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Survey of Traffic Engineering Solution for Telecommunication Network Optimization

Ahmad M. Hailan [a], **Hisham Alshaheen** [b*]
a College of Computer Science and Mathematics, University of Thi-Qar, Thi-Qar, Iraq.
b Electrical and Electronic Engineering (EEE) Department, University of Thi-Qar, Thi-Qar, Iraq.

Keywords:
CR-LDP; ISIS-TE; OSI; OSPF-TE; QoS; RSVP-TE; Traffic Engineering.

Highlights:

- The survey analyzes the principles of Quality of Service (QoS), Traffic Engineering (TE), and Network Planning and Optimization (NPO).
- The analysis showed that the TE requirements are usually fulfilled during the formulating and solving of optimization problems.
- Emerging technologies like Software-Defined Networking (SDN) and Network Function Virtualization (NFV) offer significant opportunities for efficient traffic management and automation.

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***Corresponding author:**
Hisham Alshaheen
Electrical and Electronic Engineering (EEE) Department, University of Thi-Qar, Thi-Qar, Iraq.

Abstract: Telecommunication network operators face many challenges, including network congestion, service quality, and network reliability. This study explores a solution that may mitigate these challenges. The suggested traffic engineering solutions for telecommunication network optimization are a comprehensive review of various traffic engineering techniques and tools used to optimize the performance of telecommunication networks. The survey analyzes the principles of Quality of Service (QoS), Traffic Engineering (TE), and Network Planning and Optimization (NPO). These principles aim to find acceptable solutions to improve network performance, reduce latency and packet loss, and enhance user experience by providing higher bandwidth and better network coverage. The study also investigates the role of emerging technologies, such as software-defined networking (SDN) and network function virtualization (NFV), in traffic engineering and optimization. These technologies offer new opportunities for traffic management and network automation, enabling network operators to deploy traffic engineering solutions efficiently and effectively. It emphasizes the need for more advanced traffic engineering solutions that can cope with the growing complexity of telecommunication networks. Especially the increasing demand for high-speed connectivity and the diverse range of tools and services offered over the network. The survey concludes by highlighting the key challenges and future directions of traffic engineering in telecommunication networks.

مسح الحلول الهندسية لحركة المرور لتحسين شبكة الاتصالات السلكية واللاسلكية

احمد محسن هيلان[١] ، هشام شعلان صيوان[٢]

[١] قسم علوم الحاسوب / كلية علوم الحاسوب والرياضيات / جامعة ذي قار / الناصرية – العراق.

[٢] قسم هندسة الطب الحياتي / كلية الهندسة / جامعة ذي قار / الناصرية – العراق.

الخلاصة

تتميز المرحلة الحالية في تطوير شبكات الاتصالات بزيادة مستمرة في متطلبات جودة الخدمة (QoS) التي يطلبها المستخدمون. وهذا مشروط في المقام الأول بإدخال خدمات اتصالات معلوماتية جديدة تتطلب عددًا متزايدًا من موارد الشبكة لتشغيلها. يمكن تقسيم القرارات التي تهدف إلى تحسين مستوى جودة الخدمة بشكل مشروط إلى مجموعتين كبيرتين. تهدف المجموعة الأولى من الحلول إلى زيادة موارد الشبكة، وقبل كل شيء، عرض النطاق الترددي لروابط الاتصال والشبكة ككل. يرتبط هذا بشكل مباشر بالتقديم الناجح للتقنيات والبروتوكولات المتقدمة للطبقات المادي ووصلة البيانات في النموذج المرجعي الأساسي لتفاعل الأنظمة المفتوحة (OSI)، والذي يسمح للشبكات اللاسلكية بتوفير معدلات إرسال بسعة جيجابت في الثانية وسلكية لتوفير معدلات إرسال تيرابيت في الثانية ومع ذلك، إلى جانب الحلول التي تهدف إلى زيادة عدد موارد الشبكة المتاحة، تحتل أدوات هندسة المرور مكانة مهمة في بنية QoS، ممثلة بآليات وبروتوكولات الشبكة، وطبقات النقل في OSI، وهي إدارة قائمة الانتظار، وتوصيف حركة المرور، والتوجيه، وحجز الموارد.هذه الأدوات التكنولوجية مسؤولة عن الاستخدام الفعال وتخصيص موارد الشبكة المتكونة في الطبقتين السفليتين من OSI.

الكلمات الدالة: OSI, OSPF-TE, ISIS-TE, RSVP-TE, CR-LDP, هندسة المرور، جودة الخدمة.

1.INTRODUCTION

The technological infrastructure of organizations plays a key role in the success of the organization's objectives. Among those, telecommunication networks are characterized by a constant increase in the requirements for the quality of service requested by users, primarily conditioned by introducing new services, requiring an increasing number of network resources to function properly [1, 2]. Decisions to improve the level of QoS come in a set of solutions to increase the network resources and, above all, the bandwidth of communication links, which is directly related to the successful introduction of advanced technologies and protocols of the physical and data link layers in the Open Systems Interaction (OSI) Basic Reference Model. This model allows wireless networks to provide gigabit transmission rates and wired ones to provide terabit transmission rates. Traffic engineering tools occupy an important position in the QoS architecture, represented by network mechanisms and protocols and transport layers of OSI, queue management, traffic profiling, routing, and resource reservation [3-6]. The majority of traffic engineering decisions in multiprotocol label switching technology have been improved to meet the requirements of the concept of traffic engineering (TE). The TE solutions forming and implementing ensure the balanced use of the available network resources—the queue buffer on the interfaces of routers, the bandwidth of communication links, paths, and the network as a whole. This concept has already expanded the functionality of the routing protocols for internal, such as OSPF-TE and ISIS-TE [7, 8], and external gateways, such as BGP-TE [9], as well as signaling and resource reservation protocols, such as RSVP-TE and CR-LDP [10, 11]. The attention of many scientists is also focused on implementing the ideas of TE in modern and promising technological solutions [12-25], thus emphasizing the relevance of this line of research from theoretical and practical points of view. In most scientific papers dedicated to the problems of TE, the issue of ensuring a balanced use of a network resource and load balancing is formulated in an optimization form [12-23]. However, approaches based on heuristic solutions were often followed [24, 25]. In this regard, the purpose of this paper is to review decisions on using TE ideas in optimizing network processes in infocommunication systems.

2.SPECIFICS OF SETTING AND SOLVING ROUTING TASKS BASED ON TRAFFIC ENGINEERING

The classical formulation routing problems based on TE is the approach given in [13-15]. In its framework, the network is represented in the form of a graph, in which a set of vertices (nodes) describe network routers and a set of arcs (edges or links) model the communication links. In this case, each angle corresponds to the bandwidth of the simulated communication link between the i th and $j$the routers. For each k th flow from the set K, such basic characteristics are known: $r_k$is the average packet rate (intensity) measured in packets per second (1/s); and s_k, d_k are the graph vertices that model the source node (router) and the destination node (router) for the packets of the kth flow, respectively. In the network, the order of flow routing is determined by the routing variables$x_{i,j}^k$, each of which characterizes the fraction of the ith flow in the link represented by the arc $(i, j) \in E$. According to the physical meaning of the entered variables, to implement the multipath routing strategy, they are constrained by the form:

$$\mathbf{0} \leq x_{i,j}^k \leq \mathbf{1} \qquad (1)$$

When the routing variables are calculated, the following conditions for flow conservation on the routers of the network must be fulfilled:

$$\begin{cases} \sum_{j:(i,j)\in E} x_{i,j}^k - \sum_{j:(j,i)\in E} x_{j,i}^k = 1, k \in K, i = s_k, \\ \sum_{j:(i,j)\in E} x_{i,j}^k - \sum_{j:(j,i)\in E} x_{j,i}^k = 0, k \in K, i \neq s_k, d_k, \\ \sum_{j:(i,j)\in E} x_{i,j}^k - \sum_{j:(j,i)\in E} x_{j,i}^k = -1, k \in K, i = d_k. \end{cases} \quad (2)$$

Condition (2) is responsible for the absence of packet loss on each router and in the network as a whole. To prevent congestion of network communication links and to ensure load balancing over its communication links, the following needs to be ensured:

$$\sum_{k\in K} r_k \cdot x_{i,j}^k \leq \alpha \cdot \mu_{i,j}, \ (i,j) \in E, \quad (3)$$

Under condition (3), parameter α is an additionally introduced control variable that numerically characterizes the maximum value of the utilization threshold for the communication links of the network. Its value is constrained by the following:

$$0 \leq \alpha \leq 1 \quad (4)$$

To ensure balanced use of the link resource of the network in the multipath routing of flows, the proposed approach is to use the condition of the form of the optimality criterion for the obtained solutions [13-15].

$$\alpha \rightarrow min \quad (5)$$

Thus, the parameters of TE, which are responsible for balancing the load and using the communication links of the network, and presented in model (1)–(5) by variable α, can either enter a system of constraints or optimality criterion. In this case, when formulating the TE problem, linear formulation of the optimization problem is possible. Criterion (5) is linear, and all restrictions imposed on routing variables $x_{i,j}^k$ (1)–(3) and the variable α (3), (4) are linear. As shown in [16-19], such a formulation of the routing problem based on TE has several serious shortcomings. First, it cannot provide adequate results if half-duplex or duplex communication links are present in the network. Suppose that for the network structure shown in Fig. 1 (a), their communication bandwidth is indicated in the gaps of communication links, and the links (2, 3) and (2, 4) are half-duplex. Then, when sending packets with an intensity of 40 1/s from the first router to the fifth using model (1)–(5), the routing order is shown in Fig. 1 (b). As a result, a packet looping effect occurs, i.e., the so-called "loops." This finding was manifested in the fact that packets of the same flow were transmitted between the same pair of nodes in different directions, which in practice initially leads to the increase in delays and jitter of packets, i.e., to a degradation in the QoS in general. In Ref. [16], the proposed approach was to keep the form of the optimality criterion (5) unchanged, and additional conditions should be introduced into the TE routing model (1)–(5) structure, the fulfillment of which would prevent the packet looping effect.

$$x_{i,j}^k \cdot x_{j,i}^k = 0, \ (i,j) \in E, k \in K \quad (6)$$

The fulfillment of condition (6) ensures that the rate of at least one of the two flows moving toward each other in the duplex or half-duplex links will be zero, thereby ensuring that no looping effect occurs on the packets. Figure 2 shows an example of order distribution in the flow over the network links in the course of solving the multipath routing problem based on the model (1)–(5) with introducing additional condition (6).

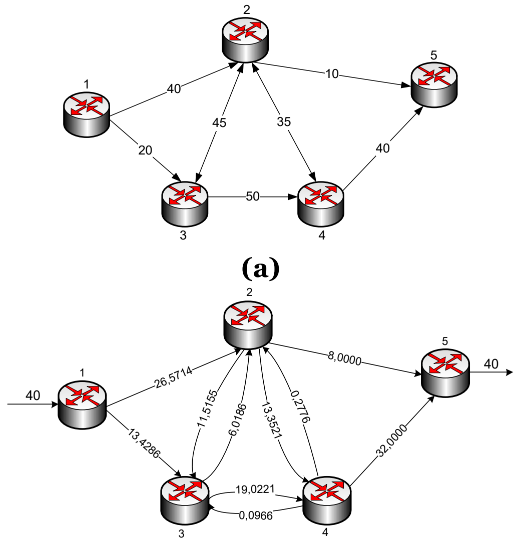


Fig. 1 The Order of Solving the TE Routing Problem for the Case of Half-Duplex Links.

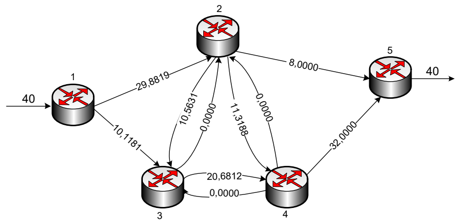


Fig. 2 Order of Traffic Balancing when Solving the TE Routing Problem, Taking Into Account the Introduction of Additional Condition (6) (α = 0,8).

The second drawback of the model (1)–(5) is, as shown in [16, 20, 21], minimizing the upper threshold of traffic congestion of the network (5) does not always help maximize the QoS in the network. This situation is typical when the network has a heterogeneous structure expressed in the asymmetry of individual network fragments in terms of its performance. Thus, if bottlenecks are present in the network with low bandwidth, their workload will determine the values of the function (5), which does not prohibit and help minimize the congestion of other network communication links. The Partial load balancing was proposed for certain special circumstances restricted to the representation of a network as a separable chart [16], balancing each connected part of the graph separately, connected by a bridge across the points of articulation. In this situation, the network's maximum load of communication links, represented by the variable's mixing value, will correspond to the link coefficient modeled by the graph bridge. The optimization of balancing in the interconnected network elements connected by a bridge allows the end-to-end solutions to enhance QoS [16, 20, 21]. However, this scheme can be adequately applied only in cases where the network or logic's physical architecture can be represented by a separable graph with multiple articulation points and a bridge. If the bottleneck of the network (the low-performance site) on the network graph model cannot be described by a single bridge or the network structure does not contain articulation points, then an approach based on the separate different solutions of balancing tasks for individual network fragments cannot be applied. Also, this conception is explained by the fact that ambiguity exists in the solutions obtained in the connected fragments of the network and the communication links, thus forming the bottleneck of the network, accompanied by a violation of the connectivity of the end-to-end routes. Therefore, in [20, 21], enhancing the basic model (1)–(5) does not concern the revision of the calculation procedure for routing variables; however, changes in the category of the optimality criterion used (5) and the inherent objective function. As a rule, Generally, to make the optimality criterion more sensitive to overloading, not only other communication links but also the bottleneck numerically related terms are included in the optimality criterion. In [20,21], the optimality criterion, modifying expression (5), already acquires a linear-quadratic form.

$$\boldsymbol{J_{lq} = \vec{x}^t \cdot H \cdot \vec{x} + g \cdot \alpha \rightarrow min} \qquad \textbf{(7)}$$

where H is the diagonal matrix, whose coordinates are route metrics (variables$1/\mu_{i,j}$). Let the values of the average delay (end-to-end packet delay) serve as an indicator of the effectiveness of the solutions, calculated for each of the flows according to the formula [20, 21].

$$\boldsymbol{\tau^k = \sum_{p \in P} x_p^k \, \tau_p^k} \qquad \textbf{(8)}$$

where P is the set of paths between the analyzed pair of source and destination nodes (routers), and x_p^k is the portion of the kth flow that moves along the pth path.

$$\boldsymbol{\tau_p^k = \sum_{(i,j)\in p} \frac{1}{\mu_{i,j} - \sum_{k\in K} r_k \cdot x_{i,j}^k}} \qquad \textbf{(9)}$$

τ_p^k is the average delay of the packets of the kth flow along the pth path in simulating the functioning of each network link by the queuing system M/M/1. The efficiency of the solution proposed in [20, 21] can be demonstrated by the following example. Figure 3 shows a network whose structural heterogeneity enables it to be described using a separable graph, in which the vertex simulating the third router (node) is the point of articulation. The bandwidths are indicated in the gaps in their communication links. The first router represents the source node, and the destination is the eighth router, transmitting packets at a rate of 400 1/s.

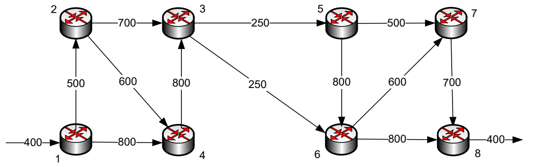
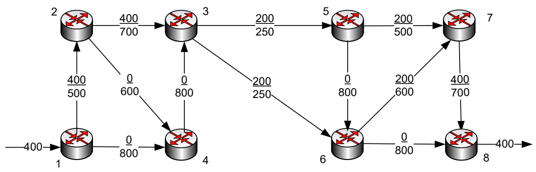
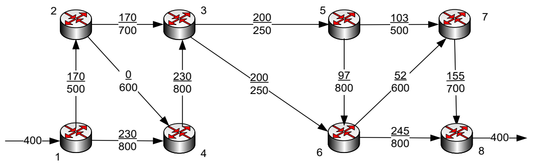


Fig. 3 The Example of a Heterogeneous Network Structure.

The network shown in Fig. 3 has a bottleneck, a cut that comprises the links that connect the third router (node) with the fifth and sixth routers (nodes), and a bandwidth of 500 1/s. The examples of optimal solutions to the load-balancing problem in the network using the model (1)–(4) with various optimality criteria are presented in Fig. 4. Criterion (5) and criterion (7) are shown in Fig. 4 (a) and Fig. 4 (b), respectively. In the gaps of each communication link, the rate of the transmitted packet flow and the bandwidth of the given communication link are represented by the fraction's numerator and denominator in Fig. 4, respectively. Each solution shown in Fig. 4 provides the same value of the parameter α = 0,8, calculated for communication links (3, 5) and (3, 6) of the minimum cut of the network. However, the order of routing and load balancing over communication links not included in this cut differs when using different optimality criteria. In Table 1, multipaths and their forming paths are described in detail from the point of view of the intensity of the flows transmitted over them (Fig. 4) and the resulting values of the average latency (8) (end-to-end packet delay). Thus, changing the form of the optimality criterion for the solutions obtained with respect to TE routing improved the average latency end-to-end packet delay by 32% without introducing an additional link resource.



(a) The Order of Load Balancing Using the Criterion (5).



(b) The Order of Load Balancing Using the Criterion (7).

Fig. 4 The Load-Balancing Problem is Solved Based on the Model (1)–(4) and Different Optimality Criteria for the First Network Architecture (Fig. 3).

Table 1 Characteristics of Solutions for the Load-Balancing Problem Using Various Optimality Criteria.

Used criterion	Routes of multipath	Fraction of the flow passing along the path	Transmission rate (1/s)	Average delay along the path (ms)	Average end-to-end packet delay (ms)
(5)	1→2→3→5→7→8	0.5	200	40	39.6
	1→2→3→6→7→8	0.5	200	39.2	
(7)	1→4→3→6→8	0.5	200	25.3	27.1
	1→2→3→5→7→8	0.2575	103	29.3	
	1→2→3→5→6→7→8	0.13	52	30	
	1→2→3→5→6→8	0.035	14	28.1	
	1→4→3→5→6→8	0.0775	31	26.7	

An important detail to note is that in [26, 27], the approach to solving the TE problems described above was adapted to hierarchical multipath source source-source routing. Simultaneously, Ref. [26] used an optimality criterion, a quadratic form of routing variables, to optimize multipath TE routing. A solution for the problem of hierarchical TE routing multipath source source-source routing was proposed in [27] based on a generalization of criterion (5) for the decomposition representation of model (1)–(4).

3.SPECIFICS OF SETTING AND SOLVING TRAFFIC PROFILING TASKS BASED ON TRAFFIC ENGINEERING

In [22, 23], the requirements of TE are adapted to the solution of the tasks of traffic profiling, i.e., limitation of the incoming load to the network under its probability of overload. The flow conservation conditions on nodes (routers) are as follows:

$$\begin{cases} \sum_{j:(i,j)\in E} x_{i,j}^k - \sum_{j:(j,i)\in E} x_{j,i}^k = 1 - y^k, i = s_k; \\ \sum_{j:(i,j)\in E} x_{i,j}^k - \sum_{j:(j,i)\in E} x_{j,i}^k = 0, i \neq s_k, d_k; \\ \sum_{j:(i,j)\in E} x_{i,j}^k - \sum_{j:(j,i)\in E} x_{j,i}^k = y^k - 1, i = d_k, \end{cases} \quad (10)$$

where y^k represents the control variable, characterized by the part of k -th flow rejected service on the edge router (node) (s_k). In addition, to prevent link overload, the following requirements must be achieved:

$$\sum_{k\in K} r_k \cdot x_{i,j}^k \leq \mu_{i,j}, \ (i,j) \in E \quad (11)$$

Some constraints are related to elimination variables related to their physical meaning, and the load-balancing scheme was implemented.

$$0 \leq y^k \leq \beta, \quad (12)$$

$$0 \leq \beta \leq 1, \quad (13)$$

where β is the dynamically managed upper bound of eliminations for all flows in a whole network. In solving the routing and policing issues, a reasonable approach is to reduce the following objective function:

$$J = \beta \rightarrow min \quad (14)$$

In the investigation, consider an example where two flows are routed at varying rates, thus causing overload within the network (Fig. 5 (a)) [22, 23]. Assume that a network structure contains six nodes (routers) and eleven links. In a network, links are given their throughputs (1/s), as shown in Fig. 5 (a). The first and fifth routers represent the source of the first and second flows, respectively. The third router represents the destination of the packets of the first and second flows.

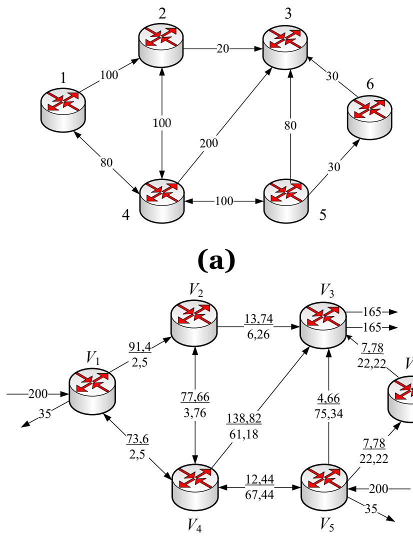


Fig. 5 Example of Network Structure and Results of Solving Routing and Policing Issues with Flow Rates $r_1 = r_2 = 200$ 1/s.

Figure 5 (b) shows an example of solving the multipath routing problem and balancing the flow of eliminations under telecommunication network overload. The rates of the first and second flows are both 200 1/s. On communication links (Fig. 5 (b)), the first flow rate is specified in the fraction's numerator, and the second flow rate is specified in the denominator. As a result of the consistent solution of routing and rejections balancing issue, both flows were limited by the same rate of access equal to 35 1/s, while the third router (destination node) receives packets at a rate of 165 1/s. In this case, the dynamically controlled upper bound for eliminations for those flows is equal to $\alpha = 0{,}175$.

4.FEATURES OF IMPLEMENTING THE TRAFFIC ENGINEERING CONCEPT FOR THE SOLUTION OF QUEUE MANAGEMENT TASKS

The concept of TE finds its active application in queue management. An example of such a solution can be considered in the model presented in [28-30]. To describe the process adequately, the assumption is that the router interface (node interface) supports M flows with the following common features: a_i denotes the rate of the ith flow. The classification of network traffic within implementing the transport technology in the network uses a set of parameters of the ith flows, representing

$K_i = \{k_i^l, l = \overline{1, L}\}$, where L is the total number of traffic classification parameters. Following from the analysis of multiple parameters$\{k_i^l, l = \overline{1, L}\}$, each ith flow, the class k_i^{flow} is assumed to be calculated as a function of the elements of the setK_i. Generally, the given function could be nonlinear. For instance, this dependency has been described as follows:

$$\boldsymbol{k_i^{flow}(p_i, d_i) = \frac{p_i}{v \cdot d_i}, (i = \overline{1, M})}, \qquad \textbf{(15)}$$

where $d_i$and p_i are the packet length and packet priority for the ith flow, respectively, and v is a standardization coefficient that smoothed out the difference between the order of priority values (0 ÷ 7) and the packet length in bytes. The assumption is that the received interface packets on the router (node) should be distributed between N queues while solving a congestion management issue when determining the set of the specific type (variables of the second type)$x_{i,j}$ $(i = \overline{1, M}, j = \overline{1, N})$. Each variable $x_{i,j}$ represents the part of ith flow served by the jth queue. To solve resource allocation issues, the set of variables b_j $(j = \overline{1, N})$ should be determined, where b_j represents a part of the bandwidth of the outbound transmission path allocated to the jth queue of queues$(j = \overline{1, N})$. Similar to the flow (packets) classification, the assumption is that in the queue management system, queue classes are also created. Therefore, each jth queue delivers the class$k_j^q (j = \overline{1, N})$, similar to ith flows class k_i^{flow} and in the dimensionless quantity that varies between zero to one (exclusive to inclusive). The same flow packets are transmitted to the same queue in the practice. Consequently, according to the physical significance of the solved issues, the variable $x_{i,j}$ is Boolean.

$$\boldsymbol{x_{i,j} \in \{0, 1\}} \qquad \textbf{(16)}$$

Further constraints (16) on the control variables $x_{i,j}$ impose the condition of flow conservation on the node interface (router interface).

$$\boldsymbol{\sum_{j=1}^{N} x_{i,j} = 1, (i = \overline{1, M})}, \qquad \textbf{(17)}$$

The values of variables b_j are represented by positive real, which also applies the constraint system.

$$\boldsymbol{0 < b_j \leq b, (j = \overline{1, N})} \qquad \textbf{(18)}$$

where $b$described the interface bandwidth of the outbound transmission path, explained by the type of implemented telecommunication technology. The constraint, which prevents queue overloading, represents this model's main characteristic. Hence, the following conditions should be satisfied:

$$\boldsymbol{\sum_{i=1}^{M} a_i x_{i,j} < b_j, (j = \overline{1, N})} \qquad \textbf{(19)}$$

The total rate of the flows directed to the service in jth queue should not exceed the bandwidth interface allocated for that queue.

When the ideas of the TE queues concept are developed and complemented into the structure of the model, multiple additional conditions that regulate the issues of providing balanced loading of queues are introduced [29, 30].

$$\boldsymbol{k_j^q \overline{n_j} \leq \beta (j = \overline{1, N})} \qquad \textbf{(20)}$$

where for each jth queue given $\overline{n_j}$ $(j = \overline{1, N})$ its current length (in the packet), and β represents the upper dynamically controlled threshold of queue length. The physical meaning of condition (20) is that queues created on the interface are loaded in a balanced manner. In addition, the higher the queue class (k_j^q) is, the shorter its length should be.

The control variables$x_{i,j}$, b_j and β were computed while solving the optimization issue by minimizing the objective function represented by the form:

$$\boldsymbol{F = \sum_{i=1}^{M} \sum_{j=1}^{N} h_{i,j}^x x_{i,j} + \beta} \qquad \textbf{(21)}$$

where

$$h_{i,j}^x = (k_i^{flow} - k_j^q)^2 + 1$$

measured value (metric value) of the ith flow packet services using the jth queue. The physical meaning was that the control variable calculation should result in the minimized total cost of use of network resources, where the first and second terms were responsible for the procedure of the queue buffer usage and the responsible for the interface bandwidth, respectively. Equation (21) corresponds to minimizing the upper limit of queue length on the router, weighted with respect to the flow features, such as the packet's priority and length [29, 30]. The specifics of the solution for balanced queue management on the router interface will be considered using the example shown in Fig. 6. The example covers the case where an interface with a bandwidth of 100 1/s receives eight flows. The intensities and classes are shown in Fig. 6.

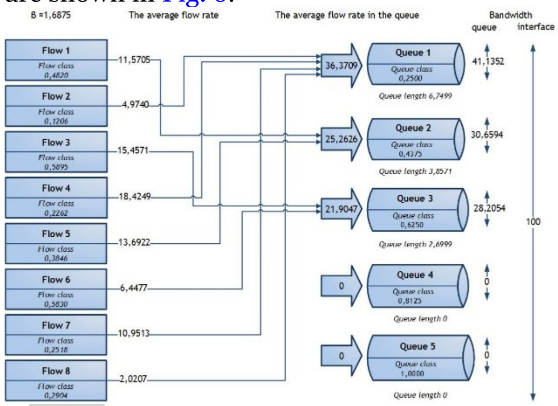


Fig. 6 Example of a Solution to the Task of Balanced Queue Management on the Router Interface.

Then, with the help of the model (16)–(21), such order of queue management is ensured when the upper threshold of queue loading along their length, considering the priority and length of transmitted packets, was 1.6875.

5.FEATURES OF SOLVING THE PROBLEMS OF BALANCED TIME-FREQUENCY RESOURCE ALLOCATION IN THE LTE NETWORK

The principles of balanced use of a network resource also refer to data link layer tasks, including those of wireless networks, such as Wi-Fi, WiMax, and LTE. The results in [31-34] are related to this issue, where the frequency and time resource represent the network resource. For Wi-Fi networks, frequency channels are allocated between user equipment (UE). In WiMax networks, frequency subchannels, slots, and bursts are allocated, while resource blocks (RBs) are allocated in LTE networks. The volume of the allocated frequency-time resource is influenced by factors, such as the specifics of the signal-to-noise ratio (SNR), the UE requirements regarding the allocated bandwidth, and the UE requirements regarding the priority of requests. An example of solving similar problems will be considered with reference to the downlink LTE technology. Solving the RB allocation problem among a set of UEs is received on the evolved NodeB. This approach considers the information about the radio link parameters represented by the channel quality indicator (CQI), which is a linear function of SNR [31, 34]. The values of this indicator determine the type of adaptive modulation and coding scheme used. It was confined to the specifics of the operation of the first resource allocation type (RAT), or RAT 1 when RBs are combined into resource block groups (RBGs). In this case, the number of RBs included in one RBG (P) depends on the frequency channel used. In the solution [31, 34] chosen for consideration, the following initial data are assumed to be known: N is the number of UEs; R^n_{req} is the required bit rate for the nth UE, M is the largest number of RBs belonging to a particular subset, and $r^p_{n,m}$ is the bandwidth allocated to the mth RB of the pth subset of the nth UE. When solving the task of balanced bandwidth allocation in LTE downlink using RAT 1, a set of Boolean control variables that determine the order of allocation of RBs should be calculated:

$$x_n^{m,p} = \begin{cases} 1, \text{if the mth RB of} \\ \text{the pth subset is allocated} \\ \text{to the nth UE;} \\ 0, \text{otherwise,} \end{cases} \qquad (22)$$

where $p = \overline{0, P-1}$; $n = \overline{1, N}$.

When the required variables $x_n^{m,p}$ are calculated, several conditions need to be fulfilled:

1) The condition for allocating each RB to no more than one UE:

$$\sum_{n=1}^{N} x_n^{m,p} \leq 1, (m = \overline{0, M-1}, p = \overline{0, P-1}) \qquad (23)$$

2) The condition for allocating RBs to the nth UE of only one subset in accordance with the RAT 1 standard:

$$x_n^{m,p} M + \sum_{\substack{j=0, \\ j \neq p}}^{P-1} \sum_{\substack{t=0, \\ t \neq m}}^{M-1} x_n^{t,j} \leq M \text{ under } m = \overline{0, M-1}; p = \overline{0, P-1}; n = \overline{1, N}; \qquad (24)$$

3) The condition of optimally balancing the number of RBs allocated to each UE:

$$\frac{(\mathrm{Pr}_n + 1)}{(CQI_n + 1)} \sum_{m=0}^{M-1} \sum_{p=0}^{P-1} r^p_{n,m} x_n^{m,p} \geq \beta \cdot R^n_{req}, (n = \overline{1, N}) \qquad (25)$$

where β is the balancing variable that characterizes the lower threshold value for satisfying users' requests for the required level of QoS at bit rate, Pr_n is the priority of the user request coming from the nth UE, and CQI_n is the numerical value of the CQI formed based on the SNR analysis in the area of the nth UE. Unlike the IP-priority values in the LTE network, the more important flow has a low numerical value Pr_n. Thus, when the number of RBs allocated to a particular UE is being balanced, the parameters of these RBs, the priority and QoS requirements of the UE concerning bandwidth, and the parameters of the SBR in the area of UE are considered. As an optimality criterion for the solutions when balancing the number of RBs allocated to UE, the condition of the form was used.

$$\max_{x,\beta} \beta \qquad (26)$$

The lower threshold of the allocated bandwidth of each UE is maximized according to its QoS requirements, the priority of the request, and the level of the SNR.

In the context of this example, the following initial data are considered as a basis:

- The number of UEs is 3 ($N = 3$);
- The width of the downlink is 5 MHz;
- The number of RBs is 15 ($N^{DL}_{RB} = 15$);
- The requirements for allocated bandwidth (Mbps) for each UE: $R^1_{req} = 2Mbps$, $R^2_{req} = 2Mbps$, and $R^3_{req} = 1Mbps$, service priority values: $Pr_1 = 1$, $Pr_2 = 0$, and $Pr_3 = 3$, and the UE data of the CQI parameter are indicated in Equation (6);
- The number of RBs in the subsets was 8 in the zeroth one and 7 in the first one;
- Transmission rates that provide RBs within subsets 0 ÷ 1 for UEs 1÷3 are represented as matrices;

$$\left\|r^0_{n,k}\right\| = \begin{Vmatrix} 0.1 & 0.2 & 0.3 & 0.5 & 0.9 & 0.7 & 0.2 & 0.1 \\ 0.4 & 0.5 & 0.6 & 0.8 & 0.9 & 0.7 & 0.3 & 0.5 \\ 0.7 & 0.8 & 0.9 & 0.3 & 0.5 & 0.2 & 0.1 & 0.6 \end{Vmatrix},$$

$$\left\|r^1_{n,k}\right\| = \begin{Vmatrix} 0.2 & 0.3 & 0.5 & 0.9 & 0.7 & 0.2 & 0.1 \\ 0.5 & 0.6 & 0.8 & 0.9 & 0.7 & 0.3 & 0.5 \\ 0.8 & 0.9 & 0.3 & 0.5 & 0.2 & 0.1 & 0.6 \end{Vmatrix}$$

Solving the problem posed using the model (21)–(26) is given in Fig. 7, showing the order of RB allocation among the three specified UEs.

With the balancing conditions introduced and the optimality criterion, the first UE received 2.4 Mbps, and the second received 4.7 Mbps because it had the highest request priority, and the third received 0.9 Mbps because it had the lowest request priority. The resulting value of the balancing variable was $\beta = 2.35$.

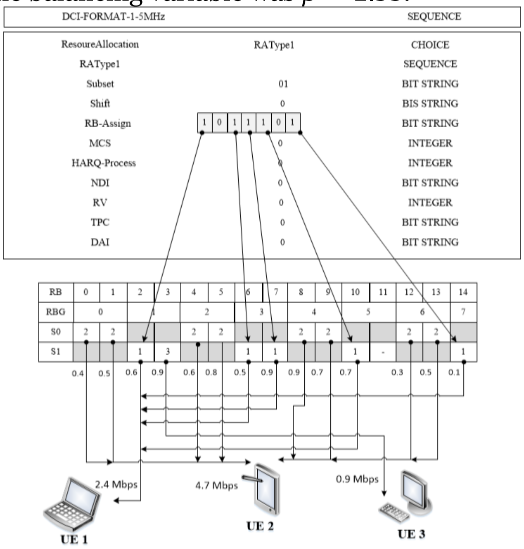


Fig. 7 A Bitmap for the First UE and the Resource Allocation Result for all UEs.

6.CONTRIBUTION AND DISCUSSION

Exploring previous studies to enhance performance, reduce latency and packet loss, and improve user experience. Additionally, reviewing articles on Software-Defined Networking (SDN) and Network Function Virtualization (NFV) for efficient traffic management and automation. The studies mentioned above clearly indicate the need for improved measures for the use of network resources. The comparison between this study and previous research on the TE topic is shown in Table 2. These issues can be enumerated into the following key points:

1) The TE concept is an important addition to many traffic management tools, contributing to the balanced use of network resources and improving the QoS in the network as a whole.
2) The analysis in this article showed that the TE requirements are usually fulfilled during the formulation and solution of optimization problems, where the optimality criterion is the threshold for using a certain type of resources, such as the bandwidth of communication links and the queue buffer on routers.
3) An important role in the formulation and solution of TE problems in the network is also given to constraint conditions imposed on the balancing variables to ensure their connection with routing variables, traffic profiling, or queue management variables. As a rule, under these conditions, the characteristics of transmitted packets (length and priority) are considered, and the available network resources are allocated.
4) When formulating the optimization task for TE, an important step, in addition to considering the specifics of the simulated telecommunication network construction and operation, is to avoid the excessive complication of the mathematical model used to ensure that the practical implementation of the resulting solution does not lead to increased requirements for the computing power of routers and to decreased scalability of traffic management in the network as a whole.
5) Applying TE ideas is not limited by the mathematical models and methods of balanced networks management, i.e., link, buffer, frequency, and time, considered above. They also find applications in improving solutions for important network tasks, such as resource allocation in the DiffServ-TE network [26] and fast rerouting [35, 36].

Table 2 Comparison between the Present Study and Previous Research on the TE Topic.

Ref.	Year	Area Focus	Contribution
[39]	2019	Traffic engineering for software-defined network	concentrates on the techniques for traditional network architecture.
[38]	2020	Challenges in Segment Routing (SR) Architecture	Evolution of Segment Routing and its Standardizations.
[37]	2023	Segment Routing Traffic Engineering (SR-TE)	Reviewing link utilization, throughput, Quality of Experience, and energy consumption.
The present Study	2024	Traffic engineering solution for telecommunication network optimization	Exploring previous studies to enhance performance, reduce latency and packet loss, and improve user experience. Additionally, reviewing articles on Software-Defined Networking (SDN) and Network Function Virtualization (NFV) for efficient traffic management and automation.

7.CONCLUSIONS AND FUTURE STUDIES

This survey comprehensively reviewed traffic engineering (TE) techniques and tools for optimizing the agility of telecommunication networks. It identified methods to enhance performance, reduce latency and packet loss, and improve user experience through higher bandwidth and better coverage. Emerging technologies, like Software-Defined Networking (SDN) and Network Function Virtualization (NFV, offer significant opportunities for efficient traffic management and automation. The study highlights the need for advanced traffic engineering solutions to address growing network complexity and increasing demand for high-speed connectivity and diverse services. Three main directions for worthwhile future research efforts: develop dynamic, adaptive traffic management using machine learning and AI for real-time optimization; optimize SDN and NFV for enhanced flexibility and automation; and develop secure traffic management protocols to protect user data and network integrity.

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