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Resource Allocation Approach for Optimal Routing in IoT Wireless Mesh Networks

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ABSTRACT Information networks organized according to Internet of Things (IoT) mesh topology have received great recognition over the past one and a half to two decades of years. The scale of projects grows from millions of users connected to hundreds of thousands of access points. IoT mesh nodes offer more fascinating regulations linking a variety of networks and radio technologies and therefore fully meet the ever-growing requirements of subscribers as mobility, quality of service (QoS) and the security. The possibility of organizing local or metropolitan networks using a mesh network topology, desegregating into wide area networks without any difficulty or effort, is considered a tempting condition for urban and individual users. This article, introduces optimal routing protocol for IoT Wireless Mesh Network (WMN) by optimizing the channel and frequency resources of the network based on mathematical calculations for resource allocation. We propose an approach to the synthesis of mesh networks, which allows determining the required number of connections between network nodes, as well as their channel width for a given frequency range while ensuring the minimum data transmission delay time. Optimization results show that the function value is improved for more than 16% and the proposed algorithm provides the most rational use of the allocated frequency range.

INDEX TERMS IoT, wireless mesh network, channel resource, frequency resource, resource allocation.

I. INTRODUCTION

Nowadays, network technologies are developing at a very fast pace. The increasing volume of information transferred, the physical growth of networks and interconnected traffic are forcing manufacturers to produce more powerful and ‘‘smart’’ devices using new (built from scratch or based on a combination with traditional) methods of transferring and sorting data.

Total informatization has a significant impact on the modern world, changing the mechanisms of interaction in society, providing new opportunities in almost all areas of activity. Due to the development of electronics, its miniaturization and cheapening, information-sharing devices show significant quantitative growth, and such concepts as ‘‘Internet of Things’’ (IoT), ‘‘Internet of Everything’’ (IoE) and Machine-to-Machine Communication (M2M) are in our everyday life. In many industries will be observed the proliferation of the Comprehensive Internet, as well as the introduction of smart home technologies (security video systems, smart meters, lighting and temperature control, etc.) and digital transformation across various business segments such as enterprise, small-to-medium business, public sector, and service provider, are already seen in modern world.

According to a forecast published in the Cisco Annual Internet Report, the number of devices connected to IP networks will exceed three times the overall population by 2023. Within the M2M connections category, which is also referred

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to as IoT and which is the main accelerator of IoT growth across many industries, will lead to 14.7 billion connections as of 2023 [1].

With the goal of increasing productivity and improving the key characteristics of the service property, innovative telecommunication nodes are required to line up in the principles of structural and functional self-organization. The realization of thoughts of self-organization makes it possible to adaptively, rapidly, and most importantly effectively respond to various changes in circumstances and conditions in innovative telecommunication networks activities, dictated, for example, by overloading nodes or nodes failure, dynamic changes in signal interference, etc. A high degree of self-organization can be achieved through the improvement of certain network protocols and elements responsible for allocating available network resources. Such resources, in the main priority, include network traffic on an equal footing as an informative source, the bandwidth of transmission channels on an equal footing as a channel source, queues on an equal footing as an intermediate source, in addition, frequencies or frequency channels on an equal footing as a radio frequency source, which in particular important for the purpose of wireless networks [2].

Constant modernization of protocols is aimed at improving the performance of wireless local access networks (WLAN). Significant gains in network performance are achieved through the use of wider channels, improved modulation efficiency, and multi-user connections (MIMO) [3], [4]. Along with the introduction of new standards in WLAN technology, performance improvements can be achieved by using multi-hop wireless mesh networks [5]–[7]. At the same time, performance largely depends on the used frequency channel allocation mechanism.

It should be noted that traditional approaches to the synthesis of structural models of telecommunication communication channels are based on the use of the mathematical apparatus of graph theory [8]. The use of graph theory provides maximum clarity when modeling networks such as an IoT mesh network, since a set of nodes is assigned a one-to-one correspondence with a set of graph vertices, and a set of radio channels a set of edges, arcs of a graph.

Thus, when modeling mesh networks, it is necessary to use more efficient ways to represent mesh networks using topological ideas. Researches related to the topology of networks is one of the most important since the choice of data transfer protocols is largely due to the specifics of the location of nodes on the plane.

In order to develop algorithms for modern types of networks and substantiate their effectiveness, adequate models of the structure of these networks are needed. Since the topology of a set of nodes and connections between them is convenient to consider as a graph, it is customary to use graph models. The most commonly used models are directed graphs [9], hypergraphs [10], infinite graphs [11] with Kőnig's lemma and theorem [12], hypernets, etc.

Further, some of these models will be considered using examples of solving problems of the functioning of modern data transmission networks.

As a result of considering the conclusions according to the distribution of frequency channels, routing, and also energy consumption, it was determined that all, without exception, are tied to one technological process, moreover, they do not make a decision on the issue of coordinated distribution of frequency and channel resources of heterogeneous nodes/networks. For this reason, it is considered an important problem to create a rational/optimal method that provides not only the radio frequency source but also the channel source of the nodes/networks. Therefore, we propose the method for channel and frequency resource allocation of the network for IoT devices in the form of a mesh to obtain the better way for routing.

This paper structure is as follows: Section II provides a literature review and design goals. Our proposed framework and system module are described in Section III. Finally, the whole research work and paper is concluded in Section IV.

II. RELATED WORK AND DESIGN GOALS

Optimization of routing algorithms can be performed in different ways. According to [73]–[86] optimal routing methods use various metrics, while suboptimal routing may use few metrics, nevertheless obtained results lay close to each other.

In our time period, there are no specific criteria that characterize the term IoT mesh network according to the concepts of broadband wireless access systems. A more unified setting sounds like this: "A mesh is a network topology in which devices are interconnected by multiple, often redundant connections, established for strategic reasons" [13]. First of all, the IoT mesh theory establishes a rule for the construction of a network, a distinctive feature of which is a self-organizing structure that will implement the corresponding capabilities, similar to the formation of zones of constant informative coverage of a huge area; the scalability of the network in the option of increasing the coverage area as well as the density of the informative provision in the order of self-organization; the use of wireless transport channels for the interconnection of access points in the "each with each" mode; network stability against the loss of single components.

Mesh access points of IoT devices or of LTE, 5G, LoRa, WiFi, Bluetooth or any of other [13]–[21], not only provide subscriber access services but also act as relay routers for other access points on the same network. This makes it possible to create a self-aligning and self-healing segment of the broadband network. Mesh networks are created as a set of clusters. The area of compensation is divided into cluster areas, the number of which has not been reduced at the theoretical level in any way. One of these points is considered a gateway and also connects to the main information channel with the support of an optical or electrical cable or according to a radio channel using broadband access concepts. Access points, as well as other nodes in the cluster, are connected to other close neighbors by means of a transport radio channel.

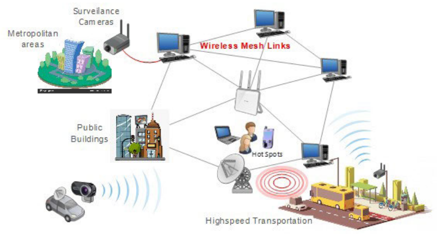


FIGURE 1. Wireless mesh network topology.

In connection with a certain decision, the access points have all the chances to perform the functions of a repeater/transport channel or the functions of a repeater as well as a subscriber access point. Figure 1 shows the mesh network topology.

It is also worth noticing in the literature review, that in terms of their physical structure, wireless mesh networks are similar to wireless sensor networks (WSNs), so many researchers combine these two networks to obtain a more reliable network [87]–[89]. The routing procedure of these protocols operates in the same way on these networks. In WSN, data is collected from sensors that read the environment [90], while in WMN, data is processed by a newly connected client [91]. Nodes in WMN communicate with each other, just like in WSN.

Since, a mesh network can be formed of IoT or of different technologies like in [13]–[21], further, we take into consideration a wireless mesh network as a whole and survey existing methods of WMN optimization and routing models in it through literature review, and design and model proposed model in the sequel.

A. MESH NETWORK FREQUENCY RESOURCE OPTIMIZATION

In the article [22], the mathematical model was based on the following requirements:

- provision of a coordinated resolution of issues in accordance with the allocation of radio interfaces in mesh nodes and the purpose of non-overlapping channels for them;
- calculation of scientific and technical distinctive features of nodes characterizing the distance of interconnection, saturation of subscriber traffic entering the line, the number of non-overlapping channels used;
- elimination of the result of the hidden node;
- taking into account the state of being distant from mesh nodes, their high activity in energy consumption, and the number of supported mesh nodes of broadcasting interfaces.

In the exact modification, the corresponding information is familiar: the number of mesh nodes, the number of broadcasting interfaces in any mesh node, the number of non-overlapping channels in the network, and a large number of stable reception areas.

The territorial distance of mesh nodes is taken into account using a matrix of stable reception areas. The matrix is rectangular with the number of rows corresponding to the number of stable reception areas and with the number of columns corresponding to the total number of mesh nodes in the network.

Within the framework of this article, it is necessary to calculate the Boolean variable. $b_{i,j}^{z}$ will be true if the j^{th} radio interface of the i^{th} node operates on the z^{th} frequency channel.

Restrictions on the order of distribution of the frequency channel in the network are set:

- condition for switching on the i^{th} node;
- one mesh node radio channel is allocated to one radio interface;
- no more than one radio channel is allocated to one node behind one radio interface;
- nodes work with each other on no more than one radio channel;
- any node with a channel enabled on the radio interface works with at least one node;
- one node belonging to different areas of stable reception should not operate on the same radio channel with nodes in different areas;
- condition of connectivity of different collision domains in each stable reception area;
- the condition for balancing the number of nodes by collision domains depending on the state of being distant and the number of stable reception zones: a) the condition of membership of the maximum number of nodes in a particular collision domain; b) the condition for the membership of the maximum number of nodes in a particular collision domain located in the same stable reception area; c) the condition of membership of the maximum number of nodes in a particular collision domain, located in the same stable reception area, with the node load factor; d) the condition for the membership of the maximum number of nodes in a particular collision domain, located in the same stable reception area, with the node load factor (also the factor depends on the total number of nodes in the network due to the uneven load of the radio interface of the nodes).

The calculation is reduced to determining the minimum number of working nodes in the created collision domains, which, as is known, helps to increase the overall performance of the network.

Objective function:

$$J = \sum_{i=1}^{n} s_{c,i} * \frac{\beta_i}{\sum_{z=1}^{Z} \sum_{j=1}^{m_i} b_{i,j}^{z}} * \sum_{j=1}^{m_i} b_{i,j}^{z} \tag{1}$$

where n is the set of nodes; $s_{c,i}$ is the i^{th} node in the c^{th} cluster (0 or 1); c is the set of areas of stable reception (clusters); Z is the number of non-overlapping channels; m_i is the j^{th} interface at the i^{th} node; β_i is the activity coefficient of the i^{th} node, which depends on the number of connected users, the intensity, and the type of traffic.

Objective function: $J \leq l$, where l is the number of nodes operating in an arbitrarily chosen collision domain.

In the work of authors [23], an algorithm for allocating sub channels of one frequency channel is assumed. The algorithm is focused on increasing network performance by balancing the number of sub channels allocated for one radio channel. This contributes to the reduction of low bandwidth sections.

Primary interference occurs when one frequency is used per node to communicate with multiple nodes. Secondary interference occurs when the same frequency channel is used by different pairs of nodes that are in the reception area of each other.

Conditions for exact modification:

- calculating the heterogeneity of the mesh network;
- provision of effective use of the frequency resource;
- minimization of interference;
- focus on the dynamic nature of the frequency distribution;
- maximizing network performance;
- coordinated resolution of issues of radio channel allocation and sub channel assignment;
- calculation of scientific and technical distinctive features of the network, similar as well as traffic, distance and the number of resources.

Initial information: the number of nodes, the number of sub channels, a single number of radio channels (2 nodes presenting in the exchange of data in the absence of secondary methods) in the network.

The representation of the matrix of the radio channel has been established, the dimension r is the number of radio channels.

$n_{r,s} = 1$, if a single node takes part in formation of r and s of the radio channel.

$q_{r,t} = 1$, if the t^{th} sub-channel is allocated to the r^{th} radio channel.

Limiting requirements:

- requirement, the presence of which must apply to any radio channel;
- the requirement to avoid primary and secondary interference. The complete removal of the use of one sub channel for the purpose of exchanging with many nodes (primary). The complete removal of the use of a sub channel by a node that is located in the exchange area in the same sub channel by another two nodes.
- the requirement to allocate the smallest number of sub channels per radio channel.

The task is to find the maximum number of sub channels for each radio channel.

Objective function:

$$J = \sum_{t=1}^{T} q_{r,t} \tag{2}$$

where T is the number of sub-channels used.

Objective function: $J < Q$, where Q is the upper dynamic control threshold of the number of WMN allocated to an arbitrarily selected radio channel.

In [24]–[26] within the framework of the modification, the theory of a stable reception area is applied. Numerous nodes have a one-to-one relationship.

For the node to belong to the stable reception area, the incidence matrix of the hypergraph G is formed.

$s_{z_j,n_i} = 1$ if the i^{th} node is the part of the j^{th} stable reception area.

In this article, the network is converted from a hyperspace representation to a flat Kőnig representation.

Initial information: the number of nodes, the number of sub channels, the set of areas of stable reception and the number of nodes introduced into any area of stable reception.

In the course of solving the problem, one should find the significance of the Boolean variable $b_{n_i,z_j}^{k_t} = 1$ if the t^{th} sub channel is allocated to the i^{th} node in the j^{th} reception area. As a result of the calculations of the variables b, the assignment of sub channels to the nodes must be carried out.

When calculating b several restrictions should be adhered to:

- the requirement to allocate sub channels for the mesh node only within the boundaries of the reception area to which it belongs (the requirement to assign radio channels only among the nodes located in the same reception area);
- the operating condition of a node located in several reception areas, it is required to be done to interact with whole quantity of reception areas;
- the requirement for a node to interact with several nodes in different sub channels;
- requirement to avoid primary interference;
- requirement to avoid secondary interference;

Objective function:

$$J = \sum_{t=1}^{T} b_{n_i,z_j}^{k_t} \tag{3}$$

where J is the number of sub channels allocated to the i^{th} node in the j^{th} stable reception area; T is the total number of sub channels.

Objective function: $J < Y$, where Y is the lower dynamic threshold for the number of sub channels, in an arbitrarily chosen WMN.

A brief analysis of methods for the distribution of frequency channels in multichannel mesh networks is laid out in [27]–[29]. A mathematical form of channel distribution in multichannel mesh networks is proposed, taking into account the state of being distant of mesh nodes.

The created form is based on a 3-index modification of the distribution of frequency channels among the nodes staying in the same stable reception area:

- the requirement to switch on the i^{th} node;
- one mesh node radio channel is allocated for one radio interface;
- no more than one radio channel for one radio interface is allocated to one node;
- nodes work with each other on no more than one radio channel;

- the requirement to connect to different collision domains in each stable reception area;
- the requirement to balance the number of nodes according to the collision domains due to the territorial remoteness and the number of stable reception areas;
- the requirement to adapt to one or another collision domain of the largest number of nodes staying in one stable reception area;

The computation is reduced to establish the smallest number of working nodes in the generated collision domains, which can help increase the overall efficiency of the network.

Objective function:

$$J = \sum_{i=1}^{n} s_{c,i} * \sum_{j=1}^{m_i} b_{i,j}^{z} \tag{4}$$

where n is a set of nodes; $s_{c,i}$ is the i^{th} node is in the c^{th} cluster (0 or 1); c is the set of areas of stable reception (clusters); z is the number of non-overlapping channels; m_i is the j^{th} interface at the i^{th} node.

Objective function: $J \leq l$, where l is the number of nodes operating in an arbitrarily chosen collision domain.

B. MESH NETWORK CHANNEL RESOURCE OPTIMIZATION

Authors in the article [30] propose a method for allocating resources in a network, independent of wireless transmission technology.

Problem setting: wireless channel S is established, which is divided into K streams, where each stream responds to a stream from this node to another node in the channel. T_i is the throughput of the i^{th} stream. The key issue in resource allocation is to determine whether these streams $(T_i \ldots T_K)$ are possible or not.

For the purpose of setting this problem, it is assumed to apply the representation of the linear bandwidth of the channel. The method is appropriate if:

$$\sum_{i \in S} c_i T_i \leq C \tag{5}$$

where c_i is precisely stated as the capacity of the i^{th} stream; C is the capacity of the wireless network. A piece of work of this pattern is to calculate c_i and C.

The throughput of the i^{th} stream is calculated as:

$$T_i = \frac{p(o_i)\, x}{p(o)\, t_o + p(cl)\, t_{cl} + p(em) t_{em}} \tag{6}$$

where x is the average packet length; t_o, t_{cl}, t_{em} are the average duration of successful transmission of any stream, collision and empty interval, and the probability of these time intervals; $p(o_i)$ is the probability of successful transmission of the i^{th} stream. Authors inhere describe in detail the calculation of each constituent element of this equation.

Objective function:

$$J_j = \frac{2}{\sum_{i \in F_j} \tau_i} - 1 \tag{7}$$

In order to find the optimal configuration, τ_i must be minimal.

Bandwidth allocation is performed according to the following:

$$\frac{T_i}{T_j} = \frac{C_i}{C_j} \tag{8}$$

The proposed form makes it possible to simply establish whether this distribution is a unit, and for this reason it can be very useful for the purpose of researching efficient routing methods.

The task of model is to maximize the number of targeted streams in a situation where streams do not have every chance of being split.

In the article [31], the authors focus on the tasks of the network layer, the main of which are the routing problems from the point of view of the impact on the final quality of service for users and the efficiency of using the resources of the wireless communication network. Distribution of routes is not many as required. It is also required to assign a certain amount of resources to each route.

The standard provides a time slot as a single channel layer resource, containing the following number of OFDM symbols:

$$\frac{K_{OFDM\ per\ frame} - K_{ctr\ slots} \times 7}{K_F} \tag{9}$$

where $K_{OFDM\ per\ frame}$ is the total number of OFDM symbols in the frame; $K_{ctr\ slots}$ is a parameter defined by the standards as *MSH_CRTL_LEN*, referring to the number of control slots in the frame and set aside by the telecom operator; K_F is the number of slots in one frame used to transfer user data.

The purpose of channel resource allocation is the purpose of assigning each stream a specific set of time slots within one frame.

The authors report that the most efficient formulation of the problem is streaming, according to which the routing rules should be formed taking into account the incoming user requests.

For the purpose of displaying the structural qualities of the network, directed weighted graph $G(V, E)$ is used. Where, V is the set of vertices modelling the set of all nodes of the mesh network, including MSS and MBS; and E is the set of arcs reflecting the set of channels between them, where the presence of a channel (i, j) means the possibility of direct transmission of the user stream from the i^{th} node to the j^{th}.

A slot is a single channel layer resource; in order to control the process of their distribution, introduced the below variable:

$$\tau_{i,j}^{p,l} = \begin{cases} 1, & \text{if the } p^{th} \text{ slot is used in the channel } (i,j) \\ & \text{to transmit the stream addressed to the} \\ & l^{th} \text{ node} \\ 0, & \text{otherwise} \end{cases}$$
$$(i,j) \in E, \quad p = \overline{1, K_F}, \quad l = \overline{1, K_v}, \quad l \neq i \tag{10}$$

where K_v is the total number of mesh network nodes.

Objective function:

$$J = \min[\sum_{k=1}^{b} \left[\vec{q}^{T}(k) W_q \vec{q}(k) + \vec{\tau}^{T}(k) W_\tau \vec{\tau}(k)\right]] \quad (11)$$

where b is the number of intervals Δt for which the calculation of control variables is carried out; W_q, W_τ are the diagonal non-negative definite weight matrices; $\vec{q}(k) = [q_{1,2}(k), \ldots, q_{i,j}(k), \ldots, q_{K_v,K_v-1}(k)]^T$ is the state vector of the mesh network for the k^{th} sampling interval of the size $K_v(K_v - 1) \times 1$, reflecting the workload of the queues at its nodes; $\vec{\tau}(k)$ is the control vector of size $K_F K_e(K_v - 1) \times 1$, whose elements are the variables $\tau_{i,j}^{p,l}$; K_e is the number of channels in the network, $K_e = |E|$.

The specificity of the 802.16 standard, which allows reuse of slots, can be expressed in the objective function as:

$$J = \min[\sum_{k=1}^{b} \left[\vec{q}^{T}(k) W_q \vec{q}(k) + \vec{\tau}^{T}(k) W_\tau \vec{\tau}(k) - \vec{\tau}^{T}(k) W_{reuse} \vec{\tau}(k)\right]] \quad (12)$$

where W_{reuse} is a diagonal non-negative definite weight matrix that reflects the advantages from the slot reuse.

The work in [32] is timed to the issue of scheduling the transmission of information according to multistage connections, which is of paramount importance in organizing the communication with established parameters, similar as well as delay and bandwidth.

The optimal schedule must maximize the lowest throughput skill, reduce the highest end-to-end latency, or maximize the allocated to requested throughput capability.

Data streams are transferred in mesh networks by means of a set of multilink connections combined in conditional channels, for the purpose of transferring which the basis of the network creates routes and a schedule. End-to-end latency is considered to be the main aspect of optimization in scheduling in a mesh network. The end-to-end delay is equal to the number of cycles that elapsed from the sending of the first bit of the frame by the source node until the final bit of this frame is received by the receiving node, multiplied by the clock time.

Inversions are the main resource for latency. When building a schedule, it must be reduced. The advantage should be given to a long route, the schedule of which is permissible in one super frame, but not a short one, in which inversions are occurred.

The sub channel transmission schedule is represented as a matrix $M = \{lj\} E \{0, 1, \ldots, K\}^{|S|\times|E|}$ in which $l_{se} = 0$ if the edge e is not used to transmit a multilink connection s, and is nonzero otherwise. Using the matrix M, it is easy to calculate the delay $u_{s,p}$ of the transmission of a multilink connection s at step p:

$$u_{s,p} = \begin{cases} l_{s,e_p} - l_{s,e_{p-1}}, & l_{s,p_m} > l_{s,e_{p-1}} \\ K + l_{s,e_p} - l_{s,e_{p-1}}, & l_{s,e_p} < l_{s,e_{p-1}} \end{cases} \quad (13)$$

If the length of the route t, along which the multistep connection s is transmitted, is equal to N_t, then to calculate the final delay U_s, it is sufficient to add the delays in N_s steps: $U_s = u_{s,p+1}$. The task of constructing a schedule with minimization of end-to-end $p = 1$ delays is now formulated as the problem of finding the matrix M, on which the minimum of the maximum delay is achieved for all multistep connections:

$$M = \min[\max_{s\in\overline{1,|S|}} (U_s)] \quad (14)$$

In [33], the authors assess the issue of gateway placement in order to optimize throughput in multi-hop mesh networks. It was planned that any node must be provided with a channel with a finite bandwidth in order to transmit traffic. Taking into account the fact that the number of gateways marked with g, for the purpose of the network is considered a fixed constant also the effect of interference on the network, in this case the issue of placing the gateways g in such a way that the network bandwidth meets the needs of absolutely all network nodes is investigated. An improved cross-layer algorithm is assumed that can be extended to mesh networks. Measurements revealed that this method increases the network throughput.

C. MESH NETWORK ENERGY EFFICIENCY OPTIMIZATION

In [34] a method has been proposed for clustering the nodes of a dynamic network used for hierarchical routing. To balance the load on the cluster controllers, a self-organizing procedure has been implemented for collision nodes. The estimation of the efficiency of self-organization of a mobile network is given according to the total energy efficiency criterion of the information transfer between nodes.

Delivery of packets with minimal energy consumption, ensuring the maximum network lifetime are resolved.

The goal is the self-organization of the network, excluding the formation of clusters with a high current load thus providing the longest period of the network existence.

As the initial data, nodes with known functions of changing the power are given in connection with the distance from the node up to the cluster controller, the number of transmitted data, the maximum probable range of the node impact.

The task requires:

- to determine the number of cluster controllers;
- to divide the network into a large number of non-overlapping clusters with controllers with the highest level of connectivity;
- to implement self-organization of nodes, the presence of which is the optimal structure of clusters created in the circumstances of movement of nodes between clusters from one to another, changes in the energy of nodes, or movement of the cluster controller.

The goal of self-organization comes down to minimizing the energy efficiency function of information transfer.

The solution to this challenge is performed in two stages: network initialization and self-organization.

It is necessary to comply with conditions-restrictions as below to carry out the issue:

- the network connection is obliged to be; there is one cluster for all the nodes;

- the amount of signal attenuation is inversely proportional to the square of the signal frequency or the square of the distance between nodes.

The steps for establishing a connection are described as below.

Objective function:

$$J = \frac{S_R * \Delta U}{\sum_{i=1}^{n} S_R * \Delta U} = \frac{\frac{S_T*(4*\pi*d_{T\to R})^2}{\lambda^2} * \Delta U}{\frac{S_T*(4*\pi)^2}{\lambda^2} * (d_{T\to i} + \ldots + d_{i+n\to R})^2 * \Delta U} = \frac{d_{T\to R^2}}{(d_{T\to i} + \ldots + d_{i+n\to R})^2} \quad (15)$$

where S_R is the signal power at the receiving node; S_T is the signal power at the transmission node; $d_{T\to R}$ is the distance between the transmitter and receiver; $d_{T\to i}$ is the distance between the transmitter and intermediate node; ΔU is the amount of data transmitted.

Objective function: $J \ll 1$.

D. DESIGN GOALS AND SYSTEM MODEL

The routing model in the form of a graph is widely proposed in the studies of different author papers.

As the analysis of known routing solutions has shown [24]–[26] and [35], [33], they are all based on the use of the graphical representation of WMN. One of them is based on approach to the use of Kőnig graphs for modeling multichannel multiradio mesh-networking, transforming hypergraphs into a flat Kőnig representation [36].

The same graphical model has been proposed in [37]. The notion of radio channels is introduced into the mathematical model, allowing to take into account the territorial remoteness of WMN in the network. The matrix of radio channels has a rectangular shape; the number of rows and columns corresponds to the total number of radio channels C and has the form:

$$P = \|p_{k,l}\|, \quad (l, k = \overline{1, C}) \quad (16)$$

where,

$$p_{k,l} = \begin{cases} 1, & \text{if the node participates in formation of the } k^{th} \text{ and } l^{th} \text{ radio channels} \\ 0, & \text{otherwise} \end{cases} \quad (17)$$

Figure 2 demonstrates the WMN example with the indication of nodes $n = 6$, with the radio channels being formed with these nodes $C = 8$. Below is the sample of radio channel matrix for WMN in Figure 2.

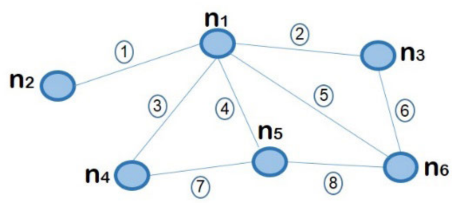
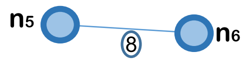


FIGURE 2. WMN example with n = 6 and C = 8.

TABLE 1. WMN topology representation.

	The node with the serial number 2.
	The 5th and the 6th nodes form a radio channel 8.

	1	2	3	4	5	6	7	8
1	0	1	1	1	1	0	0	0
2	1	0	1	1	1	1	0	0
3	1	1	0	1	1	0	1	0
4	1	1	1	0	1	0	1	1
5	1	1	1	1	0	1	0	1
6	0	1	0	0	1	0	0	1
7	0	0	1	1	0	0	0	1
8	0	0	0	1	1	1	1	0

where, the description of the above topology representation is explained below in the Table 1:

Another Boolean sensing model with clustering has been researched in [38] for Wireless Sensor Network (WSN). Authors in this paper demonstrate a data topology optimization scheme in a local tree reconstruction form. A monitoring node n is sensed n_j, if it lies within the sensing range of the sensor node. q is the sensing radius of the node. X_j sensing area is defined as a disk with x, as the center and a radius of q. The probability represented a monitoring node n is:

$$P(x_i, n_j) = \begin{cases} 0, & \text{if } d\left(x_i, n_j\right) \le r^q \\ 1, & \text{otherwise} \end{cases} \quad (18)$$

where, $d\left(x_i, n_j\right)$ is the Euclidean distance between two nodes.

Collision domain based method is an another way of the capacity analysis of the network, represented as a graph [39]–[41]. In [39] authors perform spatial channel reuse in accordance with the wireless standards such as link adaptivity. That is, the collision domain C_m including L_m links characterized by load D_i and bandwidth W_i the below equation must be held:

$$\sum_{i\in C_m} \frac{D_i}{W_i} = 1 \quad (19)$$

The quantity D_i/W_i defines the percentage of time available for link i. since the transmission time (in other words the available resources) must be shared among all links forming the collision domain to carry all its load.

Further, the design goals of the proposed system will be as follows:

a) Network topology will be represented as a graph.

b) Incoming and outgoing communication channels will be assigned as an edge, arc between communication elements.

c) Routing algorithm will be determined through resource allocation among network.

d) The design should be empirically verified with mathematical computation to increase the speed of searching.

These goals guided the design of our system, which is described in the next section.

III. DEVELOPMENT OF A METHOD FOR OPTIMIZING THE CHANNEL-FREQUENCY RESOURCE OF THE MESH NETWORK

As a result of considering decisions according to the distribution of frequency channels, routing and of the consumed power, it was determined that all, without exception, are tied to some one technology, and does not make decisions on the issue of coordinated allocation of frequency and channel resources of a heterogeneous network. For this reason, an important problem is considered to be the creation of an optimal technique that provides not only the radio frequency resource, but also the channel resource of the network.

After analyzing the available exact modifications and methods to optimize the mesh network [22]–[34], as well as, other types of resource allocation such as bandwidth allocation [42]–[47], throughput optimization [48]–[53] and other different network resources allocations [54]–[59], it can be noted that in fact the mathematical model proposed in the article [31] is optimal for mesh networks using WiMAX technology. A characteristic feature of WiMAX technological processes is considered to be a mechanism of admission to the medium with a limited number of channels and their fixed bands, which in no way allows this system to be adapted to mesh networks with different admission technologies to the transmission medium, methods of allocating channels with a random number of channels, as well as their frequency band. Combined with the data, this paper proposes an approach to the synthesis of mesh networks that allows the required number of connections between nodes to establish a frequency range, and in addition, a channel width, while providing the lowest latency for information transmission.

Taking into account the mathematical approaches of the authors in [36] and [37], the idea of graphical representation of a WMN is used to solve the optimal routing in the network.

Simulation scenario's are as following: we used 12 nodes, the design of the system is presented in the form of graphs, where the nodes are the vertices of the graph, and the communication channel between the nodes is in the form of edges between the vertices.

A. SOLVING AN OPTIMIZATION PROBLEM

This section provides a solution to the problem for 12 nodes, as shown in Figure 3, and provides a unified definition of the problem of configuring routing and resource allocation in a mesh network.

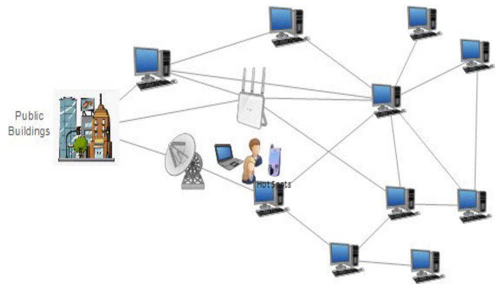


FIGURE 3. Network topology with 12 nodes.

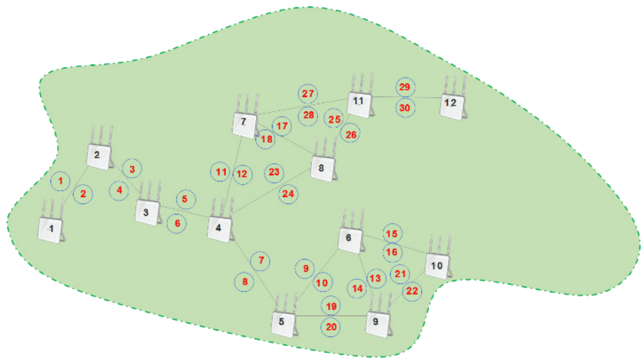


FIGURE 4. Queuing network for the network of 12 nodes.

Based on the above topology, it is possible to notice that the entire network is fully connected, and the initial step towards optimizing this network is to create a queuing network for the original topology, changing the inbound and outbound interconnect links with the queuing concept, as well as in Table 1. Queuing network is presented in Figure 4.

Let there be given n nodes of a mesh-network, which are allocated a frequency range ΔF, source nodes and receiver nodes of the transmitted data are connected to K nodes, where $K \leq n$. Every source node causes traffic for m receivers with $m \leq n$. The task is to determine the required number of radio channels between base stations, the bandwidth of the frequency channel and the optimal distribution of traffic according to the criterion of the minimum number of packets in service.

We will then analyze the linking rule among mesh nodes in the sample topology shown in Figure 3. Any node is capable of including *n-1* transceiver modules, which have a circular radio pattern. In a similar way, the node creates two-way communication channels with devices that end up in the coverage area of the node. The distance of exposure of the antenna can be thought out according to the formula:

$$A_r = \sqrt[4]{\frac{P_{TX} D_a^2 \sigma \Lambda^2}{(4\pi)^3 P_{min}}} \tag{20}$$

where P_{TX} is the transmitting antenna power at the output; D_a is the antenna directivity factor; σ is the effective antenna

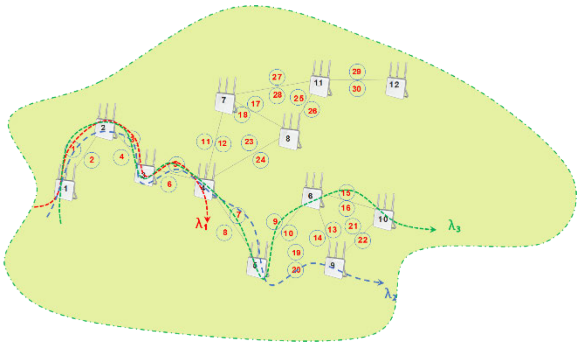


FIGURE 5. Example of routes from the first node.

cross section; P_{min} is the receiver sensitivity power; Λ is the signal wavelength [60]–[62].

By replacing each interconnection channel with a queuing concept, the topology shown in Figure 4 emerges.

Beyond structuring the topology, it is required to determine the routes from the transceiver to the receiver. In our case the transceivers and receivers will be nodes numbered 1, 4, 9, 10, and 12. Ideally, it is necessary to use the algorithm for finding all the shortest paths [63], but for the demonstration, 1 or 2 random shortest paths are used. Basic flows are shown in Figure 5 where n_i is the i^{th} queuing system. The sums of flows from the transceiver node to the receiver node are determined in numerical form. These restrictions are shown in Table 2 and Table 3. That is, the proposed model allows one information flow to be transmitted along several routes.

M/M/1 queuing systems are used as a mathematical model of mesh network communication channels. This is a concept with one serving line, incoming Poisson flow, exponential distribution of services, and service discipline in the order of traffic mode [64]. The average number of served packages in absolutely all concepts will be set in the following way:

$$F = \sum\nolimits_{i=0}^{n} \frac{\frac{\lambda_i}{\mu_i}}{1-\frac{\lambda_i}{\mu_i}}, \quad \lambda \geq 0, \ \mu \geq 0 \tag{21}$$

where Λ_i is the intensity of packet arrival on the i^{th} communication channel, μ_i is the intensity of traffic servicing on the i^{th} communication channel.

$$\lambda_i = \sum_{x=1}^{y^i} \lambda_x \tag{22}$$

where y^i are the streams passing through the i^{th} channel.

Service intensity refers to the rate of data transmission through each wireless communication channel, Λ_x is the total number of communication channels in the network. The transmission rate will be intent on by the formula:

$$\mu_i = \Delta f_i \log_2 N \tag{23}$$

where Δf_i is the width of the i^{th} communication channel ($\Delta f \geq 0$); N is the index of the multi-position signal.

TABLE 2. Routes from transmitting mesh nodes.

routes from the first node	
Λ1	n1→n3→n5
Λ2	n1→n3→n5→n7→n19
Λ3	n1→n3→n5→n7→n9→n15
Λ4	n1→n3→n5→n7→n9→n13
Λ5	n1→n3→n5→n11→n27→n30
Λ6	n1→n3→n5→n11→n18→n25→n30
Λ7	n1→n3→n5→n23→n25→n30
Λ8	n1→n3→n5→n7→n9→n15→n22
routes from the fourth node	
Λ9	n6→n4→n2
Λ10	n7→n19
Λ11	n7→n9→n13
Λ12	n7→n9→n15
Λ13	n11→n27→n30
Λ14	n11→n18→n25→n30
Λ15	n23→n25→n30
Λ16	n7→n9→n13→n21
routes from the ninth node	
Λ17	n20→n8
Λ18	n20→n8→n6→n4→n2
Λ19	n21
Λ20	n14→n15
Λ21	n20→n9→n15
Λ22	n14→n10→n8→n6→n4→n2
Λ23	n20→n8→n23→n25→n30
Λ24	n20→n8→n11→n27→n30
Λ25	n20→n8→n11→n18→n25→n30
routes from the tenth node	
Λ26	n22
Λ27	n16→n13
Λ28	n16→n10→n19
Λ29	n16→n10→n8
Λ30	n22→n20→n8
Λ31	n16→n10→n8→n6→n4→n2
Λ32	n16→n10→n8→n11→n27→n30
Λ33	n16→n10→n8→n23→n25→n30
Λ34	n16→n13→n20→n8
routes from the twelfth node	
Λ35	n29→n28→n12
Λ36	n29→n26→n17
Λ37	n29→n26→n24
Λ38	n29→n28→n12→n6→n4→n2
Λ39	n29→n26→n24→n7→n19
Λ40	n29→n26→n24→n7→n9→n15
Λ41	n29→n28→n12→n7→n9→n13
Λ42	n29→n26→n24→n6→n4→n2

TABLE 3. Stream rate limits (in Mbits).

Λ1+Λ2 = 1.25	Λ21+Λ22 = 1.5
Λ3 = 0.5	Λ23+Λ24 = 1.25
Λ4+Λ5 = 1.25	Λ25+Λ26 = 1.25
Λ6+Λ7 = 1.25	Λ27+Λ28 = 0.75
Λ8 = 0.75	Λ29+Λ30 = 1.25
Λ9+Λ10 = 1.25	Λ31+Λ32 = 0.5
Λ11+Λ12 = 1.25	Λ33+Λ34 = 0.75
Λ13+Λ14 = 1.25	Λ35+Λ36 = 1.5
Λ15+Λ16 = 0.75	Λ37+Λ38 = 0.5
Λ17+Λ18 = 1.25	Λ39+Λ40 = 0.75
Λ19+Λ20 = 1.5	Λ41+Λ42 = 0.75

Let's set restrictions on the objective function. In order to avoid interference in the mesh network, the following condition must be met for the k^{th} node:

$$\sum \Delta f_{k,j} + \sum \Delta f_{j,n} \leq \Delta F \tag{24}$$

where $\Delta f_{k,j}$ is the communication channel from the k^{th} node to the j^{th} node; $\sum \Delta f_{j,n}$ is a communication channel from the j^{th} node to the n^{th} node (including node k).

1. $\Delta f_1 + \Delta f_3 + \Delta f_5 \leq \Delta F$;
2. $\Delta f_1 + \Delta f_3 + \Delta f_5 + \Delta f_7 + \Delta f_{19} \leq \Delta F$;
3. $\Delta f_1 + \Delta f_3 + \Delta f_5 + \Delta f_7 + \Delta f_9 + \Delta f_{15} \leq \Delta F$;
4. $\Delta f_7 + \Delta f_9 + \Delta f_{13} \leq \Delta F$;
5. $\Delta f_7 + \Delta f_9 + \Delta f_{13} + \Delta f_{21} \leq \Delta F$;
6. $\Delta f_{11} + \Delta f_{18} + \Delta f_{25} + \Delta f_{30} \leq \Delta F$;
7. $\Delta f_{20} + \Delta f_8 + \Delta f_6 + \Delta f_4 + \Delta f_2 \leq \Delta F$;
8. $\Delta f_{20} + \Delta f_8 + \Delta f_{23} + \Delta f_{25} + \Delta f_{30} \leq \Delta F$;
9. $\Delta f_{16} + \Delta f_{10} + \Delta f_8 + \Delta f_{11} + \Delta f_{27} + \Delta f_{30} \leq \Delta F$;
10. $\Delta f_{16} + \Delta f_{13} + \Delta f_{20} + \Delta f_8 \leq \Delta F$;
11. $\Delta f_{29} + \Delta f_{28} + \Delta f_{12} + \Delta f_7 + \Delta f_9 + \Delta f_{13} \leq \Delta F$;
12. $\Delta f_{29} + \Delta f_{26} + \Delta f_{24} + \Delta f_7 + \Delta f_9 + \Delta f_{15} \leq \Delta F$;
13. $\Delta f_{29} + \Delta f_{28} + \Delta f_{12} + \Delta f_6 + \Delta f_4 + \Delta f_2 \leq \Delta F$;
14. $\Delta f_{29} + \Delta f_{26} + \Delta f_{24} + \Delta f_7 + \Delta f_{19} \leq \Delta F$;

In addition, it is required that the totality of absolutely all flows in the channel does not exceed the rate of the interconnection channel:

$$\sum \lambda_k \leq \Delta f_k \log_2 N \tag{25}$$

where Λ_k is the data flow passing through the k^{th} communication channel; $\Delta f_k \log_2 N$ is the speed of the k^{th} communication channel.

Since there can be several shortest paths from $k_{\text{transmitter}}$ to $k_{receiver}$, the condition followed below must be met:

$$\lambda_i = \sum_n \lambda_i^n \tag{26}$$

where Λ_i is a constant.

The acquired goal of optimization belongs to the problem of nonlinear programming. Since we are unfamiliar with the spectrum of the smallest meanings of the function, in order to solve the problem, we use the genetic algorithm by the iterative method in order to establish the minimum of this function as clearly as possible.

TABLE 4. Initial values for finding the minimum of the objective function (in Mbits).

$f_{1...30}$ = $\Delta F/30Hz$	Λ11 = 1	Λ22 = 0.75	Λ33 = 0.5
Λ1 = 0.5	Λ12 = 0.25	Λ23 = 0.25	Λ34 = 0.25
Λ2 = 0.75	Λ13 = 0.75	Λ24 = 1	Λ35 = 0.75
Λ3 = 0.5	Λ14 = 0.5	Λ25 = 0.75	Λ36 = 0.75
Λ4 = 0.75	Λ15 = 0.25	Λ26 = 0.5	Λ37 = 0.25
Λ5 = 0.5	Λ16 = 0.5	Λ27 = 0.25	Λ38 = 0.25
Λ6 = 0.5	Λ17 = 0.75	Λ28 = 0.5	Λ39 =0.25
Λ7 = 0.75	Λ18 = 0.5	Λ29 = 0.5	Λ40 =0.5
Λ8 = 0.75	Λ19 = 1	Λ30 = 0.75	Λ41 =0.25
Λ9 = 0.5	Λ20 = 0.5	Λ31 = 0.25	Λ42 =0.5
Λ10 = 0.75	Λ21 = 0.75	Λ32 = 0.25	

TABLE 5. Channel widths (in MHz).

f1 = 0.873	f9 = 1.467	f17 = 1.575	f25 = 1.476
f2 = 0.988	f10 = 1.212	f18 = 1.244	f26 = 0.695
f3 = 1.176	f11 = 0.701	f19 = 1.088	f27 = 1.198
f4 = 0.859	f12 = 1.089	f20 = 0.479	f28 = 0.765
f5 = 1.462	f13 = 0.967	f21 = 0	f29 = 1.224
f6 = 0.958	f14 = 1.011	f22 = 0	f30 = 0.676
f7 = 1.203	f15 = 1.340	f23 = 1.021	
f8 = 1.498	f16 = 1.763	f24 = 1.312	

Before the optimization was based, the initial frequency values were also established for flows with a full frequency band equal to $\Delta F = 20MHz$, $F_{lower} = 100MHz$, and $F_{upper} = 120MHz$. These values are full filled in Table 4. The objective function value in this case is $F = 12.9$, which is big for such a network with the given low data rate. Already after the solution of the problem of nonlinear programming with linear constraints, the value of the objective function acquired the significance $F = 2.3 * 10^{-7}$, indicating the success in minimization of the function. The values of the calculated values of the variables during optimization are located in Tables 5, 6 and 7. The accuracy of the values of the variables are taken as 1kHz and 1kbit/s correspondingly. In addition, the center frequencies of the channels were established, which are distributed taking into account the mutual influence on each other.

As a consequence of the resolution of the optimization problem, it is possible to single out that the significance of the objective function has decreased more than by eight digits. All main threads without exception are parallelized, there are no zero threads, in this case, the presented method does not reduce the number of threads in the network in any way. For the 21st and 22nd communication channels, the values

TABLE 6. Channel center frequencies (in MHz).

fc1 = 104.354	fc9 = 107.32	fc17 = 109.326	fc25 = 110.380
fc2 = 101.766	fc10 = 110.12	fc18 = 111.729	fc26 = 117.121
fc3 = 104.574	fc11 = 109.354	fc19 = 109.379	fc27 = 114.118
fc4 = 100.213	fc12 = 108.99	fc20 = 115.443	fc28 = 115.222
fc5 = 105.98	fc13 = 115.432	fc21 = 0	fc29 = 114.355
fc6 = 103.178	fc14 = 119.514	fc22 = 0	fc30 = 111.468
fc7 = 111.921	fc15 = 111.143	fc23 = 109.19	
fc8 = 109.178	fc16 = 111.853	fc24 = 115.31	

TABLE 7. Value of streams (in Mbits).

Λ1 = 1.121	Λ12 = 1.032	Λ23 = 0.273	Λ34 = 1.145
Λ2 = 1.235	Λ13 = 0.337	Λ24 = 1.012	Λ35 = 0.521
Λ3 = 0.5	Λ14 = 1.014	Λ25 = 1.134	Λ36 = 1.02
Λ4 = 0.448	Λ15 = 0.731	Λ26 = 0.901	Λ37 = 0.399
Λ5 = 0.275	Λ16 = 0.973	Λ27 = 0.271	Λ38 = 0.673
Λ6 = 0.348	Λ17 = 0.311	Λ28 = 0.111	Λ39 = 0.441
Λ7 = 0.532	Λ18 = 0.568	Λ29 = 0.218	Λ40 = 0.279
Λ8 = 0.75	Λ19 = 0.331	Λ30 = 0.098	Λ41 = 0.591
Λ9 = 0.87	Λ20 = 1.012	Λ31 = 1.244	Λ42 = 1.022
Λ10 = 1.015	Λ21 = 0.978	Λ32 = 0.721	
Λ11 = 0.548	Λ22 = 1.036	Λ33 = 0.925	

of the width of the frequency range are defined as zero, since routes are not laid through these channels, indicating a decrease in the number of channels in the mesh network. Since there are a limited frequency range, the frequencies in the network were reused on the 2nd and 9th, 3rd and 7th, 5th and 9th communication channels. The existing method is required to be improved in terms of automating the inputting the initial values, since all initial values are entered manually, so that require tremendous amount of time. In addition, the constraint requirement should also be facilitated in tandem with the algorithm for finding the minimum of the objective function due to the speed conditions of the network optimization.

B. SOLUTION OF THE FREQUENCY PLANNING PROBLEM

In this section, it is assumed to resolve the difficulty of allocating the frequency spectrum among any two interacting nodes, taking into account their secondary use, thereby maximizing the allocated radio frequency spectrum. This method will make it possible to use the capabilities of the computer in order to increase the speed of searching for cyclic frequencies in the network.

Let the mesh network consist of N nodes of radio nodes R_Nd with coordinates (X_i, Y_i), $i \in 1 \ldots N$. Each R_Nd_i has an omnidirectional antenna with a range of R_i. The requirement is to define the communication channel width $\Delta f_{ij}, j \in 1 \ldots N$, among each pair of R_Nd, with the provision that the total allocated frequency range is from F_{low} to F_{up}.

Understanding the location of each R_Nd, we calculate the distance from the transmitting R_Nd to all other R_Nd by calculating the root of the sum of squares of the difference of the same coordinates:

$D_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$ further, the distance from R_Nd_i to R_Nd_j will be denoted by D_{ij}.

Next, we compose an $N \times N$ receive-transmit matrix, in which the main diagonal is zero, and where the row number is defining the number of the transmitting node. Compare D_{ij} with R_i. If $R \geq D$, then the R_Nd lays within the signal propagation range of the transmitting R_Nd and 1 is put in the receive-transmit matrix, otherwise 0.

$$\begin{array}{c|ccccc|} & 1 & 2 & 3 & \ldots & n \\ 1 & 0 & 1 & 0 & \ldots & 0 \\ 2 & 0 & 0 & 1 & \ldots & 1 \\ 3 & 0 & 1 & o & \ldots & 1 \\ \ldots & \ldots & \ldots & \ldots & 0 & \ldots \\ n & 1 & 1 & 1 & \ldots & 0 \end{array}$$

We optimize the receive-transmit matrix. If the i^{th} row does not have a single unit and the i^{th} column does not have a single unit, in that case it means that the R_Nd with number i does not enter anyone's wave propagation field, and neither any R_Nd is entered the wave propagation field of the R_Nd with number i (i^{th} R_Nd is isolated). In this case, we remove both the column and the row numbered i in the receive-transmit matrix.

Further compose the matrix of mutual signals W from the receive-transmit matrix. Next move away from a particular receive-transmit matrix all the elements that are equal to 1, and the elements equal to 1 will be indicated by f_{ij}, where i is defining the row number, and j is defining the column number. Then create a matrix of mutual signals $M \times M$, in which the main diagonal is 0, and where the row number and the column numbers are f_{ij}.

Let's define the frequency ranges that can be reused. If two frequency ranges f_{ij} and f_{mn} are reused, on that occasion the element in matrix W provisioning at the intersection of the corresponding column and row will be equal to 1, otherwise 0. Fill in the matrix of mutual signals W. Consider the signal f_{ij}. Let's head to the receive-transmit matrix. In it, select the pivot columns i, j, pivot row i, and row j, which is not pivotal. If there is 1 in the given pivot columns, then the row in which it is located is highlighted, and if in this pivot row there is 1, then the column in which it is located is also highlighted. No selection is made from non-pivotal rows or columns. If there is an unselected 1's in the receive-transmit matrix in position k, s – where k is a row and s is a column, on that occasion it will mean that the signal f_{ij} would be able to be located with the signal f_{ks} at the same frequencies. Thus, in the matrix of mutual signals in the row f_{ij} and the column f_{ks}, 1 is put. This course of action is carried out for all outstanding unselected 1's.

Next, we optimize the acquired matrix of mutual signals. If the i^{th} row does not contain 1, then select the i^{th} row and the i^{th} column.

Let's compose preliminary communication equations. Then break down the subsequent actions into points.

After all, let's calculate the weight for each row in the optimized matrix of mutual signals. That is, the sum of the 1's in the row will be added to the column of the optimized matrix of receive-transmit in the column "weight" (a). If all the elements have the same weight equal to the number of elements minus 1, on that occasion the preliminary communication equation will consist of all elements (b). Select the row f_{ij} from the matrix and assign priority 1 to it (c). Remove the columns in which the given row f_{ij} has zeros (d), remove the rows in which the column f_{ij} has zeros (e), and obtain the matrix of signals f_{ij} (g).

Sort the remaining rows from maximum weight to minimum. Select the row with the highest weight f_{ke}. Delete the columns where the given row f_{ke} has zeros, delete the rows where the f_{ke} column has zeros. If there are several rows with the maximum weight, on that occasion its needed to find out which of them interact with each other. For the best result, the maximum number of links is selected. Then branch this step and return to it after completing points d and e. Such rows will subsequently be considered as one, and the columns (rows) in which it is necessary to delete rows (columns) must contain at least one zero.

If the resulting row has the same weight as f_{ij}, on that occasion it is assigned priority 2.

We continue deleting of rows as long as there is a maximum element in the weights of the remaining rows.

Next, evaluating the rest of the rows. If there are no more rows left, on that occasion go to step g. In the case row weight is equal to the number of rows with priority, it is required to write down in the preliminary equation of communication the names of rows with priority 1 and 2, as well as one of the remaining rows. The number of resulting pre-links is equal to the number of rows with no priority.

Then write down in the preliminary communication equation the names of the rows with priority 1 and 2, write out the elements with priority 2 as a separate entity.

We return to the optimized matrix of the signal f_{ij}. Delete the rows and columns in this matrix that have priority 2 (from points a to e). In the case if in the optimized matrix of the signal f_{ij} all elements have a weight equal to 1 or only the element f_{ij} remains in the matrix, then go to point g, otherwise point a.

Further, we allocate frequencies. The acquired frequency equations should be sorted according to the weights from highest to lowest. We get the equality with the highest weight, and we also write the elements of the equation with the highest weight in the unit line S. And write the received equation in the list of accepted equations. Select the accepted equation from the general list of equations. We exclude the elements that coincided from row S. If the equation of the communication came out with a weight of 1 in absolutely all equations of the communication, in this case, it is also selected from the general list. Continue repeating step a from the very beginning, up to the point the general list becomes empty. Therefore will acquire a list of accepted equations. These are the signals of single equations, which have every chance to appear in similar frequencies. Let's denominate each equation as $\mu_i(f_{ij}, \ldots, f_{km})$ and define it as a set of single-frequency signals, in which μ_i is the notation of the equation, and $(f_{ij}, \ldots, f_{km})$ is the constituent of the set of single-frequency signals. The remaining of the signals that are not included in the list of accepted equations must be at different frequencies.

Let's distribute the frequency range for each signal. Define ΔF be equal to the difference between the upper and lower boundaries of the allocated frequency range, and ε be equal to the minimum frequency range. To obtain the maximum frequency distribution, these two cases should be considered: a) the absence of set of single-frequency signals and b) since all signals cannot be at the same frequencies, then when distributing frequencies, the sum of all signal frequencies cannot exceed the allocated frequency range, therefore ΔF is divided by the number of signals and distributed within the obtained value d.

For the first frequency, we assign the left frequency boundary equal to the minimum boundary of the selected frequency range. And the right border set equal to the left plus the step equal to d minus q (frequency spacer, not equal to zero). For subsequent frequencies, the left boundary is equal to the left boundary of the previously considered frequency plus step d, and the right boundary is equal to the left boundary of the considered frequency plus step equal to d minus q.

With the presence of groups of single-frequency signals, subtract from ΔF the value equal to the product of the number of frequencies included in the groups and ε. The resulting value f' will be distributed between the remaining frequencies. Among the groups of single-frequency signals, the one that has the largest number of frequencies included in it is selected. From the value of f' we take away the value equal to the product of the number of remaining (not maximum) groups and ε. The resulting value f'' will be allocated among the set of signals that have the maximum number of frequencies included in them. To obtain this, it is needed to split f'' into the largest number of sets. Obtained value is f'''.

For the frequencies of the first group, we assign the left-side frequency border, which is the same as the minimum border of the selected frequency spectrum. We also set the right border equal to the left-sided plus a step equal to d^* minus q (radio frequency limiter, not equal to zero). For the purpose of subsequent frequencies (frequencies of other sets), the left-side edge is the same as the left-side edge of the previous frequency being examined plus a step d^*, but the right edge is the left-side edge of the frequency being examined plus a step equivalent to d^* minus q.

The step d^* for the frequencies of the sets having the maximum number of frequencies is f'''. For the remaining frequencies, d^* is equal to ε.

TABLE 8. Matrix of mutual signals.

$W =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	1	0	0	0	0	0	0	0	0	0	0
2	1	0	1	0	0	0	0	0	0	0	0	0
3	0	1	0	1	0	0	0	0	0	0	0	0
4	0	0	1	0	1	0	1	1	0	0	0	0
5	0	0	0	1	0	1	0	0	1	0	0	0
6	0	0	0	0	1	0	0	0	1	1	0	0
7	0	0	0	1	0	0	0	1	0	0	1	0
8	0	0	0	1	0	0	1	0	0	0	1	0
9	0	0	0	0	1	1	0	0	0	1	0	0
10	0	0	0	0	0	1	0	0	1	0	0	0
11	0	0	0	0	0	0	1	1	0	0	0	1
12	0	0	0	0	0	0	0	0	0	0	1	0

TABLE 9. Frequency reuse matrix for f2, f14 and f16.

	2	14	16	27	28	29	30	Weight	priority
2	*0*	*1*	*1*	*1*	*1*	*1*	*1*	**23**	**1**
14	*1*	*0*	*1*	*1*	*1*	*1*	*1*	**19**	**2**
16	*1*	*1*	*0*	*1*	*1*	*1*	*1*	**16**	**3**
27	*1*	*1*	*1*	0	0	0	0	**14**	**4**
28	*1*	*1*	*1*	0	0	0	0	**13**	
29	*1*	*1*	*1*	0	0	0	0	**14**	**4**
30	*1*	*1*	*1*	0	0	0	0	**12**	

Using this algorithm, we will search for frequencies for the topology in Figure 3, which can be reused without mutual influences.

Let's define the frequency reuse matrix. The row and column numbers correspond to the frequency in the communication channel. And define the matrix W of interaction of nodes in Table 8.

where, row number and column number correspond to node number.

Next, we designate the reuse matrix for *f1 or f2*, removing columns and rows in the frequency reuse matrix if the values in row and column number 1 or 2 are zero.

Based on the results, the best use case with *f2* is only *f14*. Continue to remove in the matrix in this table rows and columns with zero elements.

As a result of the conversion in the matrix, it turns out that, with *f2* and *f14*, it is most preferable to use *f15, f16 or f23* because of the greatest weights. Then we continue to remove rows and columns from this matrix. The conversion results are shown in Table 9.

As seen in the result of the conversion in Table 9, it turns out that, with *f2, f14* and *f16* it is most preferable to use *f27* or *f29* because of the greatest weights. Then we continue removing rows and columns in the matrix.

Thus, the matrix shown in Table 10 is obtained.

As a result of the above conversion in Table 10, the following frequency reuse combinations are obtained *f2, f14, f16, f29* or *f2, f14, f15, f29* or *f2, f14, f23, f29*; *f2, f14, f16, f27* or *f2, f14, f15, f27* or *f2, f14, f23, f27*.

TABLE 10. Frequency reuse matrix for f2, f14, f16 and f29.

	2	14	16	29	Weight	priority
2	*0*	*1*	*1*	*1*	**23**	**1**
14	*1*	*0*	*1*	*1*	**19**	**2**
16	*1*	*1*	*0*	*1*	**16**	**3**
29	*1*	*1*	*1*	*0*	**14**	**4**

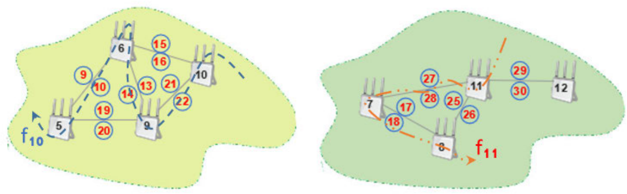


FIGURE 6. Frequency reuse combination: a) frequency reuse option for *f* 10 and b) frequency reuse option for *f* 11.

Next, it is needed to build reuse matrices for each frequency and perform the conversions shown above. Finally, we get the following frequency reuse options as in Figure 6 in the form of a graph as explained in previous optimization method.

Already after the selection of sets of frequencies, which do not repeat in any way, the following list of frequencies comes out, which can be used a second time: *f1, f14, f15, f27*; *f3, f14, f29*; *f13, f1, f16, f29*; *f24, f1, f14*.

It should be emphasized that the method acquires the maximum number of signals, which have every chance of being in similar frequencies, thereby providing a more reasonable use of the allocated frequency range. In this way, a significant data transfer rate is guaranteed. In the course of the method, the optimization of the receive-transmit matrix is carried out. This makes it possible to eliminate isolated radio nodes, which leads to a decrease in the period of activity of the method. In addition, during the activity on this work, the matrix of mutual signals is optimized, which also reduces the period of the activity of the method. The subsequent improvement of the recommended and proposed method will be based on the resolution of the clustering problem, in which a solution should be found to the problem of selecting clusters, in which similar frequency spectra are used.

IV. CONCLUSION

To simulate modern data transmission networks, it can be used various graph models that adequately describe the network topology and provide the necessary mathematical apparatus for solving optimization problems. The article has not yet described many graph models that arise for specific tasks of complex systems. For example, a copy model [65], with the help of which it is easy to show dense communities on the Internet, a linear chord diagram, associated with the formation of a web graph [66]–[68]. All these models are used for various problems of data transmission reliability, analysis of the growth of global networks, etc.

TABLE 11. Abbreviation table.

IoT	Internet of Things
IoE	Internet of Everything
QoS	Quality of Service
WMN	Wireless Mesh Network
M2M	Machine to Machine
MTN	Modern Telecommunication Networks
WLAN	Wireless local access networks
MIMO	Multiple input-Multiple output
LTE	Long Term Evalution
LoRa	Short for long range
OFDM	Orthogonal Frequency-Division Multiple Access
WSN	Wireless Sensor Network
WiMAX	Worldwide Interoperability for Microwave Access
R_Nd	Radio node

The paper proposes an approach to the use of graphs in modeling IoT mesh networks, both at the stage of setting the problem of frequency channel distribution and in analyzing its structure. This, in turn, made it possible to more fully and in detail describe the possible configurations of both the entire mesh network as a whole and its individual elements represented as vertices and edges of the graph. We propose an approach to the synthesis of mesh networks, which allows, for a given frequency range, to determine the intensity of traffic flow among network nodes, as well as their channel width, at the same time making a certain minimum delay time for data transmission.

Two algorithms of implementation of this approach are presented. The advantages of the first algorithm are clarity, in this case, routes from the source to the receiver are calculated, in contrast to the second method, where a total load of radio channels is determined. The disadvantage is the complexity of implementing in algorithmic form and the greater number of iterations.

In addition to that, it is necessary to highlight the frequency planning method, which ultimately finds the number of signals that have every chance of being located in similar frequencies, thereby providing the most reasonable use of the allocated frequency spectrum. In this way, a significant information transfer rate is guaranteed. In the course of the method, the optimization of the reception-transmission matrix is carried out, which makes it possible to exclude isolated radio nodes, which entails a decrease in the algorithm operation time. Also, the matrix of mutual signals is optimized, which also reduces the operating time of the algorithm.

The proposed mathematical apparatus can be properly used at the stage of setting the problem of allocating frequency channels, in order to assess the characteristics of the initial configurations of IoT mesh networks, as well as in a comparative analysis of the results of its solution.

Further improvement of the proposed method will be based on the solution of the clustering problem, in which a solution should be found to the problem of selecting clusters, in which similar frequency spectra are used.

FUTURE RESEARCH

Further improvement of the proposed algorithm will be based on the solution of the clustering problem as in [69]–[72], in which it is necessary to solve the problem of choosing clusters in which the same frequency ranges are used.

ABBREVIATIONS

See Table 11.

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