Cross-Layer Model of Dynamic Distribution of Radio Resources and Data Flow Service in LTE Networks

Original Scientific Paper

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Abstract – *In this article, the results of the development of a mathematical model for the time-frequency resource allocation of the uplink channel and flow service in LTE (Long Term Evolution) networks are given. The proposed model is aimed at ensuring the maximum performance of the radio channel and the guaranteed quality of service for data flows of wireless network users. A comparative analysis of the proposed model with the existing methods of the time-frequency resource allocation of the LTE technology is carried out in terms of ensuring the overall performance of the uplink and allocating the required transmission rate to user stations while maintaining the quality of service. It is shown that the proposed model of dynamic distribution of radio resources and servicing of data streams increases the overall performance of the uplink compared to the Round Robin and Proportional Fair methods, by 1.42 and 1.23 times, respectively.*

Keywords: *LTE, time-frequency resource, resource block, scheduling block, cross-layer mathematical model, required transmission rate, guaranteed quality of service*

1. INTRODUCTION

At present, the implementation of modern infocommunication services in terms of increasing their mobility and accessibility is directly related to the further implementation of wireless telecommunication technologies. However, the limiting factor on this path is the low performance compared to wired solutions, provided by wireless technologies. At the same time, to improve the performance of wireless technologies, all available tools are being used to manage the available network resource: frequency, time, channel, buffer, and information [1,2]. In this regard, more and more attention from scientists, designers of network equipment, and developers of relevant standards are being paid to finding effective solutions for the formation and optimal distribution of the time-frequency resource available at the data link layer, and subsequently at the network layer of the OSI (Open Systems Interconnection Basic Reference Model) model. The basic principles of the hierarchical system are the principles of consistency and coordination adopted at all levels of management. In telecommunication networks, all functions of the functional levels must be coordinated with each other to achieve the specified indicators of quality of service. A characteristic feature of existing solutions for the implementation of functional levels is a statistical strategy for the distribution of network resources. In this regard, an important scientifically applied problem arises, which consists in optimizing the processes of distributing a network resource and servicing flows based on the development of cross-layer models.

In this paper, a cross-layer model is developed in which the distribution of a network resource at the data link layer is formulated as an optimization problem of distributing radio resources between network users according to the criterion of maximum uplink channel performance, and at the network layer - as an optimization problem of distributing the allocated amount of radio resources between different classes of flows according to the criterion of minimum average packet delay.

2. BRIEF DESCRIPTION OF THE OBJECT OF STUDY

The main function of the MAC (Media Access Control) protocol of the LTE-Advanced is the dynamic distribution of radio resources between subscribers of the UE (User Equipment) network.

The scheduler is responsible for the allocation (scheduling) of resources for user stations. Such resources primarily include symbols (time resources) and frequency subcarriers (frequency resource). The entire channel resource is divided into the RB (resource blocks) [1,2]. One block consists of 12 adjacent subcarriers occupying a bandwidth of 180 kHz and a one-time slot (6 or 7 OFDM (Orthogonal frequency-division multiplexing) symbols with a total duration of 0.5 ms). Each OFDM symbol on each of the subcarrier's forms a RE (resource element), which is characterized by a pair of values {k, l}, where k is the subcarrier number, and l is the symbol number in the resource block. In a typical configuration (with 7 OFDM symbols in one slot), each resource block includes $12 \cdot 7 = 84$ resource elements. Some of the resource elements are used to transmit a pilot signal, which is used for synchronization and radio channel state estimation. The resource allocated to the subscriber is always a multiple in the frequency domain of a 180 kHz bandwidth, and in the time domain, an interval duration is 1 ms, which corresponds to two radio signal slots or one subframe.

The base station distributor block (eNodeB) receives several service signals: the AR (allocation request) from the user equipment, radio channel parameters, the QoS (Quality of Service) requirements (QoS Class Identifier, QCI), etc.

The eNodeB receives information about the radio channel parameters from the UE using the CQI (Channel Quality Indicator). The UE reports the obtained CQI to the eNodeB by comparing the measured SNR (Signal-to-noise ratio) according to a linear function.

Based on the obtained CQI value for each SB (Scheduling Block), the data transmission rate of user stations is adjusted on the allocated time-frequency resource by using adaptive modulation and coding [2]. Then the bandwidth of the subframe allocated to a particular user station directly depends on the MCS (modulation and coding scheme) used and is numerically equal to the number of bits transmitted in a time equal to the duration of the temporary subframe. The choice of the MCS used depends entirely on the characteristics of the signal-interference situation in the area of the user station, including and from its territorial remoteness from the base station.

Thus, the task of scheduling a frequency and time resource in LTE technology should be formulated as a task of distributing SB between network UEs depending on the declared transmission rate and distributing the allocated transmission rate between different queues, considering the requirements for the quality of service of data flows.

In works [3-8], the tasks and functions of the following main known methods of radio resource distribution are characterized:

- cyclic method (Round Robin Scheduler);
- method of maximum carrier power to interference level (Max C/I Ratio, Best CQI scheduling).
- method of proportional fair distribution of service (Proportional Fair Scheduling);

The essence of the cyclic method (Round Robin Scheduler) is that the entire available time-frequency resource is sequentially allocated to each UE [4]. Even though the network resource is allocated to stations, as a rule, for the same time interval, they get access to different channel bandwidth, because the distance to the base station and the signal-to-interference situation in the region of each UE is generally different. This is accompanied by the selection of different MCSs, which will result in different allocated bit rates.

The use of the Max C/I Ratio method helps to maximize the performance of the radio channel because the entire time-frequency resource is allocated to those UEs that have the maximum SNR ratio (CQI) values. At the same time, the QoS requirements of other stations are practically ignored. If several stations have the same SNR values, then the downlink bandwidth is shared equally among them. Therefore, stations with low SNR will receive service only when user stations with high SNR do not communicate with the base station, which is the main disadvantage of this method. The Proportional Fair Scheduling algorithm favors a UE that has a high SNR while providing sufficient frequency and time resources for the UE with the worst SNR [5]. This technique is aimed at providing high network throughput and ensuring a balanced distribution of frequency and time resources between UEs.

The tasks of distributing radio resources are also relevant in 5G (fifth generation) networks [9-12]. In [13], UE's CQI state for each RB is considered simultaneously in LTE MAC layer resource allocation with cross-layer support. In [14], an Adaptive LTE-Advanced cross-layer packet Scheduling to guarantee real-time high-speed packet service for LTE-Advanced is purposed. In [15], the long-term time-average optimization problem is converted into a series of the single-time-slot online problem by using the Lyapunov optimization technique. In [16], the performance of three well-known uplink schedulers namely, Maximum Throughput (MT), First Maximum Expansion (FME), and Round Robin (RR) are compared.

Table 1. The comparison of the related works

Reference	Objective	Application area	Method
[9]	Enhancing the QoS architecture	5G Network	The agile multi-user scheduling
[10]	Implementing the correspondent optimal solution	Mobile Network	User-centric schedular
[11]	Scheduler for Public Safety Communications	5G Network	LTE Scheduling in Downlink/ Uplink
[12]	Resource allocation in spectrum-sharing OFDMA femtocells with heterogeneous services	LTE Network	Practical Low-Complexity Algorithm
[13]	A smart and flexible scheme for Enhanced Utilization Resource Allocation	LTE Network	Enhanced utilization resource allocation (EURA) scheme
[14]	Adaptive LTE-Advanced cross-layer packet Scheduling	LTE Network	Adaptive Reward Priority Scheduling and Dynamic Resource Allocation algorithm
[15]	Cross-layer resource management mechanism for an indoor multiuser visible light communication (VLC) access network	VLC access network	VLC Resource Management Algorithm
[16]	Executing the scheduling algorithm for an open issue in the Long Term Evolution (LTE) standard.	LTE Network	Scheduling algorithm

3. CROSS-LAYER MODEL OF RADIO RESOURCE ALLOCATION

In the proposed cross-layer model, the methods of queuing theory [17,18] and optimization [19] are used.

When solving the problem of distributing frequency and time resources, it is necessary to consider the configuration of the LTE frame, since uplink subframes alternate with downlink subframes and subframes for transmitting service information [2].

Assume that the number of UEs transmitting a request for allocation of a radio resource is equal to N, the number of subframes allocated for transmitting information in the uplink is equal to M, and the number of SBs in one subframe is equal to K. Each UE has S queues for different types of data flows. It is necessary to allocate the total number ($K*M$)of SBs among N UEs and the allocated transmission rates for the UEs to be distributed among S queues.

It is necessary to calculate the control variables of $x_{n,m,k}$, which determines the order of distribution of SB:

$$x_{n,m,k} = \begin{cases} 1, If\ k-th\ SB\ on\ m-th\ subframe \\ \quad is\ allocated\ to\ n-th\ UE; \\ 0, \quad otherwise. \end{cases} \tag{1}$$

As a result of the calculation of variables (1), subframes are assigned and SBs are distributed by user stations, which will transmit data with an effective rate of $R_{n,m,k}$ by the specified MCS. When calculating the required variables, it is necessary to fulfill two constraint conditions

The first condition is for sticking the k-th SB during the transmission of the m-th subframe for no more than one UE.

$$\sum_{n=1}^{N} x_{n,m.k} = 1, \quad m = \overline{1,M}\,, k = \overline{1,K}. \tag{2}$$

The second condition of allocation for the n-th UE is the number of SBs providing the required transmission rate of (R_n^t).

$$\sum_{m=1}^{M}\sum_{k=1}^{K} x_{n,m.k} R_{n,m,k} \geq R_n^t, n = \overline{1,N}. \tag{3}$$

The SB allocation problem can be solved using an optimality criterion aimed at maximizing the overall uplink performance.

$$max \sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} x_{n,m,k} \tag{4}$$

considering the constraint conditions (2,3).

Each n-th user station distributes its allocated transmission rate (3) among S queues. It is necessary to calculate the control variable of $y_{n,s}$ ($0 \leq y_{n,s} \leq 1$), showing the share of the allocated transmission rate for servicing the s-th queue (data flow).

$$\sum_{s=1}^{S} y_{n,s} = 1, \quad n = \overline{1,N}. \tag{5}$$

When calculating the required variable $y_{n,s}$, it is necessary to ensure that the average delay s - data flow ($T_{n,s}$) must be less than or equal to the allowable value ($T^t_{n,s}$).

$$T_{n,s} \leq T_{n,s}^t, \quad n = \overline{1,N} \tag{6}$$

The problem of distributing the allocated transmission rate between queues can be solved using the optimality criterion aimed at minimizing the total average delay of data flows.

$$min \sum_{s=1}^{S} T_{n,s}\,, \quad n = \overline{1,N}, \tag{7}$$

when considering constraint conditions (5.6). The service rate of the s-th data flow of the n-th UE is defined as:

$$\mu_{n,s} = \frac{1}{y_{n,s}\sum_{m=1}^{M}\sum_{k=1}^{K} x_{n,m.k} R_{n,m,k}}\,, \ n = \overline{1,N}, s = \overline{1,S} \tag{8}$$

Considering the UE as a queuing system of the M/M/1 type, the average delay of the s-th data flow can be determined by the formula [13,14]

$$T_{n,s} = \frac{1}{\mu_{n,s} - \lambda_{n,s}}, \qquad n = \overline{1,N}, s = \overline{1,S} \tag{9}$$

where $\lambda_{n,s}$ is the rate of arrival of the s-data stream in the n-th UE, $\lambda_{n,s} < \mu_{n,s}$.

Expression (8) determines the functional relationship of the variables responsible for the distribution of radio resources at the data link ($x_{n,m,k}$) and network ($y_{n,s}$) layers of LTE.

The problem of distributing radio resources at the data link layer (4) is a linear programming problem. The required variables (1) are boolean. The problem of the distribution of radio resources at the network layer (7) is a non-linear programming problem.

To solve the linear programming problem, we will use the capabilities of the MatLab system [15], represented by the Optimization Toolbox package and the program "intlinprog".

$$[x, fval] = intlinprog(f, intcon, A, B, Aeq, Beq, lb, ub) \tag{10}$$

where *intlinprog* uses this basic strategy to solve mixed-integer linear programs. *intlinprog* can solve the problem in any of the stages. If it solves the problem in a stage, *intlinprog* does not execute the later stages. f is a linear optimization criterion (4), A and B define linear inequality constraints (3), Aeq and Beq define linear equality constraints (2), *intcon* - defines the integer value of the required variables (1), which takes the value 0 (*lb*) or 1 (*ub*).

To solve the problem of nonlinear programming, we will use the program "fmincon".

[y,fval]=fmincon('myfun',y0,[ ],[ ],Aeq,Beq,lb, ub,'confun')(11)

where *fmincon* finds a constrained minimum of a scalar function of several variables starting at an initial estimate. This is generally referred to as constrained nonlinear optimization or nonlinear programming. *myfun* - non-linear optimization criterion (7), Aeq and Beq set linear equality constraints (5), *confun* - sets non-linear constraints (6), *y0* - sets the initial values of the required variables, taking values from 0 (*lb*) to 1 (*ub*).

4. ANALYSIS OF NUMERICAL RESULTS

To analyze the solutions to problems (10) and (11), we consider an example in which the following were used as initial data:

- number of active UEs – N= [5,10,15];
- the number of subframes for the uplink direction of transmission - M=4 (LTE frame duration is 10 ms, duration of one subframe is 1 ms);
- the number of SBs generated during the transmission of one subframe is K=25 (the number of resource blocks is 50 at a frequency of 10 MHz, the number of resource elements is 84, and the number of symbols is 7).
- effective user information transfer rates by CQI and MCS are given in table 1.
- the number of queues in the UE - S=3.

Table 2. Effective UE Information Rates (R) According to CQI and MCS.

Number of UE	Indices of CQI	MCS		R bit/s/Hz Total period
		Modulation	Code Rate	
1	15	64QAM	948/1024	5.5547
2	14	64QAM	873/1024	5.1152
3	13	64QAM	772/1024	4.5234
4	12	64QAM	666/1024	3.9023
5	11	64QAM	657/1024	3.3223
6	10	64QAM	466/1024	2.7305
7	9	16QAM	616/1024	2.4063
8	8	16QAM	490/1024	1.9141
9	7	16QAM	378/1024	1.4766
10	6	QPSK	602/1024	1.1758
11	13	64QAM	772/1024	4.5234
12	12	64QAM	666/1024	3.9023
13	11	64QAM	567/1024	3.3223
14	10	64QAM	466/1024	2.7305
15	9	16QAM	616/1024	2.4063

During the experimental process, the following constraints were adopted:

- the incoming packet stream is Poisson [M/M/1];
- packet service time is described by exponential distribution;
- the amount of buffer memory is unlimited.

For example, all user stations were set to the same required transmission rates. In Fig. 1, how the overall uplink performance varies from the required transmission rate for N=5 is shown.

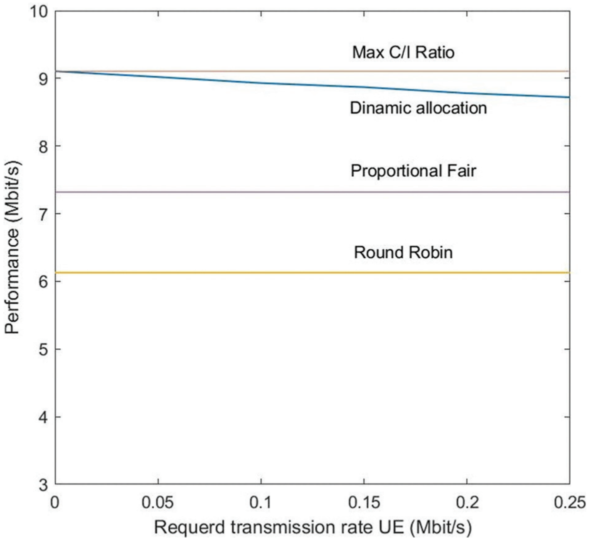

Fig. 1. The dependence of the overall performance of the uplink on the required transmission rate.

Table 3. The performance of uplink communication

Required transfer UE, Mbit/s	Performance, Mbit/s			
	Max C/I Ratio	Round Robin	Proportional Fair	Dynamic Allocation
0.05	9.105	6.13	7.32	9.02
0.1	9.105	6.13	7.32	8.93
0.15	9.105	6.13	7.32	8.87
0.2	9.105	6.13	7.32	8.78
0.25	9.105	6.13	7.32	8.72

As shown by the simulation results (Fig. 1), the overall performance of the uplink using known methods did not change throughout the entire measurement interval and amounted to 6.13 Mbit/s for the Round Robin method, 7.32 Mbit/s for the Proportional Fair method, and 7.32 Mbit/s for the Max C / I Ratio - 9.11 Mbit/s. The overall performance of the uplink when using the dynamic method (4) in the section of $R_n^t = 0 \div 0.025\ Mbit/s$ had a maximum value corresponding to the Max C/I Ratio Mbit/s method. On the interval of $R_n^t = 0.025 \div 0.25$ Mbit/s, the overall performance decreased by 4.2% to 8.72 Mbit/s. $R_n^t = 0.025 \div 0.25$ Mbit/s

In Table 4, the results of the calculations are shown, and a graph of the total uplink performance versus the required transmission rate using the dynamic distribution method (4) and various values of N is illustrated.

Table 4. The performance of uplink communication on dynamic allocation

Required transfer UE, Mbit/s	Performance, Mbit/s		
	N=5	N=10	N=15
0.05	9.02	8.28	8.01
0.1	8.93	7.63	7.18
0.15	8.87	7	6.51
0.2	8.78	6.48	5.68
0.25	8.72	5.89	4.93

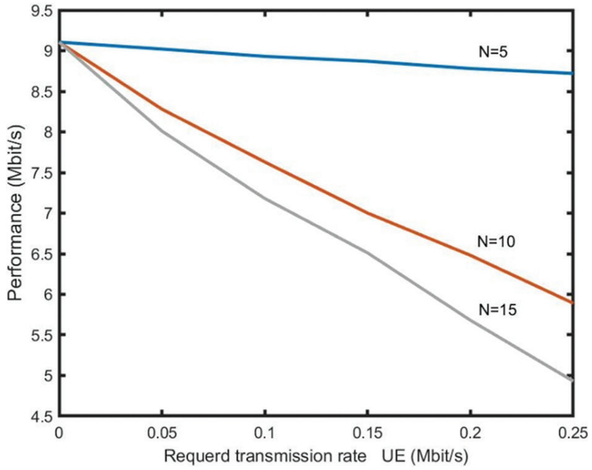

Fig. 2. The dependence of the overall uplink performance versus required transmission rate using the dynamic allocation method and different values of N.

Obviously, as the number of active UEs increases, the overall uplink performance decreases because some UEs have a low CQI due to poor SNR (Table 1).

With the number of active UEs N=10 and the dynamic resource allocation method, the first user sees 6.46 Mbit/s. This resource, by (7), is distributed among three queues intended for three data flows. Let the allowable delay time of the first flow be 0.3 ms, the second flow is 0.6 ms, and the third flow is 0.9 ms. In table 5, the results of the calculations are shown, and in Fig. 3, the dependence of the average delay of flows on the intensity of arrival of the first flow at a given intensity of the second (0.03 Mbit/s) and third (0.01 Mbit/s) flows is shown.

Table 5. The delay in the data flow

The intensity of the 1 st stream, Mbit/s	Delay, ms		
	1 st flow	2 nd flow	3 rd flow
0.01	0.3	0.6	0.707
0.1	0.3	0.6	0.755
0.2	0.3	0.6	0.816
0.4	0.305	0.601	0.9
0.5	0.312	0.603	0.901
1	0.34	0.61	0.906
1.2	0.356	0.618	0.908
1.4	0.368	0.624	0.911
1.6	0.38	0.63	0.914
1.8	0.39	0.635	0.916
2	0.403	0.641	0.92

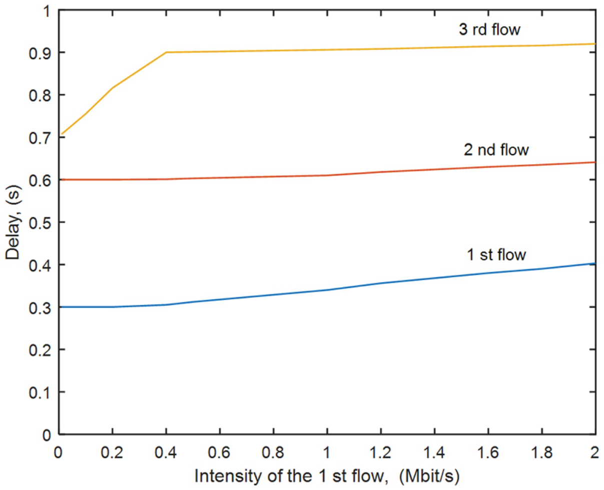

Fig. 3. The dependency graph of the average delay of data flows on the intensity of the arrival of data flows.

The obtained results show (Fig. 3) that for the first data flow the allowable delay time is up to $\lambda_{1,1}$=0.3 Mbit/s, for the second flow – up to $\lambda_{1,1}$=0.9 Mbit/s, and for the third flow – up to $\lambda_{1,1}$=1.4 Mbit/s. In the interval $\lambda_{1,1}=0 \div 0.4$ Mbit/s, the average delay time of the third data flow is less than the allowable value.

Thus, the practical implementation of the proposed cross-layer model allows:

- to improve the efficiency of radio resources, use;
- to provide the required indicators of the quality of service of data flows.

5. CONCLUSION

The analysis of existing methods of distribution of radio resources of the uplink communication channel of the LTE network has been carried out. The shortcomings of the known methods are determined and the requirements for promising solutions for the distribution of radio resources between user stations are formulated. A cross-layer model of radio resource distribution between user stations in the data link layer and various data flows in the network layer is proposed. The criterion for the optimal distribution of radio resources in the data link layer is the maximum performance of the uplink. The criterion for the optimal distribution of radio resources in the network layer is to minimize the sum of delays of various data flows with constraints on the allowable delay time for each data flow. The proposed cross-layer model provides a guaranteed transmission rate in compliance with the requirements for the delay time of data flows.

In future works, the influence of the amount of service information on the quality indicators of the transmission of user information, as well as the possibility of using a single optimality criterion in the problems of distributing radio resources at the data link and network layers of the network, will be researched.

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