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METHOD OF HIERARCHICAL CROSS-LAYER ROUTING IN 802.16 MESH NETWORKS. CLUSTERING ALGORITHM

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Abstract *– In TDMA-based IEEE 802.16 mesh wireless networks problem of link resource allocation is turned into problem of time slot assignment which in order to improve network efficiency should be solved jointly with routing as integral cross-layer routing task. In order to increase network scalability a concept of hierarchical cross-layer routing is offered. Main idea is related to clustering and two-level hierarchical control. Lower level is associated with traffic routing and slot allocation within single clusters, where own pool of slots is available and slots' reusing is prohibited. But upper level controls sizes of the slots' pools and their allocation among different clusters. Upper control level assumes availability of clusters with same pool of slots thereby saves link resources. And lower and upper control levels are supposed as optimization procedures based on dynamic model in space of states. The offered hierarchical cross-layer routing method includes four components, namely clustering algorithm, algorithm for allocation of pools of slots between different clusters, low and upper level control algorithms. The article is focused on algorithms for clustering and pool allocation. As it was shown every WMN has own optimal cluster' size which depends on size of WMN and its structure, number of available slots per frame, and incoming traffic intensity. In turn problem of allocation of slots' pools can be formulated as graph coloring task and can be solved by appropriate algorithms.*

Анотація *– В рамках бездротових mesh-мереж стандарту IEEE 802.16 проблема розподілу часових слотів з метою підвищення ефективності використання ресурсів повинна розглядатися в комплексі з задачею маршрутизації. Для підвищення масштабованості такого підходу в статті пропонується концепція дворівневої ієрархічної маршрутизації. Нижній рівень управління пов'язаний з маршрутизацією в окремих кластерах, в кожному з яких використовується власний пул слотів. Верхній рівень управління визначає розміри пулів слотів і їх розподіл поміж кластерами. Управління на всіх рівнях сформульовано у вигляді оптимізаційної задачі на основі динамічної моделі в просторі станів. Стаття присвячена алгоритмам кластеризації та розподілу пулів слотів.*

Аннотация *– В рамках беспроводных mesh-сетей IEEE 802.16 проблема распределения временных слотов с целью повышения эффективности использования ресурсов должна рассматриваться в комплексе с задачами маршрутизации. В рамках повышения масштабируемости такого подхода в статье предлагается концепция двухуровневой иерархической маршрутизации. Нижний уровень управления связан с маршрутизацией в отдельных кластерах, в каждом из которых используется собственный пул слотов. Верхний уровень управления определяет размеры пулов слотов и их распределение между кластерами. Управление на всех уровнях сформулировано в виде оптимизационной задачи на основе динамических моделей в пространстве состояний. Статья посвящена алгоритмам кластеризации и распределения пулов слотов.*

Introduction

IEEE 802.16 mesh wireless networks were developed to provide high bandwidth access to large number of users within metropolitan area networks. They are able to combine flexibility of wireless with high capacity, reliability and security at similar to wired networks level. Substantially it's caused by possibilities of a mesh-station to interwork with every adjacent mesh-station and to work as client and as router for other clients at same time. On the other hand the capability complicates problems of traffic control such as routing and link's resource allocation in Mesh Wireless Networks (WMNs). While routing problem is related to finding the best path (or paths) from source to destination, problem of resource allocation corresponds to assignment required amount of network resources along chosen routes. Within IEEE 802.16 mesh wireless networks (so called WiMax) network resources to be allocated are time slots, number of which in every frame is limited [1].

There are two approaches to solving routing and resource allocation problems, namely, separately and jointly. In first case there are two not sophisticated tasks which can be solved sequentially and independently. The best delivering path (or paths) can be found by using some shortest path algorithm but time slot's allocation should be based on flow requirements. It is possible situation when chosen route will not have enough resources (available time slots) to deliver given flow. It means new path should be recalculated. But so long as algorithm for path searching doesn't take into account flow features second iteration cannot guarantee that another path will satisfy the flow's requirements. From the viewpoint joint solution of routing and resource allocation problems becomes more preferable.

Thus within IEEE 802.16 mesh wireless networks routing and resource allocation problems should be solved jointly as integral cross-layer routing task, that taking into account limited number of time slots per frame requires optimization approach.

I. Basic model on cross-layer routing in IEEE 802.16 mesh network

In order to increase efficiency of network resource's usage they should be allocated in optimal way based on appropriate mathematical model. The model should be

- Adequate to the physics of WMN that ensures accuracy of control decision;
- Flow-based that allows to control network resources according to features and requirements (rate, delay, etc.) of arriving flows;
- Dynamic that allows to adapt to traffic and network structure variations with time;
- Multipath that as it was shown in [2] allows to improve network productivity.

In order to obtain flow-based dynamic multipath routing algorithm for IEEE 802.16 WMN let us define binary control variables $\tau^{r,j}_{i,v}(k)$,

$$\tau^{r,l}_{i,j}(k) = \begin{cases} 1, \mathit{if\ during\ k\text{-}th\ time\ interval\ r\text{-}th\ slot\ is\ used\ in\ the\ link}\,(i,j) \\ \mathit{for\ transmission\ of\ the\ flow\ addressed\ to\ l\text{-}th\ station;} \\ 0, \mathit{otherwise,} \end{cases}$$

and focus on mathematical model in space of states [2, 3]:

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

$$q_{i,j}(k) \ge 0, \qquad \sum_{\substack{j=1,\\ i\ne j}}^{N_v} q_{i,j}(k) \le q_i^{\max}, \tag{2}$$

where $i, j = \overline{1, N_v}$, $j \ne i$, $, k = 0,1,2,...$; $\Delta t = t_{k+1} - t_k$ is the sampling interval; $q_{i,j}(k)$ is state variable representing 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; $m_{i,j}^r$ 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's traffic; $q_i^{\max}$ is total size of buffer at *i*-th mesh station.

System of equalities (1) describes law of flow's conservation at stations of WMN but inequalities (2) are caused by limited buffer sizes. The expressions (1) – (2) define dynamics of buffer usage but they don't take into account link capacity limitation. In contrast to wired networks where capacity of every link is fixed and known a priori, within wireless networks according to Shannon formula achieved capacity of a link depends on current signal-to-interference-and-noise-ratio (SINR) at the receiving point. If several stations transmit their signals on same frequency band at same time slot r, station-destination j can decode valid signal from station-source i successfully if and only if SINR in link (i, j) will exceed a threshold α_{ij},

$$SINR_{ij}(r) > \alpha_{ij}. \tag{3}$$

Condition (3) is formalization of so called physical interference model of relationships between wireless stations [4, 5]. Numerical value of the threshold α_{ij} depends on an acceptable level of Bit Error Rate (BER), modulation and coding scheme applied in link (i, j) [4, 5]. Then the maximum traffic rate in wireless link (i, j) over the time of r-th slot can be estimated as Shannon's capacity [5]

$$c_{ij}(r) = W \log_2(1 + SINR_{ij}(r)), \tag{4}$$

$$SINR_{ij}(r) = \frac{G_{ij}(r) P_{ij}(r)}{P_{term\_n}(r) + \sum\limits_{\substack{k=1,\\ k\ne i,j}}^{N_v} \sum\limits_{\substack{h=1,\\ h\ne i,j}}^{N_v} G_{kj}(k) P_{kh}(r)}, \tag{5}$$

where $c_{ij}(r)$ is upper bound of capacity of wireless link (i, j) over the time of r-th slot; G_{ij} is propagation gain from station i to station j; P_{ij} is transmission power at station i when it transmits data to j-th station; P_{term_n} is thermal noise power in the frequency band of operation, $P_{term\_n} = \eta W$; η is the ambient Gaussian noise density; W is bandwidth of the channel.

Thus under physical interference model average number of bits of the user's data in r-th slot $m_{i,j}^r$ in expression (1) can be calculated as $m_{i,j}^r = \frac{c_{ij}(r)T_F}{N'_F}$, where N'_F is total number of slots per frame including slots for control and user data. As a result equalities (1) become nonlinear because $m_{i,j}^r(k)$ depends on station's transmission power, i.e. on variables $\{\tau_{i,j}^{r,v}(k)\}$: if in link (i,j) $\tau_{i,j}^{r,v}(k)=0$ for all v then $P_{i,j}(r)=0$. Thus implementation of physical interference model (3) – (5) together with (1) – (2) allows to solve routing and slot allocation problems taking into account relationships between wireless stations at physical layer. In general case transmission powers of mesh stations can be treated as control variables in addition to binary control variables $\{\tau_{i,j}^{r,v}(k)\}$ and state variable $\{q_{i,j}(k)\}$. On the other hand it significantly complicates solution of cross-layer routing problem within (1) – (5).

In order to simplify formalization of cross-layer routing problem let us focus on protocol interference model. According to the model transmission on link (i,j) is successful if distance between communicated stations i and j not more than communication range R_C but several times more than distance between interfered stations h and j [4], i.e.

$$\{|h,j| \geq (1+\Delta)|i,j| \text{ and } |i,j| \leq R_C\}, \tag{6}$$

$$\text{or } \{|h,j| \geq R_I \text{ and } |i,j| \leq R_C\} \tag{7}$$

where j is receiving station; $|i,j|$ is geometrical distance between stations i and j; R_I is interference range, $R_I = R_C(1+\Delta)$; Δ is a positive parameter.

Protocol interference model (6) and its simplified version (7) (so called interference range model) allow to assume same values $m_{i,j}^r$ for all slots within same link, i.e. $m_{i,j}^r = m_{i,j}$ for all r, that turn system (1) into system of linear equalities.

Let us define graph of WMN $G(V,E)$ where V is set of nodes every from which models appropriate mesh-station but availability of edge $(i,j)\in E$ signifies possibility of direct communication between stations i and j, i.e. $|i,j| \leq R_C$. Then implementation of protocol interference model (6) requires

$$dist(h,j) \geq (1+\Delta)dist(i,j) \tag{8}$$

where $dist(u,v)$ is distance between nodes u and v in graph $G(V,E)$ that equal to minimal length from all paths from u to v measured by hops.

Because according to definition of graph $G(V,E)$ distance between transmitter and receiver is 1 hop always, and as a rule coefficient Δ in (6) and (8) lies between 2 and 4 [4, 5], in order to eliminate interference distance between interferer and receiver in graph $G(V,E)$ must be more than 2, i.e.

$$dist(h,j) > 2\,. \tag{9}$$

Thus conventional capacity constraint takes on special form in WMN. Like as in wired networks total flow rate on a link cannot exceed capacity of the link, in TDNA-based WMN number of slots in area of different stations i and j such as $dist(i,j) \le 2$ cannot exceed fixed in WMN total number of slots per frame (N_F). In other words simultaneous transmission or using of same time slots by two stations h and j becomes possible if and only if condition (9) is satisfied.

Condition (9) can be written as

$$dist(h,j) > \beta \ge 2 \tag{10}$$

where parameter β lies between 2 and diameter of WMN′ graph $D(G)$. According to definition graph diameter is upper bound for shortest path between any pair of nodes in the graph [6]. So for any nodes u and v, $u,v \in V$, it's true $dist(u,v) \le D(G)$. It means in graph $G(V,E)$ under $\beta = D(G)$ no stations which can satisfy to (10) and as a result can transmit simultaneously. Mathematically it gives rise to following constraints

$$\sum_{i=1}^{N_v}\sum_{\substack{j=1,\\ j\ne i}}^{N_v}\sum_{\substack{l=1,\\ l\ne i}}^{N_v}\tau_{i,j}^{r,l}(k) \le 1 \text{ for every } r=\overline{1,N_F}\,. \tag{11}$$

Actually expression (11) prohibits slot reusing within given wireless network. In order to improve capacity of WMN reuse of the slots must be approved, so parameter β must be equal to its low bound, i.e. $\beta = 2$. Then condition (11) is complicated and becomes set of constraints

$$\sum_{\substack{j=1,\\ j\ne i}}^{N_v}\sum_{\substack{l=1,\\ l\ne i}}^{N_v}\tau_{i,j}^{r,l}(k) + \sum_{g\in S_i^2}\sum_{\substack{j=1,\\ j\ne g}}^{N_v}\sum_{\substack{l=1,\\ l\ne g}}^{N_v}\tau_{g,j}^{r,l}(k) \le 1 \text{ for every } i=\overline{1,N_v} \text{ and } r=\overline{1,N_F}\,, \tag{12}$$

where S_i^2 is a set of stations interfered to the *i*-th station under $\beta = 2$, i.e. $S_i^2 = \{v : v \in V \wedge dist(v,i) \le 2\}$.

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

$$J = \sum_{k=1}^{a}\left[\vec{q}^{\,T}(k)W_q\vec{q}(k) + \vec{\tau}^{\,T}(k)W_\tau\vec{\tau}(k) - \vec{\tau}^{\,T}(k)W_{reuse}\vec{\tau}(k)\right] \to \mathbf{min} \tag{13}$$

subject to (1) – (2), (12),

where a 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 (13) belongs to class of integer non-linear programing, which is NP-hard in general but which can be solved by numerical methods. At same time solving can be significantly simplified if to replace constraint (12) by condition (11) but objective function (13) to replace by

$$J=\sum_{k=1}^{a}\left[\vec{q}^{\,T}(k)W_q\vec{q}(k)+\vec{\tau}^{\,T}(k)W_\tau\,\vec{\tau}(k)\right]\to\mathbf{min}\,. \tag{14}$$

Thus minimization of cost function (14) subject to (1) – (2), (11) (model#1) allows to simplify process of numerical calculation of control variables but minimization of function (13) subject to (1) – (2), (12) (model#2) assumes time slots reuse that potentially leads to network capacity improving. Because in practice computational complexity is related to scalability of control decision and network in whole, in order to find compromise between network scalability and network capacity combined solution can be proposed. Its main idea consists in hierarchical network organization and hierarchical controlling (fig. 1). It is supposed that structure of WMN is clustered, every cluster has own pool of available time slots and within singe cluster slots' reusing is prohibited, i.e. cross-layer routing problem can be formalized by model #1. At same time some number of clusters are assumed to have same pools of slots, and then routing between clusters is related to solution of problem (13) subject to (1) – (2), (12). 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.

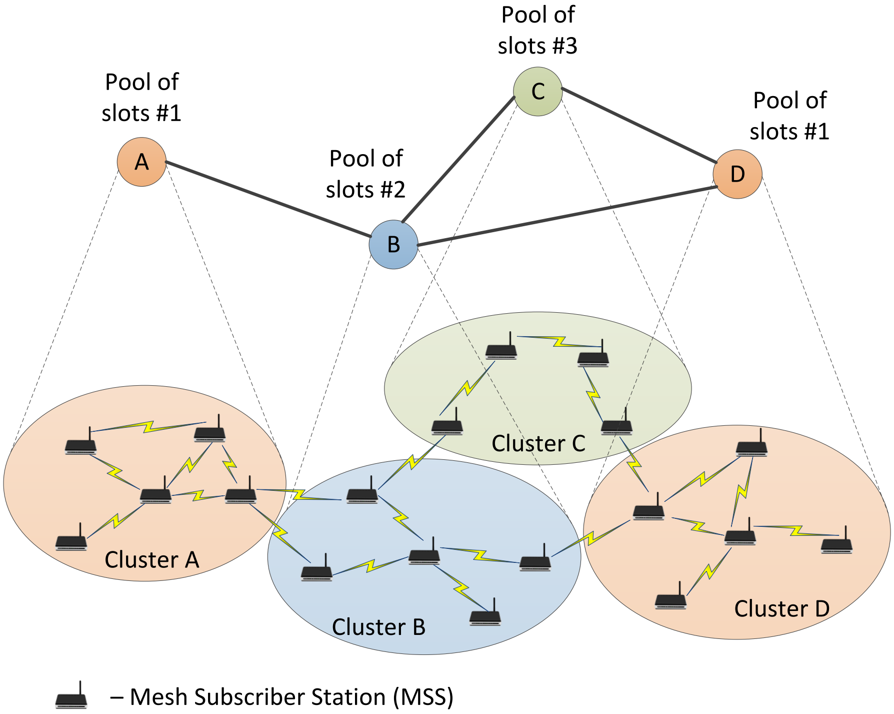


Fig. 1. Concept of hierarchical cross-layer routing

In order to realize described hierarchical approach and to develop on its basis method for hierarchical optimal cross-layer routing following algorithms must be designed:

- Algorithm for clustering of WMN' structure;
- Algorithm for allocation of pools of slots between different clusters;
- Low level control algorithm for traffic routing and slot allocation within single clusters according to model#1;
- Upper level control algorithm for traffic routing and slot allocation between clusters according to model#2.

The article will be devoted to development of clustering and assignment of pool of slots.

II. Clustering of WMN' structure

Main idea of scalability improving is related to using of model#1 for control within single clusters. Because the model doesn't allow to reuse time slots, it is rational to form cluster as set of interfered stations where slots' reusing is prohibitive through short distances between stations and as a result high level of interfering signals. In [7] an interference-based clustering algorithm is offered. It is aimed at dividing of WMN' structure on overlapping clusters within every from which distance between any pair of stations doesn't exceed 2. It means no such two stations in same cluster that can transmit simultaneously. Main disadvantage of the algorithm is related to clusters' overlapping. Under overlapping some transmitter can belong to at least two clusters every from which has own pool of slots and own control mechanism. Thus clusters' overlapping complicates control decision making and clustering algorithm [7] must be modified.

According to concept of hierarchical cross-layer routing main criterion to form cluster is interference within it. Then based on protocol interference model (9) cluster corresponds to subgraph $G_A(V_A,E_A)$, $V_A \in V$, $E_A \in E$, within which distance between any pair of stations doesn't exceed 2, i.e. $G_A(V_A,E_A)=\{\forall u,v \in V_A \wedge dist(u,v) \le 2\}$. Figure 2 shows different examples of subgraphs that satisfy to such cluster's definition but have different number of stations.

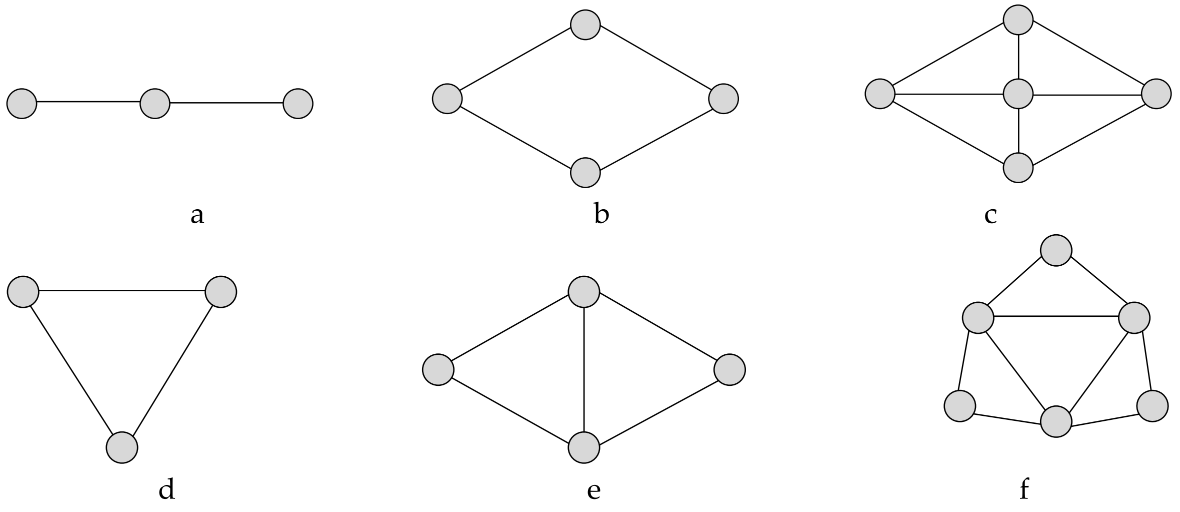


Fig. 2. Examples of subgraphs in which distance between any pair of stations doesn't exceed 2

Shown in fig. 2 examples give rise to task of optimal cluster size. Size of cluster (number of stations in it) has effect on dimension of control tasks (via the number of control variables to be calculated) and number of stations which will be able to reuse time slots. As a result size of cluster affects scalability and network capacity. Figure 3 illustrates different scenarios under cluster size 4, 3 and 2.

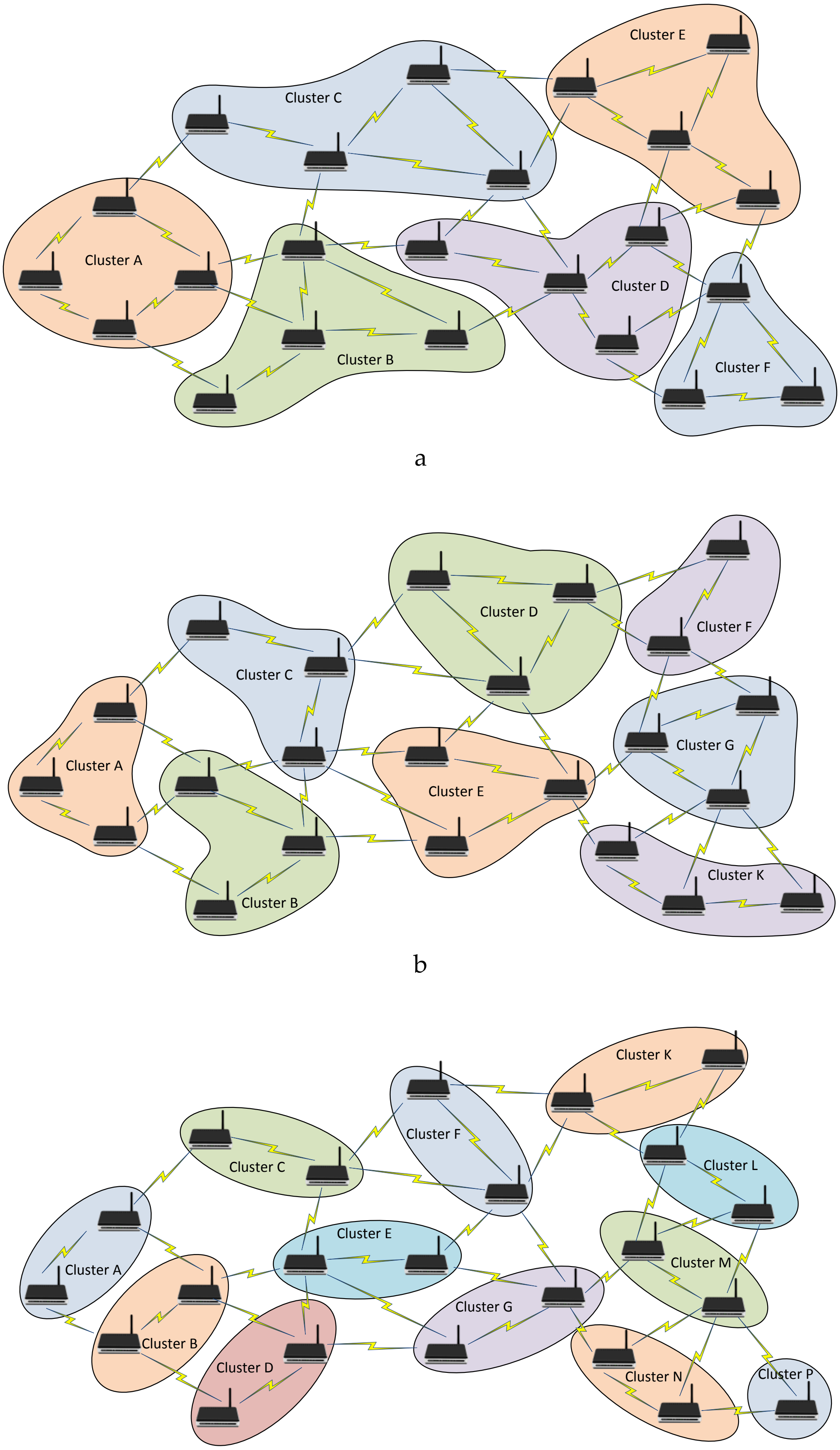
If cluster size equals to 4 (fig. 3a) there are two pairs of clusters, all stations in which don't interfere to each other. For example every node from cluster A is distant from all nodes from cluster E, and the distance satisfies to condition (9). Thus according protocol interference model stations in clusters A and E are so distant that can work at same time without interference.

It means that within before defined concept of hierarchical cross-layer routing they can use same pool of time slots. At same time distance between any station from cluster C and any station from cluster F meet condition (9) too. As a result owned to clusters C and F stations can use same pool of slots but the pool must differ from pool of slots for clusters A-E. In fig. 3a clusters which can use same pools of slots are similarly colored. Thus given structure of WMN allows 6 clusters from which two cluster' pairs can reuse link resources. In other words 7 from 23 stations are working by slot reusing.

If cluster size equals to 3 (fig. 3b) there are four pairs of clusters which allow same pools of slots within every pair. It means 11 from 23 stations are working by slot reusing that leads to more effective resource usage in comparison with previous scenario. It allows conclusion about minimization of cluster size as way to maximize resource (time slot) utilization and network performance in whole.

But on the other hand cluster size is related to computational complexity of optimal cross-layer routing at both the upper level and the lower level, i.e. within single clusters and between clusters. Reducing cluster' sizes results in greater number of clusters that in turn facilitates low scalability of routing at upper level.

Figure 4 illustrates graphs of clusters under different cluster sizes (4, 3, and 2). Graph of clusters reflects topology information about relationships between clusters without taking into account their internal structure. As it's shown in fig. 4 reducing cluster' sizes is appeared as complicated cluster' topology that in turn is related to higher number of control variables at upper level and higher its computational complexity.

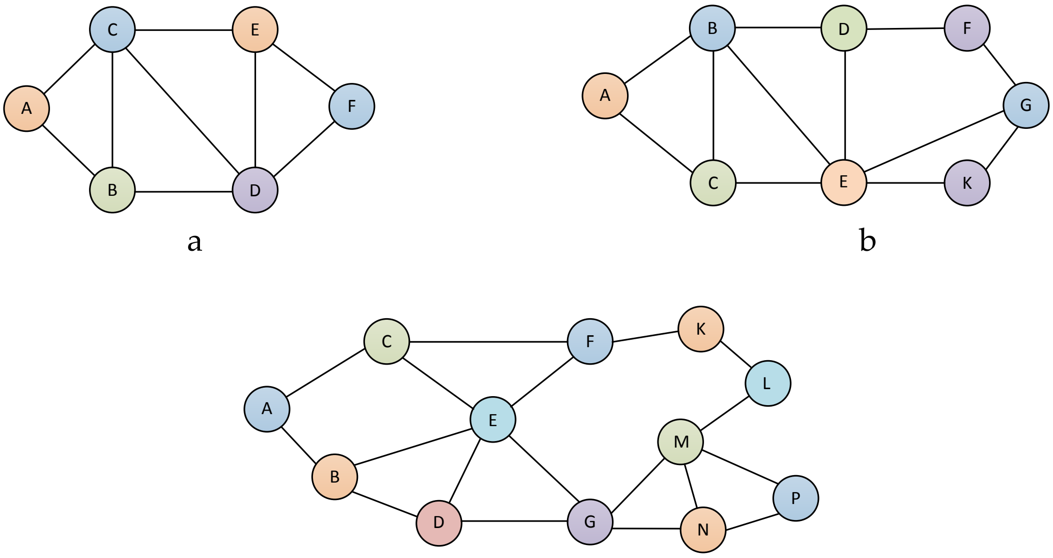


a

b

c

Fig. 3. Examples of clustering under cluster size



a b

c

Fig. 4. Graphs of clusters under different cluster sizes

Thus cluster' size is affected by two contradictory factors, there are possibility of slot reusing in order to improve resource utilization and total number of control variables (taking into account variables at both levels) in order to reduce computational complexity of decision making. As analysis shows optimal cluster' size for given in fig. 3 WMN equal to 4…3. In general case optimal cluster' size will depend on size of WMN and its structure, number of available slots per frame, and incoming traffic intensity.

III. Allocation of pools of slots between WMN' clusters

According to concept of hierarchical cross-layer routing (fig. 1) some clusters are assumed to use same pool of slots. Thus it is supposed that in every frame total number of slots available for user traffic delivering is divided into groups (so called pools) and a pool is available for using only by some group of noninterfering clusters. It gives rise to two open issues: number of slots in every pool and allocation of the pools among clusters.

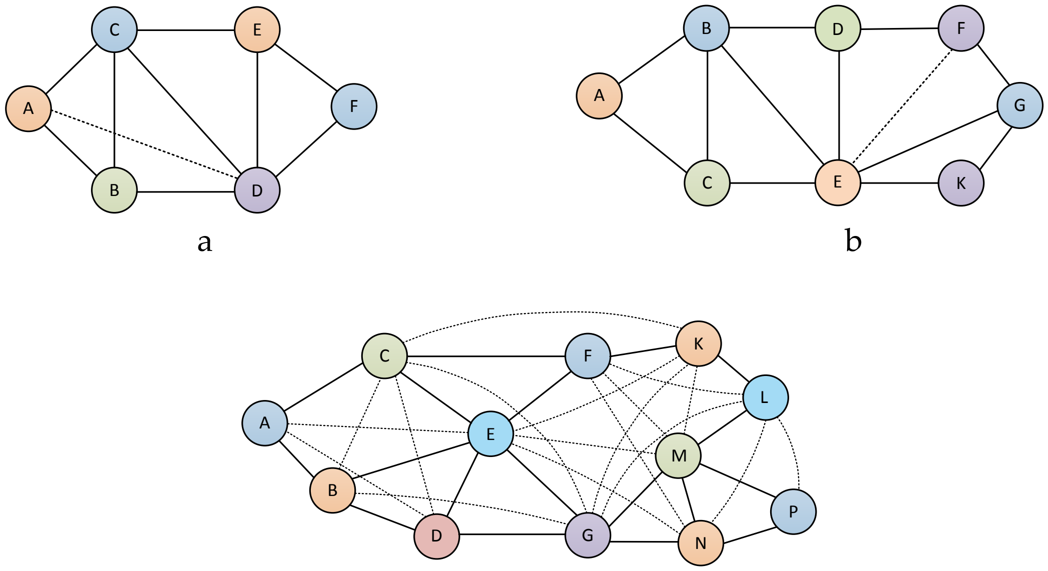
One from formulated in section I requirements to model of routing in WMN is related to dynamics. And the requirement is satisfied by using system of differential equalities of states (1) as basis of optimal cross-layer routing. In order to realize full dynamics number of slots in every pool can be defined as reconfigurable parameter calculated dynamically at upper control level. Thus the task is entrusted to algorithm of upper control level.

However structure of aggregated graph of clusters allows to determine number of required pools. As it was defined for individual stations by condition (9), simultaneous using of same slot' pool by two clusters A and H becomes possible if and only if condition (9) is satisfied for any pair of stations from A and H, i.e.

$$dist(v, u : \forall v \in V_A, \forall u \in V_H) > 2 . \qquad (15)$$

Information about interference between clusters is partially carried by graphs of clusters examples of which are shown in fig. 4. If some vertexes are directly connected in graphs of clusters then appropriate clusters interfere to each other and as a result the clusters cannot work at same pool of slots. However the converse is not true. If some pair of vertexes isn't directly connected in graphs of clusters they can interfere. For example in graph shown in fig. 3, a within clusters A and D not all pairs of station satisfy to (9) even if they aren't connected in fig. 4, a. As a result clusters A and D cannot be assigned to use same time resources.

In order to allocate pools of slots among noninterfering group of stations graph of clusters can be turn into conflict cluster graphs. The conflict graph indicates mutually interfering groups of stations [8]. The graph can be built on basis of graph of clusters by insertion of some additional edges. For example in case represented by fig. 3, a conflict graph is graph of clusters with addition edge $A - D$ (fig. 5a).



a

b

c

Fig. 5. Conflict graphs of clusters for different cluster sizes

Similarly if to add edge $E - F$ to graph in fig. 4, b, we'll have appropriate conflict graph (fig. 5a). Analysis of conflict graph for third clustering scenario (fig. 5c) confirms before done conclusion about unreasonableness of very small cluster size (in that case cluster size was equal to two stations). Thus described conflict graph reflects clusters which cannot be active simultaneously. Hence by using conflict graph tasks of number of required slots' pools and their allocation among clusters can be reduced to graph coloring and calculation of chromatic number.

In graph theory a coloring of a graph is a labeling of vertices where adjacent vertices never share a label (color). A graph is k-colorable if it can be colored using k colors. Chromatic number of graph G $\chi(G)$ is the smallest number k for which the graph G is

k-colorable [9]. Chromatic number of conflict clusters' graphs G' can be estimated via lower and upper bounds [6, 9]:

1) according to Brooks' theorem $\chi(G') \le \Delta(G')$ where $\Delta(G')$ maximum degree of a graph G'. The theorem is true for all connected graph except for complete graphs and cycle graphs of odd length;

2) $\varphi(G') \le \chi(G') \le \left\lceil \frac{n(G') + \varphi(G')}{2} \right\rceil$ where $\varphi(G')$ is clique number introduced as the maximum number of vertices in a complete subgraph of G'; $n(G')$ is number of vertices in G'; $\lceil x \rceil$ is the largest integer less than or equal to x;

3) $\left\lceil \frac{n(G')}{\alpha(G')} \right\rceil \le \chi(G') \le n(G') - \alpha(G') + 1$ where $\alpha(G')$ is the largest number of vertices of G' no two of which are adjacent (largest number of vertices which can be colored with any one color).

For example, for conflict clusters' graph shown in fig. 5b $n(G') = 8$, $\varphi(G') = 3$, $\alpha(G') = 3$, $\Delta(G') = 6$. So chromatic number of given conflict graphs lies between 3 and 6. Figure 6 illustrates different variants of its coloring.

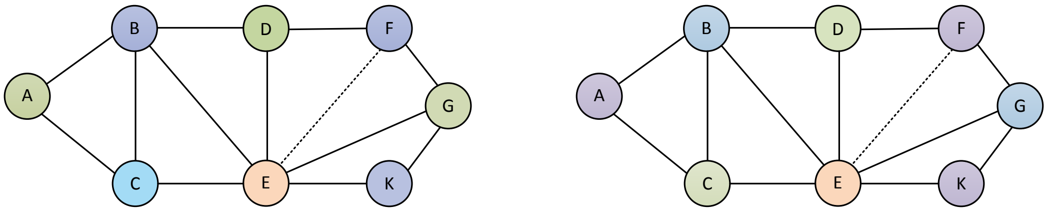


Fig. 6. Different variants of conflict graph coloring

As fig. 6 demonstrates chromatic number in the example equals to 4 and any coloring requires 4 colors. In WMN context it means that total number of slots should be divided among 4 pools. At same time shown variants of coloring (fig. 5b and fig. 6) have different number of vertices that are colored with same color. In case represented in fig. 5, b all vertices are divided into two-nodes groups, in cases represented in fig. 6 the groups are $\{3,3,1,1\}$ and $\{3,2,2,1\}$ respectively. So same pool of time slots can be assigned to different number of clusters but in practice if the clusters are noninterfering they can work simultaneously without any negative consequences. Currently graph theory accumulated good experience in exact and approximate coloring algorithms some from which are described in [9].

Conclusions

In order to improve efficiency of resource utilization and to increase scalability of IEEE 802.16 and other TDMA-based wireless mesh network a concept of hierarchical cross-layer routing is offered. Main idea is related to clustering and two-level hierarchical control. Lower level is associated with traffic routing and slot allocation within single clusters, where own pool of slots is available and slots' reusing is prohibited. But upper level controls sizes of the slots' pools and their allocation among different clusters. Upper control level assumes availability of clusters with same pool of slots thereby saves link resources.

And lower and upper control levels are supposed as optimization procedures based on dynamic model in space of states. The model allows to make optimal control decision about route for traffic delivering together with optimal slot allocation in every link along chosen path. At lower control level the matter is path inside a cluster but at upper control level the matter is path between different clusters. Moreover the tasks are formulated as flow-based and dynamic that allows to calculate vector of control variables according to requirements of arriving traffic and to adapt to structure or traffic changes.

The offered hierarchical cross-layer routing method includes four components, namely clustering algorithm, algorithm for allocation of pools of slots between different clusters, low and upper level control algorithms. As it was shown every WMN has own optimal cluster' size which depends on size of WMN and its structure, number of available slots per frame, and incoming traffic intensity. In turn problem of allocation of slots' pools can be formulated as graph coloring task and can be solved by appropriate algorithms.

References:

1. *IEEE Std 802.16-2004*, IEEE Standard for Local and metropolitan area networks – Part 16: Air Interface for Fixed Broadband Wireless Access System. IEEE, NY, 2004. – 895 p.
2. *Yevsyeyeva O., Al-Azzawi E. M.* Optimal Cross-Layer Routing in 802.16 Mesh Networks With Different Classes of Service // Scholars Journal of Engineering and Technology. – 2015. – Vol. 3 (1A). – P. 21 – 32.
3. *Yevsyeyeva O., Al-Azzawi E.M.* Mathematical model for resource allocation in TDMA-based wireless meshnetworks // Eastern-European Journal of Enterprise Technologies. – 2014. – Vol. 3, N 9(69). – P. 4-9.
4. *Iyer A., Rosenberg C., Karnik A.* What is the right model for wireless channel interference? // IEEE Transactions on Wireless Communications. – 2009. – Vol. 8, Is. 5. – P. 2662 – 2671.
5. *Shi Y, Hou Y, Liu J, Kompella S* How to correctly use the protocol interference model for multi-hop wireless networks // Tenth ACM international symposium on Mobile ad hoc networking and computing MobiHoc'09: proc. of the symposium. – ACM New York, NY, USA, 2009. – P. 239 – 248.
6. *Зыков А.А.* Основы теории графов. – М.: Наука, 1987, – 384 с.
7. *Yevsyeyeva O., Al-Azzawi E. M.* An Algorithm for Clustering And Aggregation Of Wireless Mesh Network's Topology // First International IEEE Conference «Problems of Infocommunications. Science and Technology» PICS&T-2014, 14-17 October, 2014: proc. of the conf. – Kharkiv, Ukraine, 2014. – P. 37–38.
8. *K. Jain, J. Padhye, V. Padmanabhan, L. Qiu* Impact of interference on multi-hop wireless network performance // 9th annual international conference on Mobile computing and networking MobiCom'03: proc. of the conf. – ACM New York, NY, USA 2003. – P. 66 – 80.
9. *Christofides N.* Graph theory: An algorithmic approach (Computer science and applied mathematics). – Academic Press, Inc. Orlando, FL, USA, 1975. – 400 p.