UDC 621.391

O.Yu. Yevsieieva[1], Essa Mohammed Al-Azzawi[2]

[1] *Kharkiv National University of Radio Electronics, Kharkiv*
[2] *Odessa National Academy of Telecommunication named after A.S. Popov, Odessa*

CENTRALIZED AND HIERARCHICAL CROSS-LAYER ROUTING IN WIMAX MESH NETWORKS: PERFORMANCE ANALYSIS

WiMax mesh-networks are based on time division multiple access to common frequency resource. Success of traffic delivery in the case depends on availability of appropriate number of slots at every link along path from source to destination. It gives rise to cross-layer routing problem, which interprets routing as optimal slot allocation between mesh-stations. Using mathematical model in space of states can solve the problem. In order to improve scalability the basic model were modified and hierarchical cross-layer approach were offered. Simulation results shows that the models provide multipath routing strategies, minimization of number allocated slots, balanced utilization of both link and buffer resources, but offered hierarchical approach allows to reduce size of the optimization task in the tens or hundreds of times.

***Keywords**: wireless mesh networks, model in space of states, cross-layer routing, optimal slot allocation.*

Introduction

Necessary condition for successful end-to-end delivery of user traffic, both in wired and wireless networks, is related to coordinated work of protocols at different layers, from the physical to the application. From all of them third (network) layer can be considered as the "backbone" of the system and all higher levels regard the network as a single whole, aimed at the implementation of common objectives. Among the functions of the network layer routing takes central place. Although kernel of routing problem is quite simple, there are many approaches to solve it. In whole, all known routing methods for both wireless and wired networks can be divided into two big groups: based on shortest path or flow-based. Main differences between algorithms within first group are related to use different routing metric only. Key feature of second group is taking into account the volume of network load when routing decision making. However, in the case of wireless networks the situation is somewhat complicated because there are different operational modes. Simplest and most popular mode is Point to Multipoint (PMP) where the base station plays role of the root of the routing tree, and all internal and external flows must be directed via the root. As a rule the mode is well defined by standards. In turn under mesh mode every station can perform functions of terminal device and a router at same time.

The mode is more effective from viewpoint of resource usage but requires more complicated (advanced) control algorithms including routing. For example, developed for highspeed metropolitan area networks (MAN) standard IEEE 802.16 (WiMAx) supports both modes, but for the mesh-mode routing algorithm is not defined.

Standard IEEE 802.16 defines time slots as main resource to be allocated at link layer in mesh-network. It means, a necessary condition for user traffic delivery from source to destination is the availability of time slots along the chosen route. Moreover the quantity of available unused slots at every link along the chosen route must meet the requirements to rate of delivery. Thus, it allows to consider routing problem in wireless IEEE 802.16 mesh-network as a problem of allocation of time slots in accordance with the incoming traffic flows.

As analysis shows, as a rule all of known routing and link resource allocation procedures are decentralized and based on the exchange by control messages between neighboring mesh-stations [1, 2]. For example, IEEE 802.16 defines "three-way handshake" procedure for the slot assignment, and slot allocation is based on competition procedures [3]. Other offered in literature approaches are heuristic too, for example work [4] describes the mechanism of test signals (probes). However, in order to obtain maximum benefit from the network or, in other words, to maximize network performance the heuristics needs to be replaced by a strict formal methods to ensure optimal use of network resources. In this context, the main requirements to the methods of resource allocation in wireless mesh-network are following:

– problems of routing and slot allocation must be solved jointly (cross-layer routing);

– control decisions must be optimal;

– the quality of service must be taken into account;

– state of network must be controlled and congestions must be prevented;

– obtained control solutions must be scalable.

The contradictory nature of these requirements leads to the gradual solution of the problem: to find optimal solutions in the first stage and to increase their scalability in second. In order to obtain an optimal joint solution of problems of routing and time slot allocation with the ability to manage the quality and overloads it is advisable to focus on mathematical model in space of states [5].

Basic model on centralized cross-layer routing in IEEE 802.16 mesh network in space of states

The model is based on two types of variables, control $\tau_{i,v}^{r,j}(k)$ and state $q_{i,j}(k)$. Control variable $\tau_{i,v}^{r,j}(k)$ is associated with routing and slot assignment, it is binary variable which equal to 1 if during k-th sampling interval r-th time slot is used in link (i,j) for transmission of the flow addressed to l-th station, and $\tau_{i,v}^{r,j}(k)=0$ otherwise. The state variable $q_{i,j}(k)$ represents the data volume that is kept at the instant t_k in buffer of the i-th station and intended for transmission to the j-th station. The two types of variables are connected within differential equality of states:

$$q_{i,j}(k+1)=q_{i,j}(k)-\sum_{\substack{v\in S_i^1,\\ v\neq i}}\sum_{r=1}^{N_F} m_{i,v}^r(k)\tau_{i,v}^{r,j}(k)n+ \\ +\sum_{\substack{g\in S_i^1,\\ g\neq i,j}}\sum_{r=1}^{N_F} m_{g,i}^r(k)\tau_{g,i}^{r,j}(k)n+\xi_{i,j}(k)\Delta t, \qquad (1)$$

where $i,j=\overline{1,N_V}$, $j\neq i$, , $k=0,1,2,...$; $\Delta t=t_{k+1}-t_k$ is the sampling interval; $m_{i,j}^r$ is number of bits of the user's data that can be carried by r-th slot in link $(i,j)\in E$; E is a set of links between stations of a mesh-network; N_V is a total number of stations in mesh-network; S_i^1 is a set of distance-1 neighboring stations to the i-th station; $\xi_{i,j}(k)$ is the intensity of the data arrival to the i-th station at the instant of time t_k addressed to the j-th station; n is the number of the frames transmitted during time Δt, $n=\Delta t/T_F$; T_F is the frame duration; N_F is an number of slots per frame which is used for transmission of a user traffic.

According to physical meaning state variables are limited by zero and by buffer size:

$$q_{i,j}(k)\geq 0\,, \qquad \sum_{\substack{j=1,\\ i\neq j}}^{N_V} q_{i,j}(k)\leq q_i^{max}\,, \qquad (2)$$

where q_i^{max} is total size of buffer at i-th mesh station.

Numerical values of control variables are determined by link capacity limitation that within wireless mesh-network can be formulated as

$$\sum_{i=1}^{N_V}\sum_{\substack{j=1,\\ j\neq i}}^{N_V}\sum_{\substack{l=1,\\ l\neq i}}^{N_V}\tau_{i,j}^{r,l}(k)\leq 1 \text{ for every } r=\overline{1,N_F}\,. \qquad (3)$$

Actually expression (3) prohibits slot reusing within given wireless network. In order to improve capacity of WMN reuse of the slots must be approved. Then condition (3) is complicated and becomes set of constraints for every $i=\overline{1,N_V}$ and $r=\overline{1,N_F}$:

$$\sum_{\substack{j=1,\\ j\neq i}}^{N_V}\sum_{\substack{l=1,\\ l\neq i}}^{N_V}\tau_{i,j}^{r,l}(k)+\sum_{g\in S_i^2}\sum_{\substack{j=1,\\ j\neq g}}^{N_V}\sum_{\substack{l=1,\\ l\neq g}}^{N_V}\tau_{g,j}^{r,l}(k)\leq 1\,, \qquad (4)$$

where S_i^2 is a set of stations interfered to i-th station.

Thus joint solution of routing and slot allocation problems in WiMax mesh networks is related to calculation of binary control variables $\left\{\tau_{i,v}^{r,j}(k)\right\}$, that can be formulated as optimization problem

$$J=\sum_{k=1}^{\alpha}\Big[\vec{q}^{\,T}(k)W_q\vec{q}(k)+\vec{\tau}^{\,T}(k)W_\tau\vec{\tau}(k)- \\ -\vec{\tau}^{\,T}(k)W_{reuse}\vec{\tau}(k)\Big]\rightarrow \min, \qquad (5)$$

where α is the number of intervals Δt, for which the control variables should be calculated; $\vec{q}(k)$ and $\vec{\tau}(k)$ are vectors of state and control variables respectively; W_q, W_τ are the diagonal weight matrices of buffer and link resources usage respectively; W_{reuse} is the weight matrix presenting a gain at the cost of the slots reuse.

Problem (5) belongs to class of integer non-linear programing, which is NP-hard in general but which can be solved by numerical methods. Practical implementation of offered model (1) – (5) is related to centralized decision making and agrees with concept of Software Defined Networks (SDN).

In order to analyze offered model (1) – (5) and properties of obtained control decisions, let us consider the example of routing within IEEE 802.16 mesh-network shown in fig. 1. Assume that in a given mesh-network traffic must be delivered from the MSS 15 to the MSS 1 and all links have the same characteristics at physical layer that allows $m_{i,j}^r=\overline{m}$ for all $i,j=\overline{1,N_V}$. Moreover an intensity of the traffic is assumed to be $\xi_{15,1}(k)=2\overline{m}/T_F$, $k=0,1,2,...$. This means that in order to ensure the transmission rate every station along chosen path should use at least two slots in each frame.

As simulation results show offered task (5) subject to (1) – (2), (4) provides different results depending on the initial network load and the ratio of weight coefficients W_q, W_τ and W_{reuse} in the objective function (5) (fig. 1 – 3).

Fig. 1 illustrates the operation of the model when $W_{reuse}>>W_q,W_\tau$. Physically it aims the model at minimizing of the total number of slots used in the network. At the same time, as shown by the results of simulation, the control solution is practically independent of the initial network traffic: under small loads (30-40%) as well as under the high (60-90%) the optimal routing decision contains multiple routes from station-source to station-destination. This is due to several independent (without intersections) paths in mesh-network. The paths are so distant from each other that stations along them do not interfere, and therefore can use the same time slots. Thus, one of the features of the offered model is the multipath traffic delivering that ensures minimal number of used slots.

If to relax coefficient W_{reuse} in objective function (5) (or to remove appropriate summand from it) optimal solution for the given example is single shortest path MSS 15 - MSS 10 - MSS 5 - MSS 1 (fig. 2). As before, the solution (fig. 2) delivers $2\overline{m}$ of user traffic in every frame but the total number of used slots were increased to 6 in contrast to 4 slots used in previous case. In fact, task (5) subject to (1) – (2), (4) under relaxed coefficient W_{reuse} is aimed at minimal number of active link but not at minimization of the number of slots. The results of simulation were observed under low load (less than 50%) and when $W_q < W_\tau$.

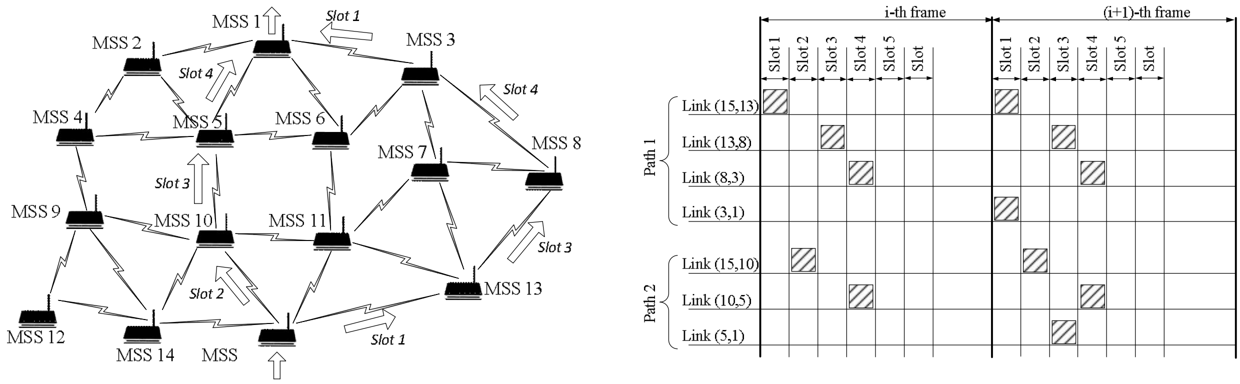

Fig. 1. Routing and slot allocation solution under $W_{reuse} >> W_q, W_\tau$

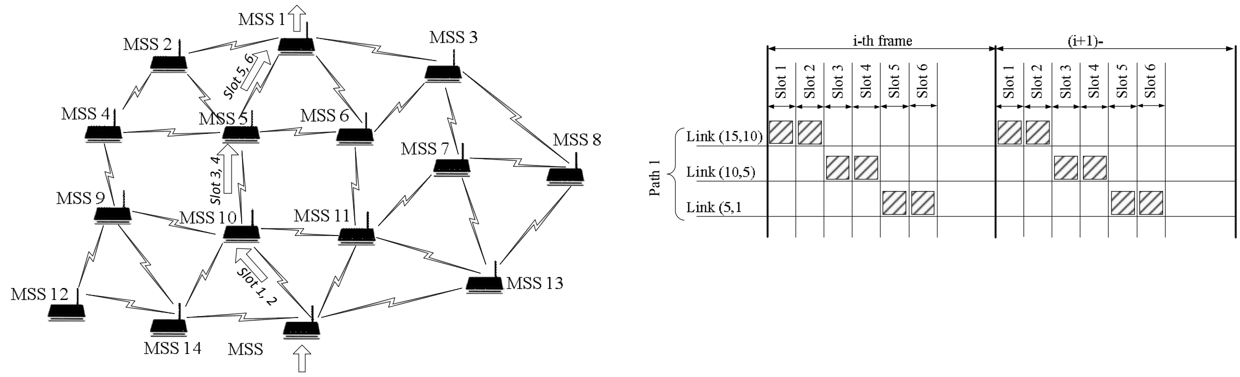

Fig. 2. Routing and slot allocation solution under relaxed coefficient W_{reuse}

If the same traffic $\xi_{15,1}(k) = 2\overline{m} / T_F$ needs to be transmitted under high initial network load, i.e. when non-zero queues in the buffers at mesh-stations, then under $W_{reuse} << W_q, W_\tau$ and $W_q \approx W_\tau$ optimal solution refers to multiple paths like the first example, (fig. 3). But now stations along different paths interfere with each other, and the use of multiple paths does not lead to the minimal number of slots (in fig. 3 six slots are allocated that exceeds the minimum number). In this case, the model is aimed at balanced use of buffer resources.

Moreover, obtained solutions depend on the current allocation of flows over the network. For example, the solution in fig. 3 takes place in the case when all of mesh- stations are equally loaded. If area of local congestion appears within mesh-network (for example, queues at some stations exceed the average number of packets awaiting in the buffers), resulting routes "bypass" these areas, as shown in fig. 4.

Thus, control decision on routing and slot allocation in wireless IEEE 802.16 mesh-network by using the model in space of states has the following features:

– the ability to adapt to the current state of the network and its changes, including structural and parametric changes as well as the dynamics of the incoming network traffic;

– multipath routing that leads to minimization of number of allocated slots;

– balanced use of both link and buffer resources that allows to avoid a congestion or to bypass areas of high load, not leading to a critical level of congestion;

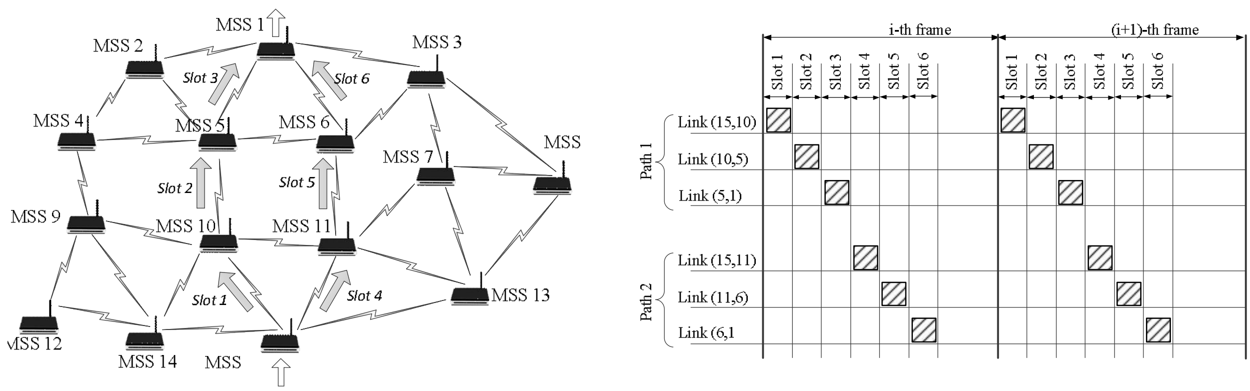

Fig. 3. Routing and slot allocation solution under $W_{reuse} << W_q, W_\tau$ and $W_q \approx W_\tau$

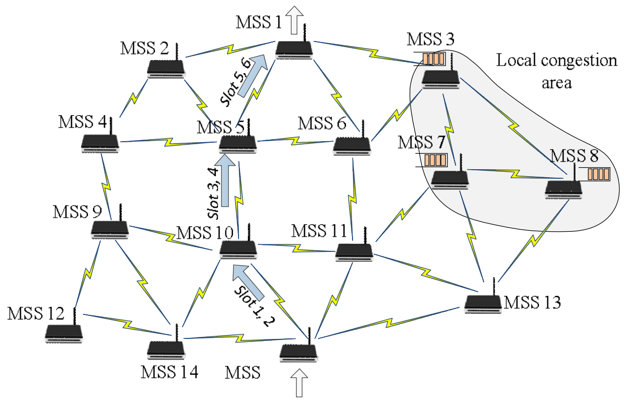

Fig. 4. Bypassing local congestion area

– compliance of route with the rate of the transmitted traffic that means a guaranteed availability of time slots along chosen route. If number of unused time slots does not meet rate requirements (or in other words, if the traffic cannot be serviced in accordance with the intensity of its arriving), the solution will not be found and a slots will not be allocated.

Hierarchical model on cross-layer routing in clustered IEEE 802.16 mesh network

Solving of problem (5) is mainly complicated by constraint (4), which is aimed at slot reuse in order to improve link resource utilization. In contrast to (4) expression (3) forbids reusing time slots, it is easer and in the case objective function can be simplified to

$$J=\sum_{k=1}^{\alpha}\left[\vec{q}^{\,T}(k)W_q\vec{q}(k)+\vec{\tau}^{\,T}(k)W_\tau\vec{\tau}(k)\right]\to\min. \quad (6)$$

Problems (5) and (6) meet different requirements, problem (6) allows to simplify process of numerical calculation of control variables but minimization of function (5) subject to (1) – (2), (4) assumes time slots reuse that potentially leads to network capacity improving. In order to combines the two important qualities a concept of hierarchical cross-layer routing were offered [6]. Its main idea is based on hierarchical network organization and hierarchical controlling (fig. 5).

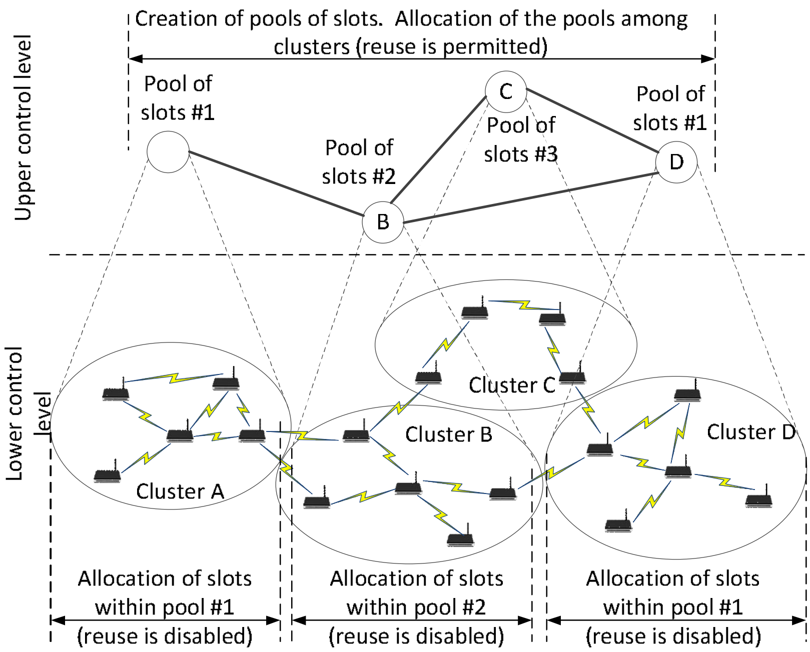

Fig. 5. Concept of hierarchical cross-layer routing

It is supposed that structure of WMN is clustered, every cluster is assumed to have own pool of slots Θ_i and some clusters are assumed have same pools. Within singe cluster slot reusing is prohibited, i.e. cross-layer routing problem can be formalized by problem (6). At same time some clusters are assumed to have same pools of slots, and then routing between clusters is related to solution of problem (5) subject to (1) – (2), (4). In this case slots' reusing is realized but number of control variables is much lower than in whole (without clustering) network that in practice means reducing of computational complexity.

Thus, hierarchical cross-layer routing expects coordinated work of control algorithms at upper and low levels. Upper level (UL) control algorithm is associated with routing and slot allocation between clusters without taking into account detailed cluster structure. But lower level (LL) control algorithm is aimed at slot allocation within single clusters taking into account solutions for transit traffic, which is sent down from upper control level.

Thus, initial task of cross-layer routing is divided in ($N_{cl}+1$) tasks, one UL task and N_{cl} LL tasks where N_{cl} is number of clusters in WMN.

The idea of hierarchical control requires modification of model (1) – (6) for clustered structure of mesh-network. In contrast to the equality (1) equality of states at upper control level must be focused on dynamics of interworking between clusters that can be described as:

$$q_{i,j}^{UL}(k+1)=$$
$$=q_{i,j}^{UL}(k)-\sum_{\substack{h\in S_i^1,\\ h\neq i}}\sum_{r\in\Theta_i} m_{i,h}^{UL\ r}(k)\tau_{i,h}^{UL\ r,j}(k)n+ \quad (7)$$
$$+\sum_{\substack{g\in S_i^1,\\ g\neq i,j}}\sum_{r\in\Theta_g} m_{g,i}^{UL\ r}(k)\tau_{g,i}^{UL\ r,j}(k)n+\xi_{i,j}^{UL}(k)\Delta t,$$

where $i,j=\overline{1,N_{cl}}$, $q_{i,j}^{UL}(k)=\sum_{x=1}^{N_v^i}\sum_{z=1}^{N_v^j} q_{i.x,j.z}(k)$ is state variable of upper control level, it represents the data volume that is kept at the instant t_k in cluster i in whole and intended for transmission to any stations in cluster j; $q_{i.x,j.z}(k)$ is the data volume that is kept at the instant t_k in buffer of the station $i.x$ and intended for transmission to the station $j.z$ (or queue $(i.x,j.z)$), $j.z\neq i.x$; $i.x$ is hierarchical address of x–th mesh-station within i-th cluster, $x=\overline{1,N_v^i}$; N_v^i is number of stations in i-th cluster; $m_{i,h}^{UL\ r}$ is number of bits of the user data that can be carried by r-th slot in aggregated external link (i,h); $\tau_{i,h}^{UL\ r,j}(k)$ is binary control variable at upper level, it is responsible for allocation of slots over aggregated links between clusters; $S_i^{UL\ 1}$ is a set of distance-1 neighboring nodes to the i-th node in graph of clusters; $\xi_{i,j}^{UL}(k)$ is the intensity of the aggregated traffic that arrives to the i-th cluster at the instant of time t_k addressed to the stations in j-th cluster (external traffic), $\xi_{i,j}^{UL}(k)=\sum_{x=1}^{N_v^i}\sum_{z=1}^{N_v^j}\xi_{i.x,j.z}(k)$; $\xi_{i.x,j.z}(k)$ is the intensity of the data arrival to the i.x-th station at the instant of time t_k addressed to the j.z-th station.

In turn dynamics of traffic flows inside i-th cluster is represented by

$$q_{i.x,i.z}^{LL}(k+1)=q_{i.x,i.z}^{LL}(k)-$$
$$-\sum_{\substack{i.s\in S_{i.x}^1,\\ s\neq x}}\sum_{r\in\Theta_i} m_{i.x,i.s}^{LL\ r}(k)\tau_{i.x,i.s}^{LL\ r,i.z}(k)n+ \quad (8)$$
$$+\sum_{\substack{i.w\in S_{i.x}^1,\\ w\neq x,z}}\sum_{r\in\Theta_i} m_{i.w,i.x}^{LL\ r}(k)\tau_{i.w,i.x}^{LL\ r,i.z}(k)n++\xi_{i.x,i.z}^{LL\ \Sigma}(k)\Delta t,$$

where $\tau_{i.x,i.z}^{LL\ r,i,s}(k)$ is binary control variable at lower level, it is responsible for allocation of slots on links inside i-th cluster; $m_{i.x,i.s}^{LL\ r}(k)$ is number of bits of the user data that can be carried by r-th slot in internal link $(i.x,i.s)$; $\xi_{i.x,i.z}^{LL\ \Sigma}(k)$ is aggregated traffic that arrives to queue $(i.x,i.z)$ on station $i.x$ at the instant of time t_k addressed to the stations $i.z$ (including external and internal traffic),

$$\xi_{i.x,i.z}^{LL\ \Sigma}(k)\Delta t=\xi_{i.x,i.z}(k)\Delta t+\xi_{i.x,i.z}^{ext}(k)\Delta t\ ;$$

$$\xi_{i.x,i.z}^{ext}(k)\Delta t$$

is amount of external incoming traffic, information about which should be down by upper control level.

Note that according to physical meaning aggregated state variables $q_{i,j}^{UL}(k)$ and variables $q_{i.x,i.z}^{LL}(k)$ at lower control level should meet constraints (similar to (2)):

$$q_{i,j}^{UL}(k)\geq 0\,,\qquad \sum_{\substack{j=1,\\ i\neq j}}^{N_{cl}} q_{i,j}(k)\leq q_i^{UL\ \max}\,, \quad (9)$$

$$q_{i.x,i.z}^{LL}(k)\geq 0\,,\qquad \sum_{\substack{z=1,\\ z\neq x}}^{N_v^i} q_{i.x,i.z}^{LL}(k)\leq q_{i.x}^{LL\ \max}\,, \quad (10)$$

where $q_i^{UL\ \max}$ is upper boundary of traffic that can be kept within i-th cluster; $q_{i.x}^{LL\ \max}$ is buffer size of $i.x$–th station.

According to offered concept of hierarchical cross-layer routing control variables $\tau_{i,h}^{UL\ r,j}(k)$ and $\tau_{i.x,i.z}^{LL\ r,i,s}(k)$ is guided by two rules. The first low index in the variable indicates cluster, to which it belongs. Because every cluster has own pool of slots Θ_i, unit value of binary variable $\tau_{i,h}^{UL\ r,j}(k)$ or $\tau_{i.x,i.z}^{LL\ r,i,s}(k)$ for i-th cluster is allowed if and only if $r \in \Theta_i$. Reuse of slot is possible for noninterfering clusters, which have same pools of slots, but every slot in pool can be used just once, or by upper level, or by lower lever. Allocation of pools, which can be obtained after coloring of conflict graph of clusters, guarantees that between colored with same colors clusters interference is absent [6]. It allows to allocate slots in every cluster within its own pool Θ_i, $i = \overline{1, N_{cl}}$, independently without taking into account process of slot allocation in other clusters. Mathematically it can be written as (for every $r \in \Theta_i$, $i = \overline{1, N_{cl}}$)

$$\sum_{\substack{j=1,\\ j\neq i}}^{N_{cl}} \sum_{\substack{l=1,\\ l\neq i}}^{N_{cl}} \tau_{i,j}^{UL\ r,l}(k) + \sum_{x=1}^{N_v^i} \sum_{\substack{z=1,\\ z\neq x}}^{N_v^i} \sum_{\substack{s=1,\\ s\neq x}}^{N_v^i} \tau_{i.x,i.z}^{LL\ r,i,s}(k) \le 1. \quad (11)$$

Thus, problem of routing between clusters and allocation of slots on external links can be formalized as

$$J^{UL} = \sum_{k=1}^{a} \Big[\vec{q}^{\,UL\ T}(k) W_q^{UL} \vec{q}^{\,UL}(k) + \vec{\tau}^{\,UL\ T}(k) W_\tau^{UL} \vec{\tau}^{\,UL}(k) - \vec{\tau}^{\,UL\ T}(k) W_{reuse}^{UL} \vec{\tau}^{\,UL}(k) \Big] \to \min \quad (12)$$

subject to (7), (9), (11) under known values of $\tau_{i.x,i.z}^{LL\ r,i,s}(k)$, where a is the number of intervals Δt, for which the control variables should be calculated; $\vec{q}^{\,UL}(k)$ and $\vec{\tau}^{\,UL}(k)$ are vectors of state and control variables at upper control level respectively; W_q^{UL}, W_τ^{UL} are the diagonal weight matrices of buffer and link resources usage at upper level respectively; W_{reuse}^{UL} is the weight matrix presenting a gain at the cost of the slots reuse at upper control level.

In turn problem of routing and slot allocation inside clusters can be formalized as optimization problem

$$J_i^{LL} = \sum_{k=1}^{a} \Big[\vec{q}_i^{\,LL\ T}(k) W_i^{q\ LL} \vec{q}_i^{\,LL}(k) + \vec{\tau}_i^{\,LL\ T}(k) W_i^{\tau\ LL} \vec{\tau}_i^{\,LL}(k) \Big] \to \min \quad (13)$$

subject to (8), (10), (11) under known values of $\tau_{i,h}^{UL\ r,j}(k)$, where $\vec{q}_i^{\,LL}(k)$ and $\vec{\tau}_i^{\,LL}(k)$ are vectors of state and control variables at lower control level respectively; $W_i^{q\ LL}$, $W_i^{\tau\ LL}$ are the diagonal weight matrices of buffer and link resources usage at lower level respectively.

Thus, formulated optimization problems (12) and (13) are associated with different control levels, every from which has own control variables.

As a result the control variables can be calculated separately, under known variables from other level. It allows to solve the problems of different levels one after other, by turn.

In order to estimate performance of offered hierarchical model two parameters will be used. One of them reflects improvement of network scalability by reduction of different databases sizes and size of problem to be solved.

By dividing initial task of cross-layer routing in mesh-network into set of subtasks associated with different control levels, total number of control variables (at both of levels together) is reduced. Within described mathematical model of mesh-network the gain from reduction in number of control variables can be calculated as

$$G_{dim} = \frac{|\vec{\tau}|}{\sum_{i=1}^{N_{cl}} \left| \vec{\tau}_i^{\,LL} \right| + \left| \vec{\tau}^{\,UL} \right|}, \quad (14)$$

where $|\vec{\tau}|$ is size of control vector in no clustered network with elements $\tau_{i.x,j.z}^{r,l.s}(k)$ (1); $|\vec{\tau}_i^{\,LL}|$ and $|\vec{\tau}^{\,UL}|$ are sizes of LL and UL control vectors respectively.

As numerical results show (fig. 6 and 7) gain from reduction in number of control variables G_{dim} is growing with increase of network and cluster sizes, and in parvo with growth of chromatic number of WMN's structure.

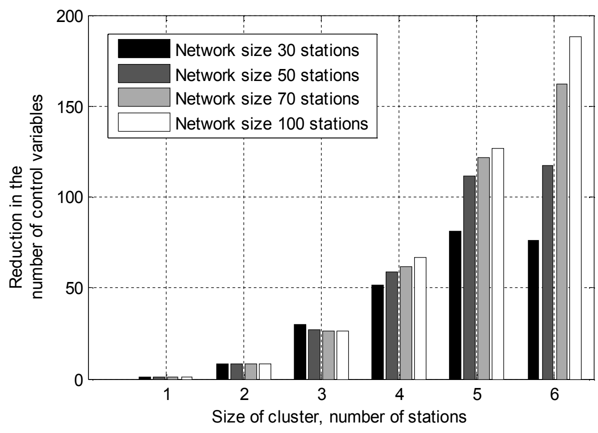

Fig. 6. Dependence of reduction in number of control variables on cluster size and network size (chromatic number is 3)

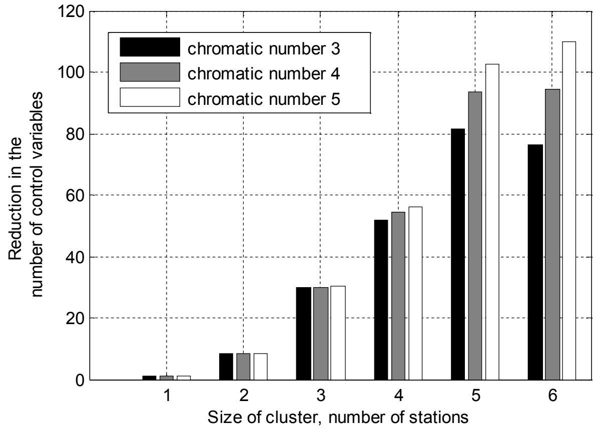

Fig. 7. Dependence of reduction in number of control variables on cluster size and chromatic number (size of network is 30 stations)

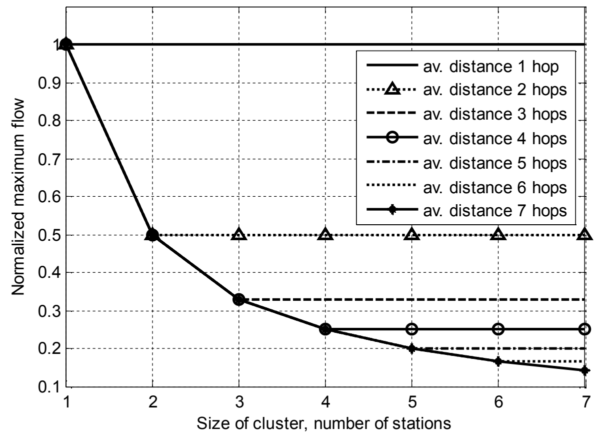

Fig. 8. Dependence of normalized maximum flow on cluster size

Other parameter reflects seamy side of decomposition approach. Because reuse of slots is disabled within single cluster, total number of slots used under hierarchical routing can be more than number of slots required under centralized implementation of model (1) – (5). In order to estimate the losses of resource utilization coefficient of flow per slot will be used:

$$K_{fps} = \left(\frac{\xi}{N_{sl}^{us}}\right) : \left(\frac{\bar{m}}{T_F}\right), \qquad (15)$$

where ξ is intensity of delivered flow; $\bar{m}$ is average number of bits of the user's data that can be carried by single slot; N_{sl}^{us} is number of used slots.

Physically non-dimensional coefficient K_{fps} reflects efficiency of slot's utilization and naturally it is growing with slot's reuse. For example, in fig. 1 number of used slots $N_{sl}^{us} = 4$ instead $N_{sl}^{us} = 6$ in fig. 2 and 3 when same delivered traffic. Then coefficient of flow per slot K_{fps} equals to 0.5 and 0.33 respectively.

Fig. 8 reflects coefficient K_{fps} implemented to the maximum flow (normalized maximum flow) that indicates negative effect of cluster size expansion and increasing distance between source and destination stations. For example, if number of hops between source and destination is 3, then reuse of slots is impossible in clustered network as well as in no clustered. If number of hops between source and destination is increased, for example, to 5 then minimal number of slots required for single path delivery of traffic $\xi(k) = 2\bar{m} / T_F$ equals to 3 ($K_{fps} = 0.33$).

When multipath delivery coefficient K_{fps} can be improved to 0.5. But under described hierarchical approach in both singe and multipath cases all of transit nodes belong to same or neighboring clusters. It disables slot reuse and coefficient K_{fps} becomes 0.2.

In order to take into account the two processes simultaneously an integral gain factor $K_{fps}G_{dim}$ was calculated (fig. 9 and 10). In general case the integral gain factor depends on network size, network connectivity, and average distance between source and destination that can be explained by different number of needed slots under different conditions.

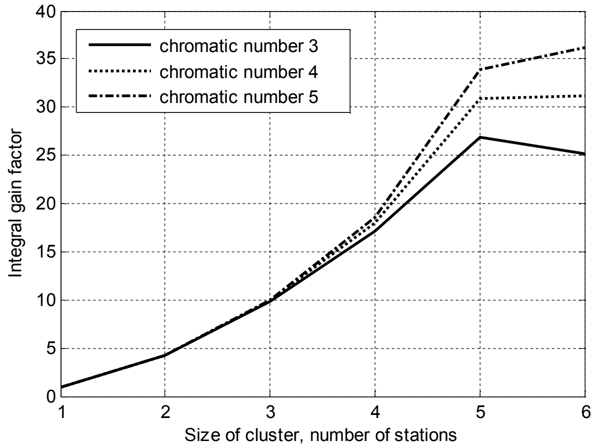

Fig. 9. Dependence of integral factor on cluster size and chromatic number of (size of network is 30 stations)

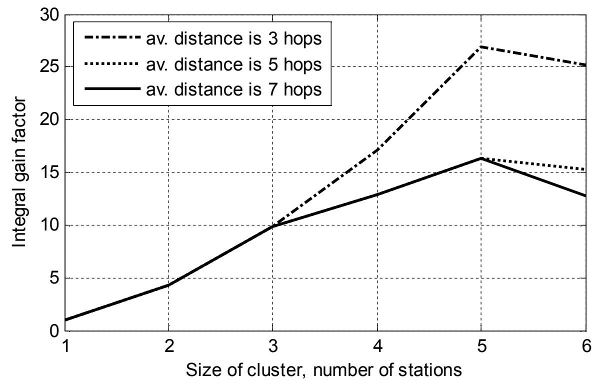

Fig. 10. Dependence of integral factor on cluster size and average distance between source and destination (size of network is 30 stations, chromatic number is 3)

As simulation results show the integral factor has strongly pronounced extremum that corresponds to optimal cluster size. In given example for WMN which contains 30 stations optimal cluster size is 5 (fig. 9 and 10) and it is growing with network size.

Conclusions

Thus, offered mathematical model in space of states describes dynamics of wireless IEEE 802.16 mesh-network and formulates routing problem in it as optimization task on slot allocation. As simulation results show it allows to obtain such routing solution, in which number of slots allocated along chosen path will meet arriving traffic. Moreover realized multipath routing strategies lead to minimization of number of allocated slots. In general the model allows to balance both link and buffer resources that leads to avoidance or minimization of network congestions.

In order to improve scalability of the cross-layer routing two-level hierarchical algorithm were developed. As simulation results show in the case size of optimization task (through number of control variables to be calculated) can be decreased in the tens or hundreds of times.

Taking into account possible losses of network efficiency through prohibition of slot reuse within single cluster, a new task of the optimal size of cluster has been rising. In general case optimal size of cluster depends on network size, network connectivity, and average distance between source and destination.

References

1. Hu H. An Effective QoS Differentiation Scheme for Wireless Mesh Networks / Honglin Hu, Yan Zhang, Hsiao-Hwa Chen // IEEE Network. – 2008. – Vol. 22, Is. 1. – P. 66-73.

2. Shou-Chih Lo. Efficient routing and centralized scheduling algorithms for IEEE 802.16 mesh networks / Shou-Chih Lo, Lyu-Chen Ou // International Journal of Network Management. – 2011. – Vol. 21, Is. 6. – P. 494-512.

3. Min Cao. System Performance Analysis for the Mesh Modeof IEEE 802.16 / Cao Min, Zhang Qian // WiMAX: Technologies, Performance Analysis, and QoS: edited by S.A. Ahson, M. Ilyas. – CRC Press, 2008. – P. 119-144.

4. Deva Priya M. A cross-layered path stability based routing protocol for WiMax networks / M. Deva Priya, ML. Valarmathi // American Journal of Applied Sciences. – 2013. – 10 (11). – P. 1325-1334.

5. Yevsyeyeva O. Mathematical model for resource allocation in TDMA-based wireless meshnetworks / O.Yu. Yevsyeyeva, E.M. Al-Azzawi // Eastern-European Journal of Enterprise Technologies. – 2014. – Vol. 3, N. 9 (69). – P. 4-9.

6. Yevsieieva O.Yu. Method of hierarchical cross-layer routing in 802.16 mesh networks. Clustering algorithm [Электронный ресурс] / O.Yu. Yevsieieva , E.M. Al-Azzawi // Проблеми телекомунікацій. – 2015. – № 1 (16). – С. 72-84. – Режим доступа к журн.: http://pt.journal.kh.ua/2015/1/1/151_yevsyeyeva_mesh.pdf.

Надійшла до редколегії 20.01.2016

Рецензент: д-р техн. наук, проф. О.В. Лемешко, Харківський національний університет радіоелектроніки, Харків.

ЦЕНТРАЛІЗОВАНА Й ІЄРАРХІЧНА КРОС-РІВНЕВА МАРШРУТИЗАЦІЯ В WIMAX MESH-МЕРЕЖАХ: АНАЛІЗ ПРОДУКТИВНОСТІ

О.Ю. Євсєєва, Е.М. Аль-Аззаві

WiMax mesh-мережі побудовані на основі часового розділення множинного доступу до загального частотного ресурсу. Успіх доставки трафіку у такому випадку залежить від наявності відповідної кількості часових слотів у кожному каналі уздовж всього маршруту доведення. Це обумовлює проблему крос-рівневої маршрутизації як задачі оптимального розподілу слотів між mesh-станціями, яка може бути розв'язана за допомогою математичної моделі в просторі станів. З метою підвищення масштабованості базова модель була вдосконалена й її ієрархічний модіфікація запропонована. Результати моделювання продемонстрували багатошляховий характер доведення з мінімальною кількістю використаних слотів, збалансоване використання буферних та канальних ресурсів, можливість зменьшення розмірності задачі в десяткі або сотні разів за умові ієрархічного підходу.

Ключові слова: *бездротові mesh-мережі, моделі в просторі станів, крос-рівнева маршрутизація, оптимальний розподіл слотів.*

ЦЕНТРАЛИЗОВАННАЯ И ИЕРАРХИЧЕСКАЯ КРОСС-УРОВНЕВАЯ МАРШРУТИЗАЦИЯ В WIMAX MESH-СЕТЯХ: АНАЛИЗ ПРОИЗВОДИТЕЛЬНОСТИ

О.Ю. Евсеева, Э.М. Аль-Аззави

WiMax mesh-сети построены на основе временного разделения множественного доступа к общему частотному ресурсу. Успешность доставки трафика в таком случае зависит от наличия соответствующего количества временных слотов в каждом канале вдоль всего маршрута доведения. Это нацеливает на рассмотрение проблемы кросс-уровневой маршрутизации как задачи оптимального распределения слотов между mesh-станциями, которая может быть решена с помощью математической модели в пространстве состояний. С целью повышения масштабируемости базовая модель была усовершенствована и ее иерархическая модификация предложена. Результаты моделирования показали многопутевой характер доведения с минимальным количеством использованных слотов, сбалансированное использование буферных и канальных ресурсов, возможность уменьшения размерности задачи в десятки или сотни раз при условии иерархического подхода.

Ключевые слова: *беспроводные mesh-сети, модели в пространстве состояний, кросс-уровневая маршрутизация, оптимальное распределение слотов.*