Optimization and analysis of wireless network characteristics with service quality maintaining

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Abstract

The problem of cross-level optimization of a real-time wireless radio network with Quality-of-Service support is considered. A new mathematical model for determining the Quality-of-Service (QoS) route is proposed, which allows a network node to determine the optimal path to minimize the use of resources while observing the necessary QoS restrictions. The proposed mathematical model uses a programming technique to determine the critical parameters and the corresponding objective functions to control the QoS-constrained route discovery process. The proposed approach significantly improves network lifetime while reducing energy consumption and average end-to-end network delays due to ongoing optimization of resource allocation in intermediate nodes compared to existing routing algorithms. Thanks to the application of methods of distributed processing of service information, in particular, cross-layer optimization, it is possible to overcome the problems of the "curse of dimensionality" in the tasks of finding optimal routes. A simulation model of the network was developed, using which the potential characteristics of the network were estimated under the conditions of a change in the structure (number of terminal nodes, gradual and sudden changes in network traffic characteristics, etc.).

Keywords

Wireless network, Quality-of-Service (QoS), real-time network, cross-layer optimization, QoS constraints

1. Introduction

The frequency and energy resource limitations of wireless radio networks stem from the nature of data exchange processes in the atmosphere or in an open environment. The way out of this situation is to rationally allocate the resource among users in the context of multimedia network traffic and adapt to changes in network operation.

In order to ensure the required Quality-of-Service (QoS), adaptation to channel transmission conditions must be implemented at all levels of the protocol stack. The key question that arises is whether adaptation methods can be implemented independently at each layer, in accordance with the classical approach to node design in the Open System Interconnection Reference Model (OSI), or whether optimization should be performed jointly at several layers of the protocol stack (cross-layer optimization). Adaptation protocols respond to and influence the level of interference and resource allocation in the network. As a result, for efficient network utilization, the adaptation protocols of each layer must be integrated so that interdependencies between layers can be exploited.

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The development of cross-layer protocols expands the network's adaptation capabilities: performance information can be transferred between layers to optimally respond to changes in transmission conditions. The speed of adaptation for a particular protocol is determined by its location in the protocol stack. However, information exchange between layers and joint optimization can significantly improve system performance.

At the network layer, exchange protocols are developed that are not sensitive to subscriber mobility and sudden disconnections. At the data link layer, medium access control protocols are modified so that redundancy can be maintained and quality assurance can be provided. Similarly, error correction mechanisms can protect against non-stationary transmission errors over wireless channels (most commonly, over the radio). At the physical layer, modulation schemes, transmit power control, and receiver sensitivity are also designed with QoS in mind.

Call admission control schemes allow for proper Quality-of-Service (QoS) in the presence of both existing and newly emerging calls. Resource reservation schemes are used to allocate the necessary resources to certain high-priority calls. On the other hand, the network is required to take full advantage of resource sharing between traffic flows to achieve the best possible channel utilization. However, achieving the right balance between these two conflicting criteria is a big challenge. This paper attempts to solve this problem.

2. Background analysis and problem statement

Researchers as well as network providers are increasingly interested in understanding how the network user experience (QoE) varies in relation to various quality of service (QoS) parameters [1], with many studies and attempts to determine the general relationship between quality of experience (QoE) and QoS [2 - 4]. [5] presents a brief overview of some existing correlation models that have been used to estimate correlations between quality of service (QoS) and quality of experience (QoE) for multimedia services [6-8]. Various models in different functional forms can be found in open literary sources [9, 10]. Thus, in [4], for example, various models were analyzed for their potential use to establish correlations between 5G network parameters in real working commercial networks. There are cases when this variety of proposed models potentially leads to the fact that one complexity has completely different solutions at the same time [9, 10]. The question then is which model is the one that can best explain this relationship [11].

Thus, as a result of the analysis of literary sources, it was established that an effective tool for end-to-end determination of QoE depending on QoS parameters has not yet been developed. Therefore, there was a need to improve existing models using machine learning algorithms, which are currently one of the most promising and versatile tools.

Setting research objectives

Given the expected increase in the amount of data in telecommunications networks, service providers need more advanced tools with a new level of understanding. Legacy solutions for managing network and service performance are no longer effective. The approach to QoS/QoE management with the introduction of 5G will create significant challenges that need to be addressed in order to manage and deliver the promised experience and coverage quality of 5G, which can be summarized as follows [4]:

1. Lack of end-to-end visibility: Traditional management tools and protocols are designed to monitor individual network components and analyze their bandwidth (traffic) and usage. But these legacy tools don't provide a complete index to measure what really matters: quality of experience (QoE), i.e. "how well the service works for the end user." Quality of experience (QoE) management requires visibility and a consistent end-to-end level of monitoring.
2. Although Best Effort QoE has been the accepted standard for Internet applications and services, it is no longer sufficient for today's evolving digital services. Customers no longer perceive service as "good" rather than "excellent". Understanding the level of QoE for different use cases is critical and can affect customers' perception of network quality and lead to churn [4].
3. Understanding the relationship between QoS and QoE. Service providers are still more comfortable monitoring KPIs and QoS than QoE, which is a holdover from traditional telephony performance monitoring. The problem is that the end-user experience is largely driven by QoE, not

QoS. Therefore, it is critical to recognize the associated network QoS requirements for each use case, and then define an appropriate performance management methodology for effective network monitoring and testing, and create a specific QoE model. To solve the problems, I propose to develop a method of analyzing the interdependencies of QoE and QoS parameters based on machine learning algorithms.

Thus, the purpose of this work, which became part of the qualification work for obtaining the Master's degree at the National Aviation University in 2022, is to develop a method to improve the quality of service to subscribers by telecommunications providers through the use of machine learning algorithms. In order to achieve the set goal, it is necessary to solve the following scientific problems:

1. To analyze the quality and mechanisms of QoE assessment of subscribers.
2. To improve the model for evaluating the user experience of the telecommunications network.
3. Development of a method for analyzing the interdependencies of QoE and QoS parameters based on machine learning algorithms.
4. Experimental study of the developed method.

3. A system for evaluating and ensuring QoS of modern cellular networks

Business considers information technology (IT) as a means of increasing its productivity and improving competitiveness. The efficiency of business processes depends significantly on the quality of IT services. The increase in the number of IT services required for the automation of business technologies, the complexity of applications and the growing number of IT infrastructure components have a significant impact on both the efficiency of IT departments and the increase in costs for maintaining the normal functioning of the IT infrastructure. The provision of IT services is regulated by a package of service level agreements (SLAs) concluded between business units and the IT unit. In SLA, the values of key performance indicators (KPI) and quality (KQI) are defined, which represent a limited set of objectively measurable parameters, which nevertheless allow a sufficiently complete assessment of the quality of IT services [12]. To maintain the values of KPI and KQI at the level fixed in the SLA, administrators ensure the uninterrupted functioning of the IT infrastructure, perform maintenance and repair using automatic, automated, and manual management methods.

Key Performance Indicators – a key performance indicator that represents the results of tests and measurements, that is, statistical data obtained directly from the technical resources of the network or applications is schematically shown in Fig. 1. Currently, there is a large list of KPIs for each type of network technologies and services/applications [13, 14]. To take into account the specifics of the network in more detail, this list can be expanded with additional KPIs determined directly by IT service representatives.

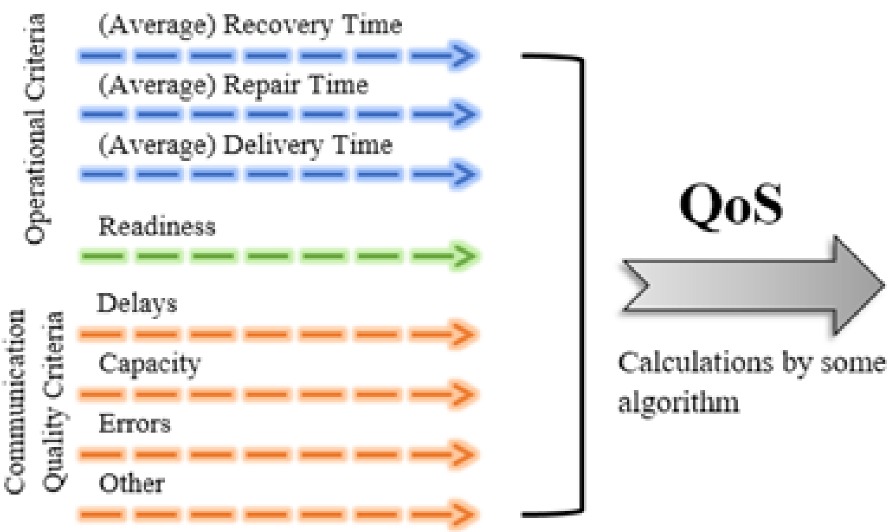

Figure 1: Relationship of KPI with service quality

In the process of further analytical processing, based on the service model, methods and technologies of their provision, KPIs are aggregated into KQI, that is, into key indicators of the quality of the service or its component part. The relationship between KQI and its defining set of KPIs, as well as their threshold values, are established both by theoretical calculations and by practical means. Fig. 2 shows connections that reflect the sequence of actions in determining key quality indicators.

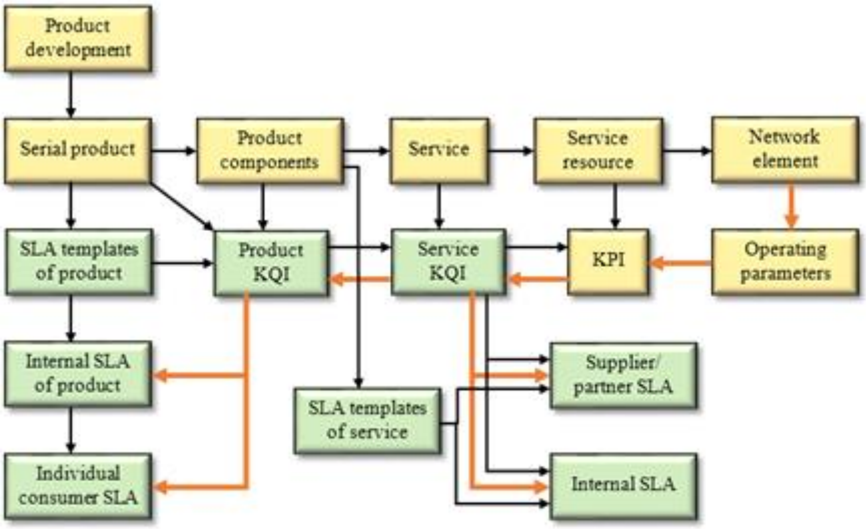

Figure 2: Sequence of actions when determining KQI

In turn, the set of relevant KQIs determines the Product Key Quality Indicator (PKQI) — a key indicator of product quality [15], which is the main metric in determining SLA. In Fig. 3 shows the hierarchy of interaction of key indicators of efficiency and quality of the cellular network [16], which determine the quality of the product to meet the level of service provided by the cellular operator.

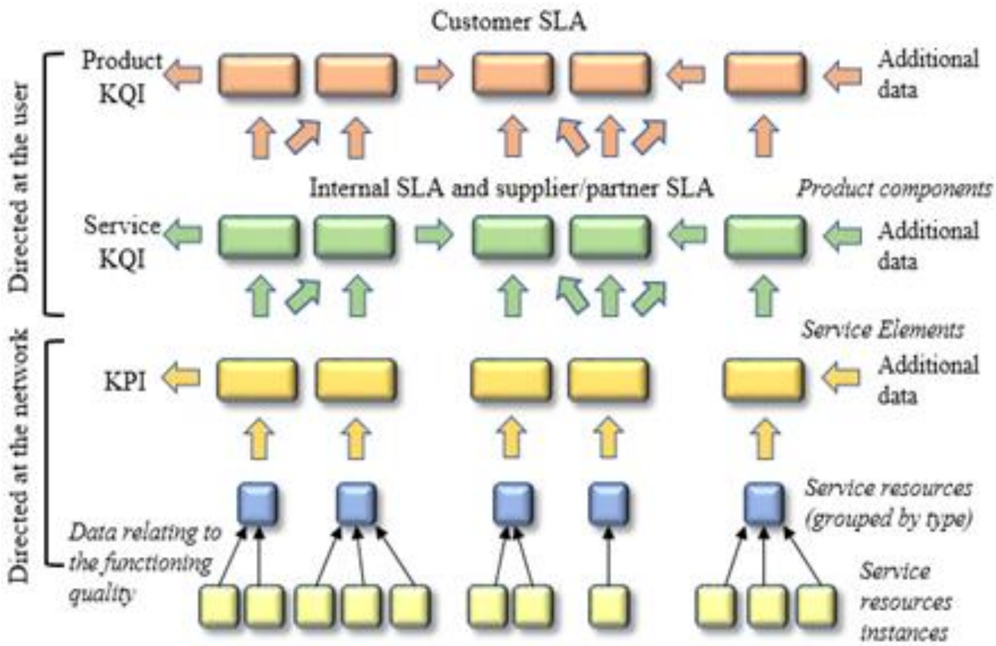

Figure 3: Hierarchy of key quality indicators (KPI/KQI)

When choosing the necessary indicators for an adequate assessment of service quality, it is necessary to minimize their number and take into account the possible "cross-over" influence of a single KPI on several different KQIs. The purpose of detailing KPIs is the need to correlate drivers for long-term network management metrics with the aggressive "business goal" of the business industry. Currently, there remains a lack of correlation between the functions performed by network management groups and the contribution of these functions to enterprise-level business objectives such as: revenue (growth and protection), cost reduction, and improved service quality. In most countries, regulatory authorities publish KPIs and target levels, as KPI indicators and target levels are mandatory minimum standards to be met [17, 18]. A network evolution system can have a large number of KPIs, so their selection depends on the types of problems and tasks being solved. In telecommunications, issues to be addressed include:

1. improving the quality of service;
2. lack of qualified technical personnel;
3. demand for next-generation telecommunication services;
4. low financial indicators and lack of financial resources.

The set of parameters and indicators of service quality should reflect all the main quality criteria of the interaction of cellular equipment with the telecommunications network and the consumer with the telecommunications service as a product provided by the cellular operator.

Today, the traditional communication services provided by the operator are aging and replaced by services that provide a wide range of services: streaming and interactive services, messaging and data exchange services. Compared to basic telecommunication services, new services require additional support from cellular operators. Therefore, it is necessary to apply mathematical models that will help ensure the necessary quality of these services.

In recent years, the technical community has shifted some of its focus from one related metric, quality of service (QoS), to a more consumer-oriented metric, quality of experience (QoE). Network operators and service providers have wanted to know the level of service quality provided to end users since the very beginning of telecommunications. This is because this knowledge can be extremely useful when trying to manage the network topology, optimize its bandwidth and operating costs, introduce new services or plan investments and network expansion.

The International Telecommunication Union (ITU) defines QoE as the overall acceptability of an application or service as subjectively perceived by the end user. QoE can be considered as an extension of traditional QoS in the sense that QoE provides information about the provided service from the perspective of the end user.

While QoS stands between the network and the application, QoE is several steps removed from the network, instead focusing on the human. In particular, QoE focuses on the person as the user interacting with the application and the person as the customer dealing with the service provider (Fig. 4).

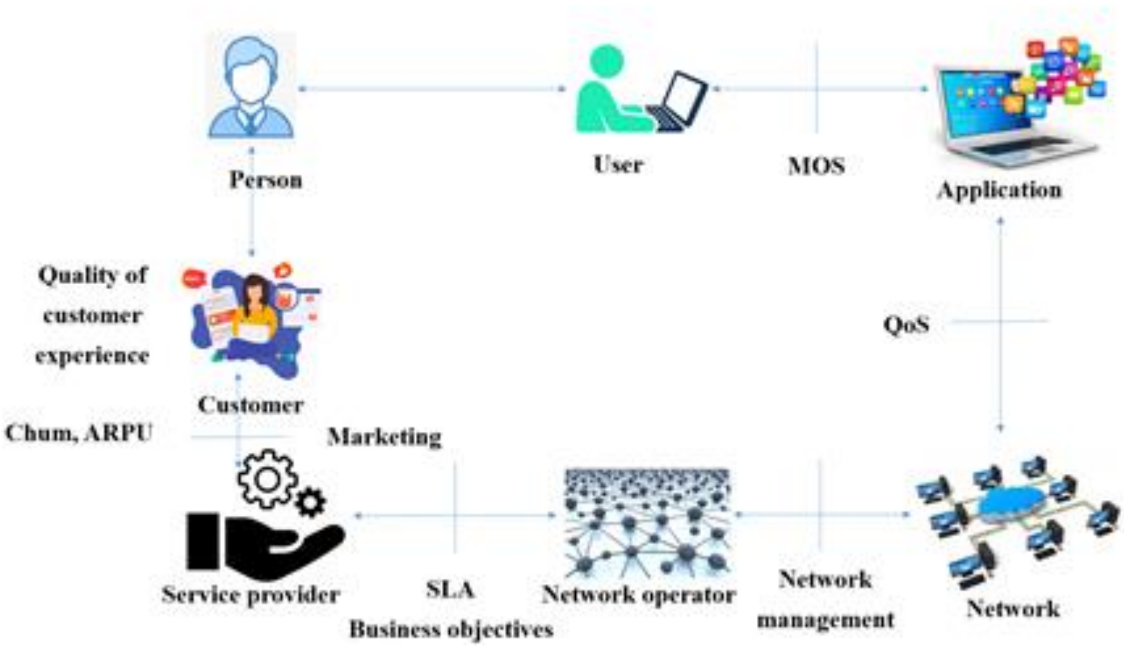

Figure 4: QoE/QoS model

Thus, service quality has some objective and subjective properties. Obviously, the user is unlikely to be satisfied if the network performance (QoS) is low. For example, if the repeated buffering of the video happens frequently during a streaming session, the user will surely be annoyed and dissatisfied. But it was also shown that achieving QoS goals does not necessarily ensure satisfied users. Something else was missing.

The difference between QoE and QoS is highlighted below.

QoS – Quality of Service:

- characteristics / behavior of the network;
- performance guarantees provided by the network provider based on measurements.

QoE – Quality of Experience:

- the impact of network behavior on the end user;
- some shortcomings may remain unnoticed;
- some flaws can make the program useless;
- is not fixed by network measurements.

Quality does not directly depend on radio channel conditions, but the expectation will increase as performance increases. Increasing expectations changes the quality of the user experience, but then so does all technology. QoE takes into account user expectations, QoS is more rational based on technical measurements (Fig. 5).

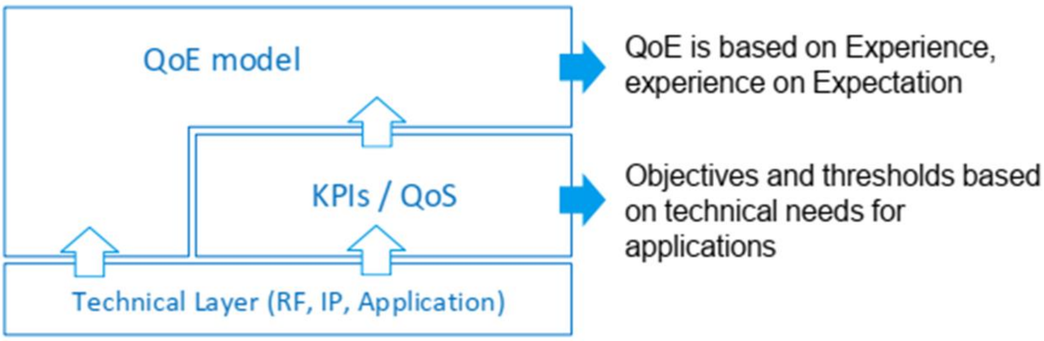

Figure 5: Relationships between QoE, QoS and KPI

4. Optimal distribution of network resources under energy limitation

The need to increase the capacity of wireless auxiliary nodes in order to improve throughput is due to the presence of interference that is not inherent in traditional wired information and communication networks. First of all, these are external interferences that exist in free space and can penetrate the wireless network quite freely.

Let's mark the set of links that can successfully communicate at the same time as $E = \{e_i = (u_i, v_i), i = 1,2, \dots, k\}$. For any $e_i \in E$ interference at the receiver v_i due to all other communications is determined as follows:

$$I(v_i) = \sum_{e_j=(u_j,v_j)\neq e_i} \frac{P(e_i)}{d(u_j, v_j)^{\alpha}}, \quad (1)$$

where $P(e_i)$ marks the power level of the signal transmitted by the u_i node, $d(u_j, v_j)$ is the destination between u_j and v_j nodes, α is the rate of losses on the distribution route. Let's define the signal/(interference-plus-noise) ratio as SINR (signal-to-interference-plus-noise-ratio). This ratio is determined taking into account the radio engineering parameters of network nodes and transmission channels:

$$SINR_{APj,i} = \frac{P_{APj} G_{APj,i}}{\sum_{k \in AP_{k\neq j}} P_{APk} G_{APk,i} + P_N}, \quad (2)$$

where P_{APj} is the transmission power from the access point AP_j, $G_{APj,i}$ is the channel amplification from the i-th user to AP_j. P_N is the internal noise power of the receiver. The wireless networks architecture consists of N wireless networks with different parameters and structures (heterogeneous wireless networks). For the i-th network, $1 \leq i \leq N$ the general interferences include intra-network and inter-network interferences, that marked as I_{intra}^{i} and I_{inter}^{i} respectively.

Let's consider the typical network node (a reference node located at the origin, which is considered to be the reference for all other nodes). Let AN_i marks the number of active nodes in the i-th network. The intra-network interferences define as:

$$I_{intra}^{i} = P_i \sum_{k=1}^{AN_i} \frac{G_k}{\left(d_k^i\right)^{\alpha}}, \tag{3}$$

where G_k is the normalized channel gain parameter from the k-th node to typical node in the i-th network, P_i is the transmission power in the i-th network, d_k^i is the destination between k-th node and typical node of the i-th network, α is the rate of losses on the distribution route. The channel gain coefficient G_k on the line between the transmitter and receiver includes the average path loss as a function of distance, shadowing, and attenuation. All G_k coefficients are positive and can take values from 0 to 1.

The inter-network interferences defined as general interferences caused by other adjacent networks. For example, the I_j interferences caused by the j-th network, represents interference from active nodes of the j-th network to typical node in the i-th network. Thus, the general inter-network interferences are presented as below:

$$I_{inter}^{i} = \sum_{j=1\ j \neq i}^{N} I_{intra}^{i} \tag{4}$$

Two types of traffic are considered (real-time and non-real-time). Soft real-time (RT) traffic, such as Voice over Internet Protocol (VoIP), needs to be transmitted with low latency and tight limits on latency variations. If this limit is exceeded, the call quality will be poor. Speech intelligibility with RMS delay deviations greater than 100-150 ms is unacceptable, and signal transmission becomes useless.

The considered coverage area is covered by several different wireless networks, and each network transmits at different power levels, has different bandwidth, power consumption, received signal energy, and cost of operation. It is impossible to compare the signal/(interference-plus-noise) ratio, Signal-to-interference-plus-noise, (SINR) of the j-th user in different network nodes (network node, N_{nd}) and unambiguously select the N_{nd}-th candidate. An access node provides local quality of service only if SINR exceeds a certain threshold $SINR_{i,creq}$. It is proposed to compare the $S_{i,c}(j)$ ratio of the received SINR and acceptable $SINR_{i,creq}$ as follows:

$$S_{i,c}(j) = \frac{SINR_{i,c}(j)}{SINR_{i,req}} \gtrless 1, \tag{5}$$

where $SINR_{i,c}(j)$ is the j-th user SINR $1 \leq j \leq N_u$ c-th class, $1 \leq c \leq C$ in N_{nd}; $SINR_{i,creq}$ is represents the requested c-th class SINR in N_{nd}; N_u is the number of users in the network segment. The user class represents, in a general sense, the functionality of the traffic parameters ordered by the user: latency $\tau_{delivery}$, variations of latency var_{τ_d}, bit error ratio (BER) coefficient, etc.

Accordingly, to the Shannon's formula, the throughput $C_{i,j}$ in bps for j-th user connected to the N_{nd} is defined as:

$$C_{i,j} = B_{j,c}\left[1 + \frac{G_j P_i \left(d_j^i\right)^{-\alpha}}{I_{intra}^{i} + I_{inter}^{i}}\right], 1 \leq j \leq N_c(i), 1 \leq c \leq C, \tag{6}$$

where $N_c(i)$ is the maximum number of the N_{di} calls in real-time (RT) or non-real-time (NRT), respectively, that can be handled at the same time; $B_{j,c}$ is the throughput for c-th class' calls; G_j is the channel gain coefficient from j-th node to access point in the i-th network; P_j is the power of transmission in the i-th network; d_j^i is the destination between j-th node and access point in the i-th network; α is the rate of losses on the distribution route.

The general power of all c-th class' users, that are connected to the N_{di} is defined as:

$$C_i(c) = \sum_{k=1}^{N_c(i)} B_{k,c}\left[1 + \frac{G_k P_i\left(d_k^i\right)^{-\alpha}}{I_{intra}^i + I_{inter}^i}\right]. \tag{7}$$

Thus, the total capacity of users in the N_{di} is the sum of the powers of different classes of all users. This power is defined as following:

$$C_i = \sum_{c=1}^{C} C_i(c). \tag{8}$$

Thus, formulas for estimating the total information capacity in wireless networks with heterogeneous traffic were derived by considered the SINR constraints. The power of the signal received by the user depends on his distance from the access point. It also depends on the number of nodes in each network segment. This provides a way to select a target network in a wireless environment, determine the permissible number of users in the network, and estimate the total information capacity of heterogeneous wireless networks.

5. Analysis of potential network characteristics

To assess the potential characteristics of a wireless telecommunication network with variable parameters and structure operating under conditions of external interference, numerical parameters are selected and a network simulation model is developed. The algorithmic diagram of the network with the architectural concept of QoS redundancy (Fig. 6) and the numerical parameters of the network (Table 1) are taken from [19, 20] of the author.

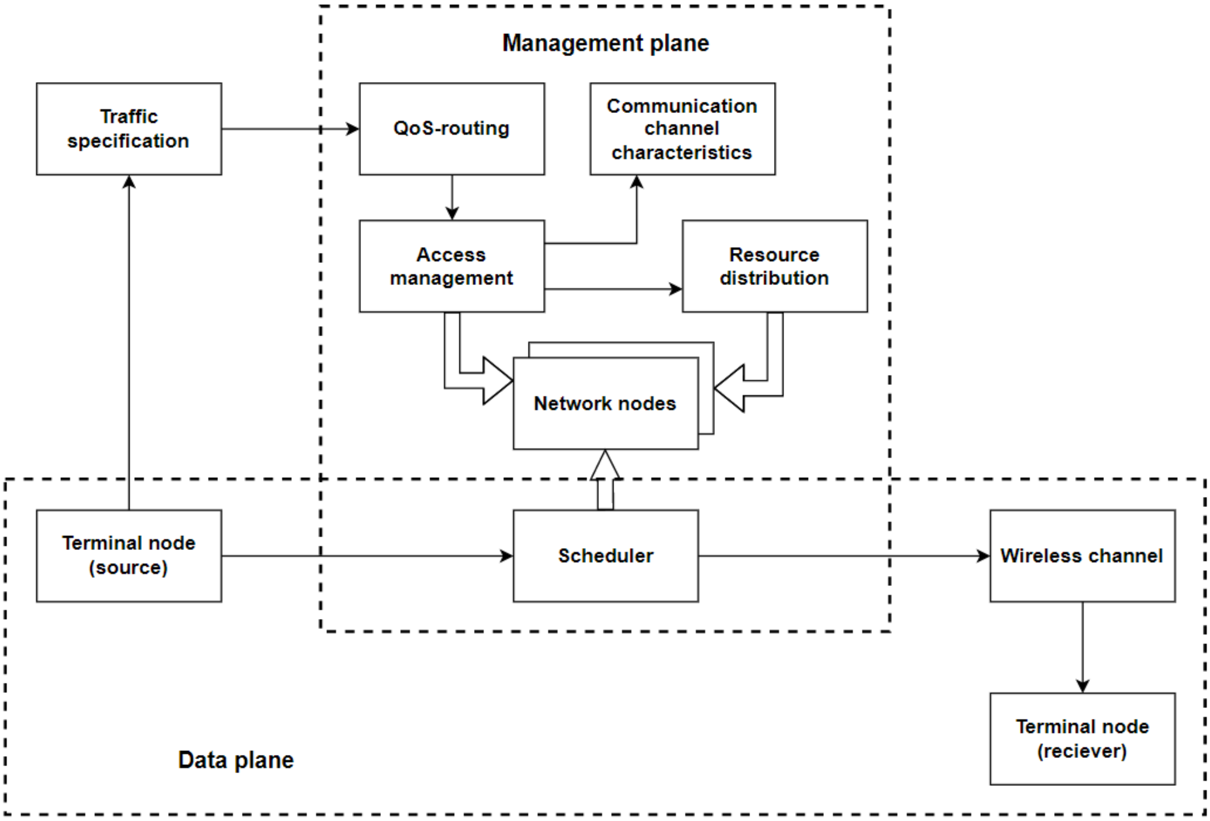

Figure 6: The network architecture for QoS redundancy

Resource allocation is usually combined with request acceptance control. The analysis of route search results based on QoS is performed on a route consisting of several transit sections and is optimal according to the criterion of minimum total delay [21, 22]. Based on formulas (1-8), computer programs for calculating the potential characteristics of the network under different conditions of its functioning have been developed.

Table 1
Numerical model parameters

Numerical parameter	Variants	
	I	II
Maximum buffer memory size, N_{cells} , cells	64	128
Availability interval duration, µs	32	32
Duration of the protection interval t_{safe} after sending an ACK confirmation, µs	16	16
Duration of the protection interval t_{safe2} after successful packet transmission, µs	32	48
Duration of the protection interval t_{safe3} after a failed packet transmission attempt, µs	128	192
Packet header length t_{head}, µs	80	80
Transmission rate v_{tr}, Mbps	8	16
Length of the polling service frame t_{RTS} , µs	72	72
Length of the service confirmation frame t_{CTS} , µs	48	48
Minimum size of the competitive window w_{min} , unit intervals	16	32
Maximum size of the competitive window w_{max} , unit intervals	512	768
Number of transmission attempts, m	5	10

6. Estimation of potential characteristics of a wireless telecommunication network with variable parameters and structure operating under conditions of external interference

Formulas (1-8) show that the network throughput depends not only on the intensity of its load (packet loss and retransmissions), but also on the presence of external interference, intra- and inter-network interference. The main factors of interference are distortion of signals as carriers of user and service information [23].

Figure 7 shows graphs of the calculated probabilities of denial of access from the relative intensity of interference σ_3 at different relative intensities of traffic α: $\alpha = \frac{\lambda}{\mu}$, where λ is the intensity of the flow of incoming packets, μ is the intensity of service.

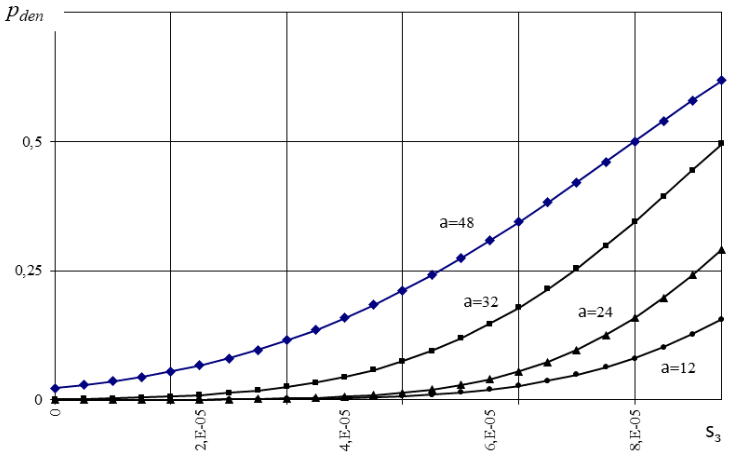

Figure 7: Estimated probabilities of access denial from the relative intensity of interference σ_3 at different relative traffic intensities α

Based on the results of analyzing the graphs in Fig. 2, it is possible to argue that the optimal choice of the number of retransmission attempts reduces the resulting probability of access denial, with a particularly noticeable gain occurring at low total network load and low relative interference level.

7. Conclusions

A method for controlling the quality of service when organizing data exchange sessions with the redistribution of resources of network and switching nodes is developed. To evaluate the potential characteristics of a wireless telecommunication network with random multiple access, variable parameters, and a structure operating under conditions of external interference, a network simulation model is developed. Using the developed model, the potential characteristics of the network are estimated under conditions of changing the structure (number of terminal nodes, gradual and sudden changes in network traffic characteristics, etc.)

8. References

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