n-1)+\tau_\varphi\right)/(n\theta)-$$
$$-\gamma_{n-2,\varphi}\left(\eta Q_\varphi(n-2)\right)/(n\theta)-\gamma_{n-1,\phi}\left(\tau_\varphi\right)/(n\theta)\forall n=\overline{2,N_\phi+1},$$

$$\begin{gathered}\sigma_{n,\varphi} = \sigma_{n-1,\varphi}\left(\eta Q_{\varphi}(n-1) + \theta(n-1) + \tau_{\phi}\right)/(n\theta) - \\ -\sigma_{n-2,\varphi}\left(\eta Q_{\varphi}(n-2)\right)/(n\theta) - \sigma_{n-1,\phi}\left(\tau_{\varphi}\right)/(n\theta), \forall n = \overline{2, N_{\phi}+1} \\ \gamma_{n,\varphi} = \gamma_{n-1,\varphi}\left(\eta Q_{\varphi}(n-1) + \theta(n-1) + \tau_{\varphi}\right)/(n\theta) - \\ -\gamma_{n-2,\varphi}\left(\eta Q_{\varphi}(n-2)\right)/(n\theta) \forall n = \overline{N_{\phi}+2, N_{\varphi}}, \\ \sigma_{n,\varphi} = \sigma_{n-1,\varphi}\left(\eta Q_{\varphi}(n-1) + \theta(n-1) + \tau_{\varphi}\right)/(n\theta) - \\ -\sigma_{n-2,\varphi}\left(\eta Q_{\varphi}(n-2)\right)/(n\theta) \forall n = \overline{N_{\phi}+2, N_{\varphi}},\end{gathered}$$

where N_{ϕ} is the maximum number of end devices whose requests can be serviced in the 5G cluster if the base station of the latter is in uplink-autonomous mode; τ_{φ} is the average duration of the frequency resource unavailability period for end devices;

3. We calculate the desired values of the stationary probabilities $q(n,\{\phi.\varphi\})$ using expressions of the form

$$q(n,\{\phi.\varphi\}) = \left(q'(n,\{\phi.\varphi\})\right) \Big/ \sum_{(i,\{j,l\}) \in \mathrm{Z}} q'(i,\{j.l\}), \; (n,\{\phi,\varphi\}) \in \mathrm{Z}_{\varphi}. \tag{4}$$

Let's conclude the theoretical part of the article by defining the efficiency category in the context of the evolution of the uplink frequency resource utilization process of the investigated 5G cluster. The concept of efficiency is closely related to a corresponding qualitative metric that allows for a comprehensive characterization of any instance of the class of investigated processes. In the context of our research, it is rational to formalize the qualitative metric regarding the interpretation of the consequences of activating the uplink-autonomous mode by the base station.

Therefore, based on the calculated stationary probabilities $q(n,\{\phi,\varphi\}) \in \mathrm{Z}_{\varphi}$ for the instance of the process $Y = \{\delta(t), \xi(t), t \geq 0\}$, we characterize its evolution in the metrics of indicators such as the probability of implementing the uplink-autonomous mode A, the probability of interruption of IIoT device servicing due to the activation of the uplink-autonomous mode I, and the average number of devices being serviced in the system during the implementation of the uplink-autonomous mode $\bar{N}$:

$$A = \sum_{n=0}^{N_{\phi}-1} q(n,\phi)\left(1 - Q_{\phi}(n)\right) + \sum_{n=0}^{N_{\varphi}-1} q(n,\varphi)\left(1 - Q_{\varphi}(n)\right), \tag{5}$$

$$\begin{gathered}I = \sum_{n=N_{\phi}+1}^{N_{\varphi}-1} \frac{\tau_{\phi} q(n,\varphi)}{\tau_{\phi} + n\theta + \eta Q_{\varphi}(n)} \left(\frac{n-1}{n - N_{\phi} - 1}\right) \Big/ \left(\frac{n}{n - N_{\phi}}\right) + \\ + \frac{\tau_{\phi} q(N_{\varphi},1)}{\tau_{\phi} + N_{\varphi}\theta} \left(\frac{N_{\varphi}+1}{N_{\varphi} - N_{\phi} - 1}\right) \Big/ \left(\frac{N_{\varphi}}{N_{\varphi} - N_{\phi}}\right),\end{gathered} \tag{6}$$

$$\bar{N} = \sum_{n=0}^{N_{\phi}} nq(n,\phi) + \sum_{n=0}^{N_{\varphi}} nq(n,\varphi). \tag{7}$$

3. Results and Discussion

We will apply the capabilities of simulation modelling to evaluate an ordinary instance of a smart factory 5G cluster for the monopolistic use of the uplink frequency resource, which (concerning the defined QoS policy) is sought after by both human operators and IIoT devices.

The evaluation of the functioning process of the investigated instance will be carried out in a qualitative metric (6), (7).

The functional scenario implies that the investigated instance of the smart factory 5G cluster is oriented towards servicing IIoT device traffic, which transmits data to the cloud, with the base station serving as the edge component. The transmission session of an informational message from an IIoT device lasts an average of 10 sec with a guaranteed speed of 1 Mbps. The human operator retains controlling functions, which involve monopolistic use of the 5G cluster's frequency resource for 3-5 min. once an hour. Based on this descriptive information, let's determine the values for the nomenclature of the input parameters capable of characterizing the investigated instance of the 5G cluster: coverage zone radius $R=500$ m; available frequency bandwidth $\omega=10$ MHz; number of concentric zones within the coverage of the base station $Z=10$; duration $\tau_{\phi}=3600$ sec; duration $\tau_{\varphi}=180\div300$ sec; power level $p_{\phi}=22\div42$ dBm; power level $p_{\varphi}=p_{\phi}/2$; guaranteed speed $v_0=1$ Mbps; intensity $\eta=10$ $1/\text{sec}$; intensity $\theta=0.1$ $1/\text{sec}$; constant $L=-60$ dBm; constant $\Psi=197$; constant $\psi=5$.

Based on the defined input parameters, we solve the system of equilibrium equations (2), and (3) using the information provided in Section 2.2, obtaining the values of the stationary probabilities (4) as a result. Therefore, all the values necessary for calculating the indicators of the qualitative metric (6), and (7) have been determined by us.

To demonstrate the informativeness of the proposed qualitative metric using expressions (6), and (7), we calculate the dependencies $\{I,\bar{N}\}=f\left(p_{\{\phi,\varphi\}}\right)$. Fig. 1 presents the graphs of the dependency $I=f\left(p_{\{\phi,\varphi\}}\right)$ calculated while varying the parameter $\tau_{\phi}=\{1300,2000\}$ at a fixed value of parameter $R=500$. In turn, Fig. 2 presents the graphs of the dependency $\bar{N}=f\left(p_{\{\phi,\varphi\}}\right)$ calculated while varying the parameter $R=\{200,500\}$ at a fixed value of parameter $\tau_{\phi}=1800$. The batch analysis of the dependencies presented in Figs. 1, 2 is since they share a common argument.

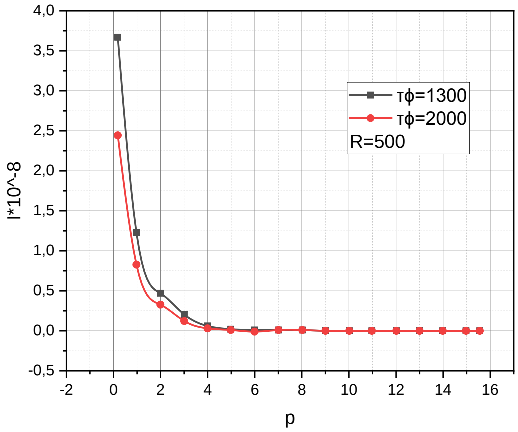

Figure 1: Graphs of the dependence $I=f\left(p_{\{\phi,\varphi\}}\right)$, calculated at $\tau_{\phi}=\{1300,2000\}$, $R=500$

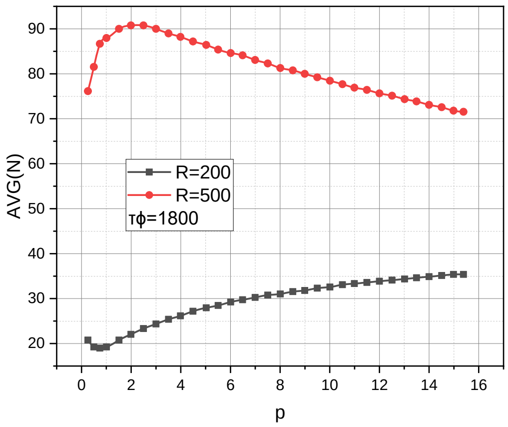

Figure 2: Graphs of the dependence $\bar{N}=f\left(p_{\{\phi,\varphi\}}\right)$, calculated at $R=\{200,500\}$, $\tau_{\phi}=1800$

From the graphs shown in Fig. 1, it can be observed that the quality indicator (6) is highly sensitive, as evidenced by the small increments on the ordinate scale. Additionally, it is evident that as the power $p_{\{\phi,\varphi\}}$ allocated to support information traffic in the frequency band ω increases, the interruption in servicing IoT device probability I value sharply decreases due to the activation of the uplink autonomous mode. Meanwhile, the duration value τ_{ϕ} does not significantly influence the shape or dynamics of the graphs presented in Fig. 1. The results presented in Fig. 2 are intriguing. We will discuss the dependency $\bar{N} = f\left(p_{\{\phi,\varphi\}}, R = 200\right)$. The fact that the graph of this dependency is concave can be explained by one of the initial conditions being the uniform distribution of IoT devices within the coverage area of the base station. Therefore, the increasing nature of this dependency up to the value of the argument $p_{\{\phi,\varphi\}} = 2$ is caused by the fact that increasing power allows for an increase in the number of IoT devices within the concentric zone with a radius $R = 200$. When this number reaches a parametrically justified maximum $p_{\{\phi,\varphi\}} = 2$, further increases in the number of IoT devices within the concentric zone with a radius $R = 200$ lead to the transition of the base station into uplink autonomous mode, accompanied by a corresponding decrease in the quality indicator $\bar{N}$ value. The increasing nature of the dependency $\bar{N} = f\left(p_{\{\phi,\varphi\}}, R = 500\right)$ indicates that for established values of the initial parameters, increasing power $p_{\{\phi,\varphi\}}$ allows for an increase in the average number of IoT devices serviced by the system without causing it to transition into uplink autonomous mode.

Now let's calculate the dependencies $\{I, \bar{N}\} = f(R)$. In Fig. 3, the graphs of the dependency $I = f(R)$ are presented and calculated while varying the parameter $\tau_\phi = \{1300, 2000\}$ at a fixed value of parameter $p_{\{\phi,\varphi\}} = 0.3$. In Fig. 4, the graphs of the dependency $\bar{N} = f(R)$ are presented and calculated while varying the parameter $p_{\{\phi,\varphi\}} = \{0.3, 15\}$ at a fixed value of parameter $\tau_\phi = 1800$.

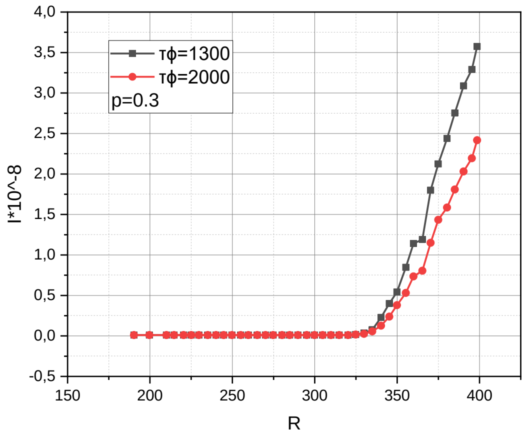

Figure 3: Graphs of the dependence $I = f(R)$, calculated at $\tau_\phi = \{1300, 2000\}$, $p_{\{\phi,\varphi\}} = 0.3$

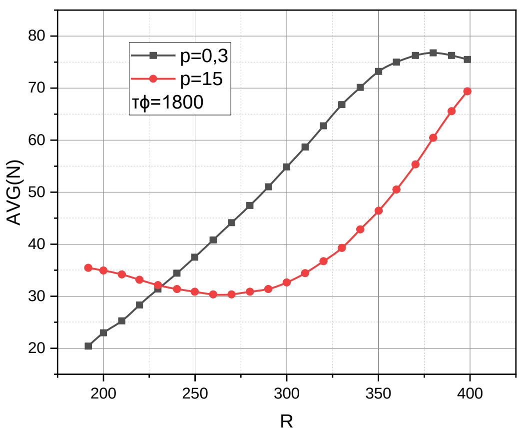

Figure 4: Graphs of the dependence $\bar{N} = f(R)$, calculated at $p_{\{\phi,\varphi\}} = \{0.3, 15\}$, $\tau_\phi = 1800$

From Fig. 3, it can be observed that the probability of interruption in servicing an IoT device due to the activation of the uplink autonomous mode I begins to increase exponentially with $R \geq 325$, and this phenomenon is practically independent of the parameter τ_ϕ but is instead fully determined by the power $p_{\{\phi,\varphi\}}$ value. This conclusion is supported by the graphs presented in Fig. 4. The graph $\bar{N} = f\left(R, p_{\{\phi,\varphi\}} = 15\right)$ increases in the range of large argument values, whereas the graph $\bar{N} = f\left(R, p_{\{\phi,\varphi\}} = 0.3\right)$ demonstrates a decrease at large argument values, attributed to the transition of the base station into uplink autonomous mode.

Finally, let's calculate the dependencies $\{I, \bar{N}\} = f(\eta)$. In Fig. 5, the graphs of the dependency $I = f(\eta)$ are presented and calculated while varying the parameter $\tau_\phi = \{1300, 2000\}$ at a fixed value of parameter $R = 500$. In Fig. 6, the graphs of the dependency $\overline{N} = f(\eta)$ are presented, calculated for combinations of characteristic parameter values, including $\{R, \tau_\phi\} = \{(500,1300),(200,2000)\}$.

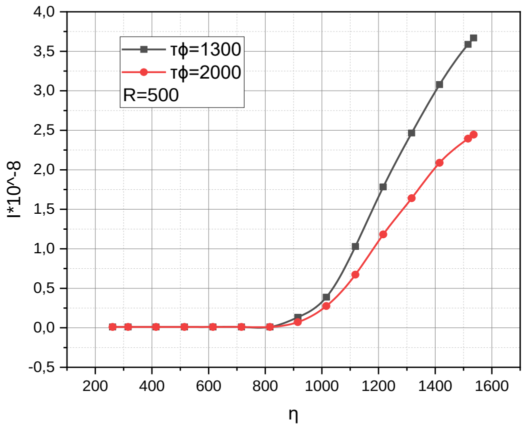

Figure 5: Graphs of the dependence $I = f(R)$, calculated at $\tau_\phi = \{1300, 2000\}$, $R = 500$

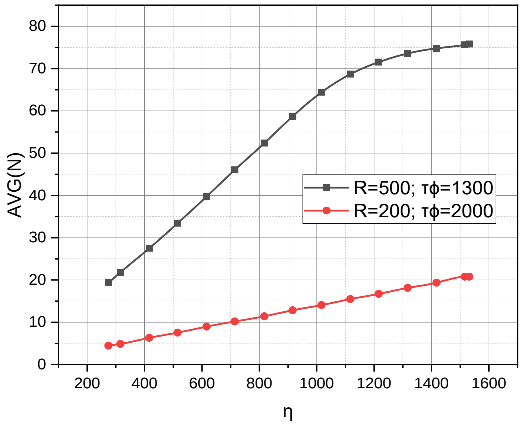

Figure 6: Graphs of the dependence $\overline{N} = f(R)$, calculated at $\{R, \tau_\phi\} = \{(500,1300),(200,2000)\}$

Based on the information presented in Figs. 5, 6, we observe trends that are characteristic of Figs. 1–4. Specifically, the quality indicator $\overline{N}$ proves to be highly informative for describing the operation of the base station of a smart factory 5G cluster environment with increasing intensity of incoming requests from IoT devices. Moreover, the duration of the information message τ_ϕ has a more significant impact on the value of the metric $\overline{N}$ for the distance at which IoT devices are located from the centre of the 5G cluster.

Overall, the results presented in Section 3 demonstrate that the generalized qualitative metrics expressed in equations (5)-(7) are informative, sensitive, and functional in describing the instance of a smart factory 5G cluster, aimed at the monopolistic use of uplink frequency resources, particularly by IoT devices.

4. Conclusions

The phenomenon of overload in the licensed frequency spectrum is a characteristic feature of smart factories with thousands of IIoT devices generating substantial uplink traffic. A promising approach to addressing the "overload problem" is the implementation of an efficient organization of alternating service periods for different types of traffic based on their source within the allocated frequency range. The article proposes an original solution to this pressing issue.

The article investigates the functioning process of a smart factory 5G cluster, where both human operators and Industrial Internet of Things (IIoT) devices contend for monopolistic use of the uplink frequency resource, based on the defined Quality of Service (QoS) policy. To analytically formalize this process, the authors have developed a Markovian model. This model reflects both the inherent characteristics of the studied process and the mechanism of adaptive power control, which considers the type of traffic being served by the base station at any given moment. In formulating the model, the authors take into account the spatial geometry of the end devices within the coverage area of the base station, segmented into concentric zones with threshold values for communication quality characteristics. Additionally, the model considers the scenario where the base station transitions into uplink-autonomous mode if it is unable to provide a guaranteed speed for servicing new incoming requests from IIoT devices. To calculate the parameters of the model, a computationally efficient information technology is formulated. Within the framework of the created model, a qualitative metric is proposed, capable of characterizing the evolution of the studied process instance through a set of indicators such as the probability of realizing uplink-autonomous mode, the probability of interruption of IIoT device servicing due to the activation of uplink-autonomous mode, and the average number of devices being serviced in the smart factory 5G cluster during the implementation of uplink-autonomous mode.

The empirical results from evaluating the instance of the smart factory 5G cluster, which exhibits characteristics of the studied process (convex and concave dependency plots), in the metrics of the proposed qualitative indicators, allow for predicting the feasibility of optimization tasks based on specific characteristic parameters considered in the authors' model. Additionally, refining the proposed model by taking into account the height of transmitter-receiver placement would be promising.

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