STUDIA INFORMATICA 2008
Volume 29 Number 4B (81)

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TOPOLOGY CONTROL FOR REDUCING A INTERFERENCE IN MOBILE AD HOC AND SENSOR NETWORKS

Summary. Topology control (TC) attempts to find efficient but sparse subgraphs of the maxpower communication graph in mobile ad hoc and sensor networks. The TC for interference reduction makes it possible to minimize link interference and improve the quality of data transmission. This paper provides an algorithm for constructing a network topology for mobile ad hoc and sensor networks, such that the maximum link interference of the topology is minimized..

Keywords: topology control, mobile ad hoc, mobile sensor networks

STEROWANIE TOPOLOGIĄ DLA ZREDUKOWANIA ZAKŁÓCEŃ W RUCHOMYCH SIECIACH SENSOROWYCH I AD HOC

Streszczenie. Sterowanie topologią pozwala na znalezienie w grafie komunikacji o maksymalnej mocy efektywnych, ale rzadkich podgrafów. Umożliwia to redukcję zakłóceń oraz poprawienie jakości transmisji. Artykuł dostarcza algorytmu dla konstrukcji topologii sieci dla ruchomych sieci ad hoc oraz sieci sensorowych, w których jest minimalizowane maksymalne zakłócenie łącza.

Keywords: sterowanie topologią, ruchome sieci ad hoc, ruchome sieci sensorowe

1. Introduction

The efficiency metrics used up till now in topology control (TC) of ad hoc and wireless sensor networks (WSNs) [1, 2] are: energy [3, 4] and interference [5]. The need to reduce energy is crucial in energy-constrained environments, while reducing interference has the potential to increase network lifetime and capacity [6].

TC is a method for selecting a suitable topology for transmission realization in a network. The general approach of a TC algorithm is to remove longer links from the network in order to force the nodes to use several shorter hops instead, while using a smaller amount of energy. However, selecting the wrong link can disconnect a network.

The first algorithm for multihop packet radio networks was presented in a paper by Hu [7]. The R&M protocol [8] builds a topology that is optimized for the all-to-one communication pattern, where one of the network nodes is designed as the master node and all the other nodes send messages to the master. Ramanatham [9] suggested two centralized algorithms for static networks to create the desired topology as well as two distributed heuristic TC protocols that adjust node transmit powers in response to topology changes.

The first TC algorithms preserved energy-efficient paths or computing planar subgraphs for geometric routing [10, 11]. The second wave of TC research was initiated by a paper [12] on the CBTC algorithm. Thus, a number of papers discussed spanner properties [13, 14] and signal propagation characteristics [15]. However, none of these algorithms could sufficiently reduce interference since message transmission can affect nodes if they are not direct neighbors of the sending node in the resulting topology.

A definition of interference in wireless networks using the concepts of congestion, power consumption, etc. was given by Meyer [16]. Certain assumptions about transmission power were presented in an early work of H. Takagi and L. Kleinrock [17], in which the interference range of a radio link depends on the transmission power. Currently, the XTC topology control algorithm described by Wattenhofer [15] can produce a subgraph of the relative neighborhood graph [18]. It was proved that no edge between nodes u and v can exist if node w exists such that $|uv| > \max(|uw|,|vw|)$. However, the XTC algorithm can also remove the edge (u,v) if $|u,v| = \max(|uw|,|vw|)$.

Our goal is to introduce a new algorithm called the Interference Reduction Algorithm for Mobile Networks (IRA4MN). The IRA4MN algorithm provides a heuristic solution for minimizing interference in mobile ad hoc and sensor networks. This algorithm uses a Lune graph to construct directed neighbor coverage in a mobile network. Besides describing the details of the IRA4MN algorithm we also show that it has the following properties:

- Its running time is proven to be polynomial. Moreover, in practical cases the running time of the algorithm competes with the most elementary heuristics.
- It can also be used for highly mobile networks.

The paper is organized as follows. Section 2 reviews previous research on interference models. Section 3 presents the IRA4MN algorithm that can solve the problem of interference reduction in mobile ad hoc and sensor networks. In section 4, we give the results of a simulation study. Section 5 concludes the paper.

2. Network and interference model

We assume that the mobile and ad hoc networks are described by graphs. Graph $G = (V, E)$ consists of a set of nodes $V \subset \Re^2$ and a set of edges $E \subseteq V^2$. The nodes represent the mobile hosts. The edges correspond to links between nodes. Edge $e = (u, v)$ can be directed only if it can be used by *u* to reach *v,* but not vice versa. Graph G can be undirected if there is a path between any two nodes in the graph. We can give some definitions.

Definition 1 (Unit Disk Graph)

Let *V* be a set of nodes and let *E* be a set of edges such that if and only if the Euclidean distance between *u* and *v* is at most 1. The Unit Disk Graph (UDG) of the nodes in *V* is the Euclidean graph.

Definition 2 (t-spanner)

A subgraph $G^{'} = (V, E^{'})$ of a finite undirected graph $G = (V, E)$ is t-spanner if and only if for each pair (*u,v*) of nodes $d_{G^{'}}(u,v) \leq t \cdot d_G(u,v)$, where $d_{G^{'}}(u,v)$ and $d_G(u,v)$ denote the shortest distances between *u* and *v* in $G^{'}$ and G , respectively.

Definition 3 (Gabriel Graph) [19]

Let *E* be the set of edges, and be the set of nodes. The Gabriel Graph (GG) of *V* is $G = (V, E)$ if and only if for each pair of nodes (*u, v*) there is an edge *E* within the circumcircle of (see Fig. 1).

Definition 4 (Delaunay Triangulation)

Let *V* be a set of nodes and *E* be a set of edges. Let there be edges (*u*, *v*), (*u*, *w*) and (*v, w*) in *E* if there is no other within the circumcircle of *u, v* and *w.* The Delaunay Triangulation (DT) of is the resulting graph $G = (V, E)$ (see Fig. 2).

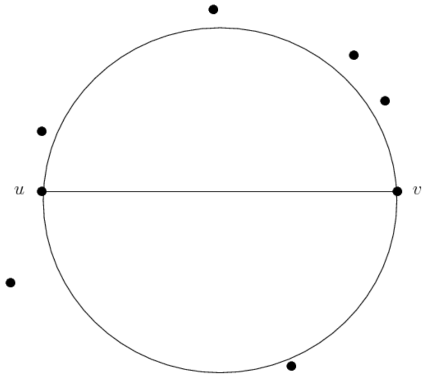

Fig. 1. An example of Gabriel Graph. Edge (u, v) is included in the GG if and only if the disk with the same edge as diameter contains no node

Rys. 1. Przykładowy graf Gabriela GG. Krawędź (u, v) jest włączona do tarczy wtedy i tylko wtedy, gdy tarcza o tej krawędzi jako średnicy nie zawiera tych węzłów

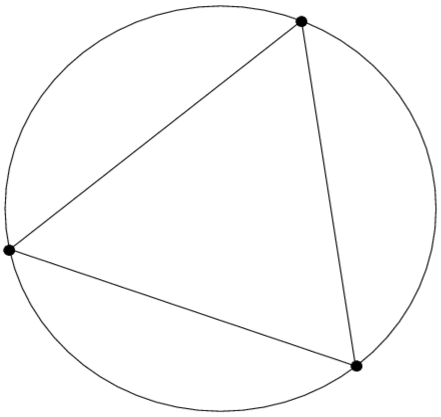

Fig. 2. Delaunay Triangulation
Rys. 2. Triangulacja Delaunaya

In the following, let $D(z,r)$ denote the disk centered at node z with radius r. Let $|u,v|$ denote the Euclidean distance between nodes u and v. Thus, we define the coverage of a directed edge $e=(u,v)$ as the set of nodes that are covered by the disk induced by e, namely

$$Cov(e) := \{z \in V[z \;\; is \;\; \text{cov}ered \;\; by \;\; D(u,|u,v|)\} \tag{1}$$

The coverage of an undirected edge $e^{'}=(u^{'},v^{'})$ is defined by

$$\begin{aligned} Cov(e^{'}) := \{z \in V[z \;\; is \;\; \text{cov}ered \; by \; D(u^{'},|u^{'},v^{'}|) \cup \\ x \in V[x \; is \; \text{cov}ered \;\; by \;\; D(v^{'},|v^{'},u^{'}|)\} \end{aligned} \tag{2}$$

The interference of a network is defined as the maximum edge coverage occurring in the network. More formally [20].

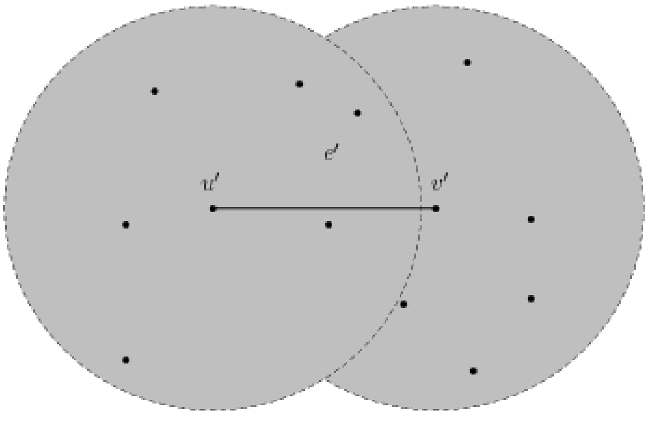

Fig. 3. Nodes covered by an undirected edge
Rys. 3. Węzły pokryte przez nieskierowaną krawędź

Definition 5 (Interference graph)

An interference graph for a finite undirected graph $G=(V,E)$ is a subgraph $G_{\inf}=(V,E^{'})$ with the maximum edge coverage in the network, where

$$Cov(e) \;=\; |\{z \in V, |u,v| \leq |u,v| \cup |u,z| \leq |u,v|\}| \tag{3}$$

In the paper by the same authors [21], the interference was defined as a graph of any node in the graph. More formally

Definition 6 (Interference graph in other form)

An interference graph $G=(V,E)$ is a subgraph $G^{'}=(V,E^{'})$ such that

$$\begin{aligned} &Cov(v)=\left[u \mid v \in V, v \mid u,v \mid < u_r\} \mid\right] \\ &\text{and} \quad MaxNodeCoverage(G) := \max_{u\in V}\; Cov(v) \end{aligned} \tag{4}$$

where u_r is the distance between node u and its farthest neighbor in G.

However, the both definitions not consider the interference in more complicated situations. For instance, a network with high interference in one place and low interference everywhere could have the same interference as another network with equally high interference everywhere. Therefore, an average edge interference was defined as follows [5]:

Definition 7 (Interference in still other form)

An average edge interface graph $G=(V,E)$ is a subgraph $G^{'}=(V,E^{'})$ such that the sum of the average of all edges in the graph is divided by number of nodes in the graph

$$AverageEdgeCoverage(G)=(\sum_{e\in E} Cov(e))\,/\,|V| \tag{5}$$

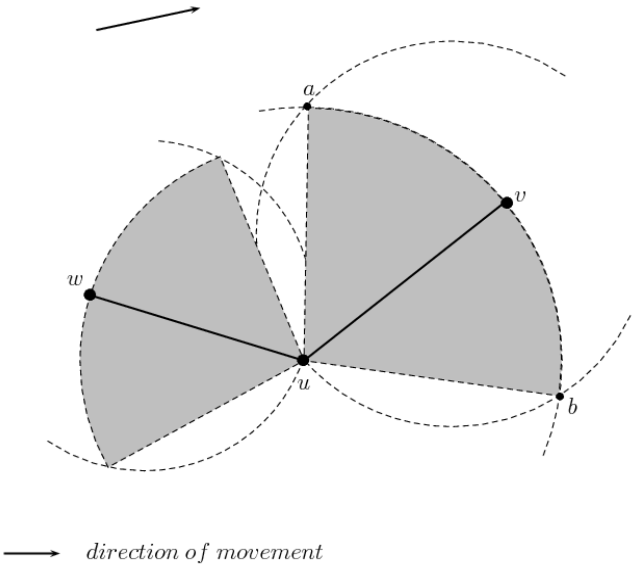

Fig. 4. The directed neighbor coverage of node *u* is defined as the cone of width $a\hat{u}b$ centered at *u*. The directed neighbor coverage of node *u* is the union of the covered region of nodes *w* and *v*

Rys. 4. Pokrycie skierowanego sąsiada węzła *u*, które jest definiowane jako stożek $a\hat{u}b$. Pokrycie skierowanego sąsiada węzła *u* jest połączeniem pokrytego obszaru węzłów *w* oraz *v*

3. A topology control algorithm for interference reduction in mobile ad hoc and sensor networks

In this section, we present a topology control algorithm for interference reduction in the mobile ad hoc and sensor network.

Let N be a set of points in the Euclidean two-space. To solve the problem of constructing an algorithm for interference reduction, we give the new definition of direction neighbor coverage, obtaining a new measure of interference associated with a link. The main aspect of these definitions is that their are explicitly designed for mobile ad hoc and sensor networks.

Definition 8 (Directed neighbor coverage)

Consider a network node u, and one of its neighbors v in the direction of movement. The directed neighbor coverage of node v, denoted by $Cov_u(v)$, is defined as the cone centered at u that spans $Lune(u,v)$ in the desired direction of movement, that is, the cone of width $a\hat{u}b$, where a and b are intersection points of the circumferences of radius $\delta(u,v)$ centered at u and v, respectively. The covered region of node u is the union set of the coverage of all its neighbors.

A $Lune(u,v)$ denotes the intersection of the circles of radius $\delta(u,v)$ centered at u and v, respectively, if and only if no other node in N lays in $Lune(u,v)$ [22]. Thus, the concepts of directed neighbor coverage and coverage region are illustrated in Fig. 4.

Furthermore, we present the definition of interference number of edge.

Definition 9 (Interference number of edge in the network)

Let $e=(u,v)$ be any edge of the edge of the communication graph $G=(N,E)$, indicating that nodes $u,v\in N$ are within each other's maximum transmitting range. Let $N_u(v)$ (resp., $N_v(u)$) be the set of all nodes within u's (resp., v's) directed neighboring coverage when u (resp., v) transmits with power $P_u(v)$ (resp., $P_v(u)$). The interference number of edge e is given by

$$INF(e)=|N_u(v)\cup N_v(u)| \tag{6}$$

Now, we introduce two measures, according to the above given definitions. The total path interference coverage is the sum of the coverage of all edges in the path, namely

$$TotalPathInterfCov=\sum_{u,v\in V}\ \sum_{e\in IpathP_{uv}} Cov(e) \tag{7}$$

where $IpathP_{uv}$ is the interference path between nodes u and v, namely

$$IpathP_{uv}=\{e_1,e_2,\ \dots\ ,e_m\} \tag{8}$$

$IpathP_{uv}$ describes the path between nodes u and v that has the lowest interference.

Based on the interference number of edge we define also the path interference cost as

$$PathInterfCost = \sum_{u,v\in V} \sum_{e\in IpathP_{uv}} INF(e) \tag{9}$$

To estimate how good is a certain network topology at reducing interference, we give the following definition.

Definition 10 (Reducing factor)

Let $G=(N,E)$ be the maxpower communication graph. Let $G'=(N,E')$ be a subgraph of G. The reducing factor RF of G' is the maximum cost source/destination pair of the ratio of the path interference cost of minimum interference path in G' to the path interference of minimum interference path in G, namely

$$RF(G') = \max_{u,v\in N} \frac{PathICost(mip\, G'_{u,v})}{PathICost(mip\, G_{u,v})} \tag{10}$$

We define $RF(G')=\infty$ if there exist nodes u,v which are connected in G, but they are disconnected in G'.

3.1. The IRA4MN algorithm

The Interference Reduction Algorithm for Mobile Networks (IRA4MN) consists of two phases. In the first phase is computed a Gabriel graph, which has optimal power stretch factor [18]. In the second phase are removed all links that lead to high interference. We give both phases.

Phase a) The Gabriel graph construction:

1. ID broadcast.
   _ send message ($u, P_{\max}$) at maximum power $P_{\max}$
2. Neighbors detection
   2a. Denote the received signal strength and store this information
   2b. Evaluate the distance *d* from node u to neighbor v using the signal degradation model
   $P_{rec} = P_{\max} \cdot d^{\alpha}$
   2c. Calculate the minimal energy cost needed for sending a message from u to v
   2d. Respond to v with the minimal energy cost, $c(u,v)$
3. Wait for messages from all neighbors to u with the $c(v,u)$, where v is the neighbor.
4. Broadcast to every neighbors the value of $c(v,u)$ for all nodes v.
5. Determine neighbor set from all the nodes $N(u)$:
   _ for each link (u,v) if no node w exists such that $c(u,w)+c(w,v) \le c(u,w)$

The next phase allows to reduce interference in the graph G. The directed neighbor coverage is calculated locally. If two links have a direction neighbor coverage smaller than a link with given directed neighbor coverage, it is removed. Therefore, the algorithm determines the minimal number of link in the direction of movement.

Phase b) The interference reduction:

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1. For each node $u$ in given direction
       For each neighbor $v$ find a node $w$ such that
           $Cov(u,w) + Cov(w,v) < Cov(u,v)$
           if exists a node $w$, the link $(u,v)$ is replaced by the links $(u,w)$ and $(u,v)$ .
           Otherwise, mark $(u,v)$ .
2. Remove all unmarked links.
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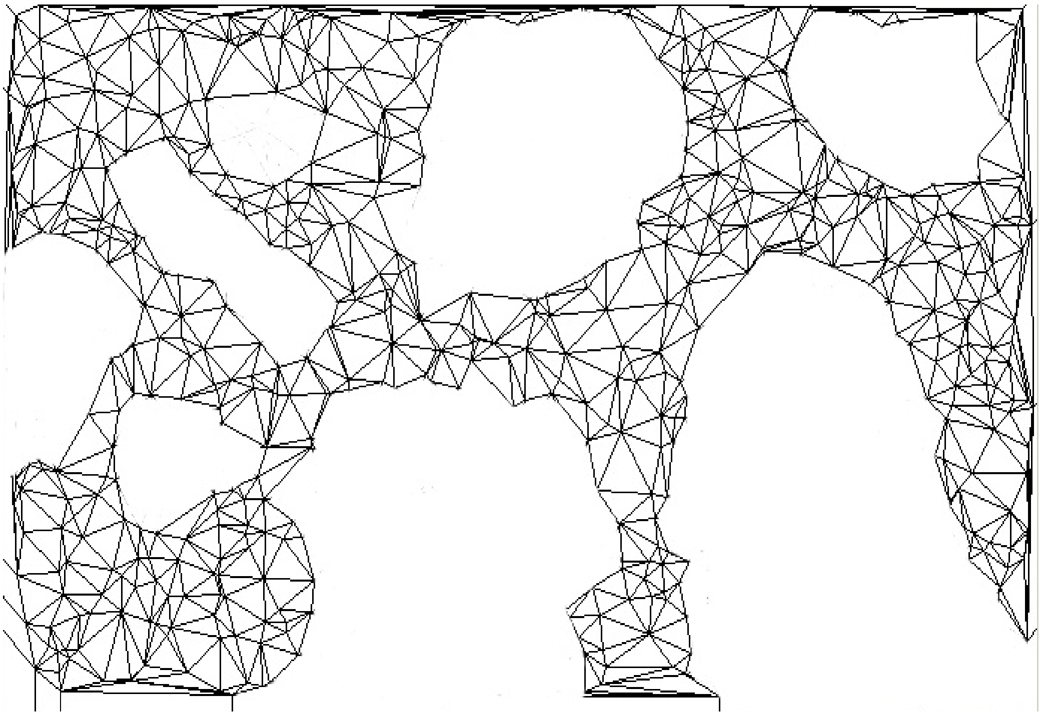

Fig. 5. The original topology
Rys. 5. Początkowa topologia

4. Simulation results

In this section, we present the simulation results using the metrics described in the previous section.

The results of our simulations are shown in Fig. 5 for the case of free space propagation. The topologies were produced by placing nodes randomly and uniformly on a square field 20 by 30 units in size, where all nodes had the identical communication range of 2.5 units. It was assumed that 1 unit is equal to 10 meters. A radio link between two nodes can exist if the distance between them is less than the communication range. The topology obtained in this way was generated for the spatial density varying from $\rho_S = 1 \cdot 10$ [m^{-2}] to $\rho_S = 10 \cdot 10$ [m^{-2}].

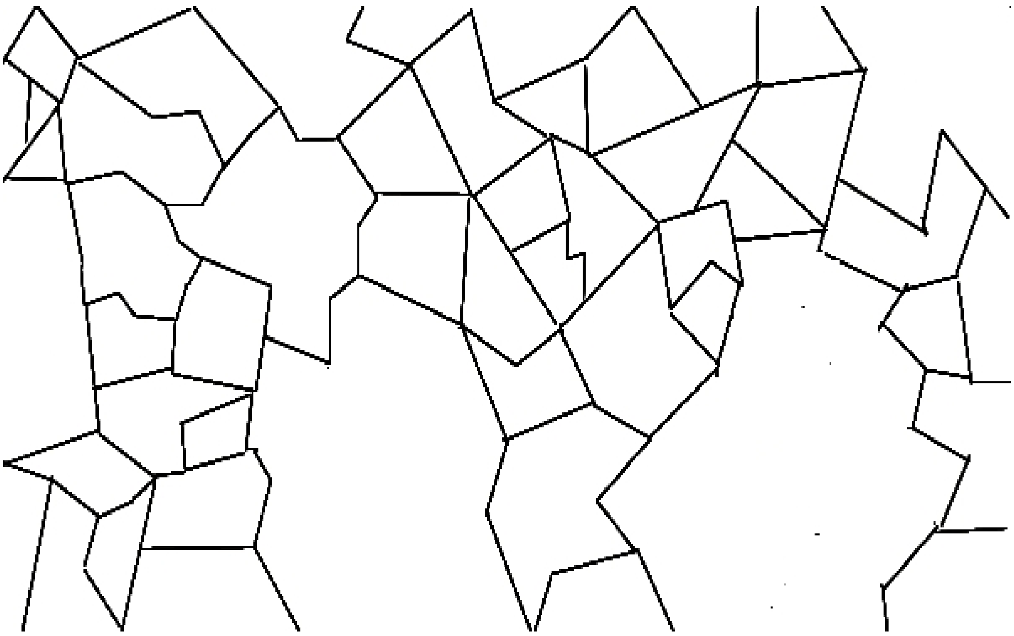

Fig. 6. The topology produced by the XTC algorithm
Rys. 6. Topologia utworzona przez algorytm XTC

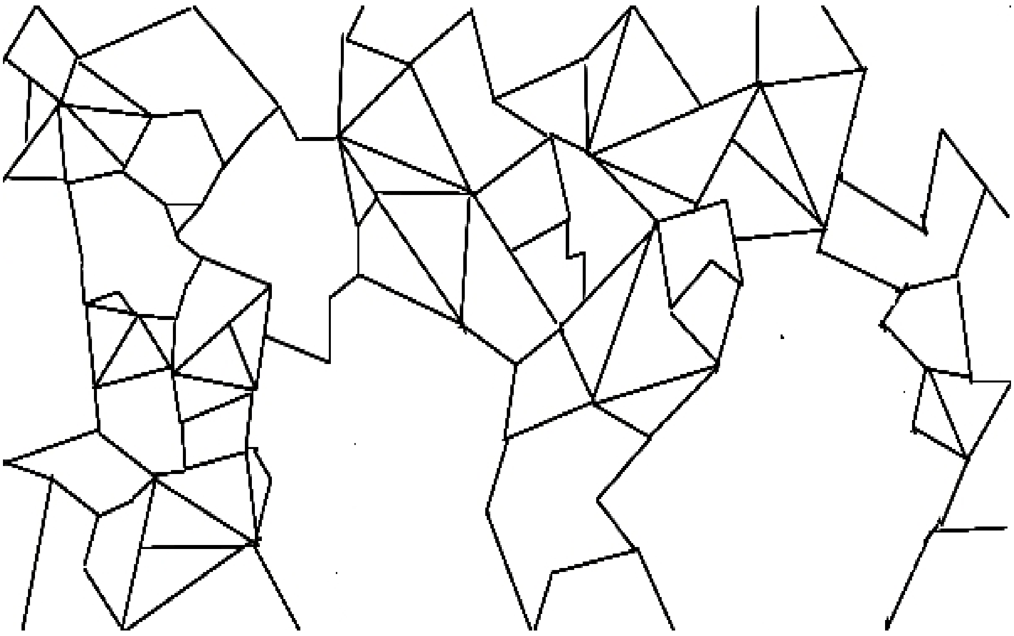

Fig. 7. The topology produced by the IRA4MN algorithm
Rys. 7. Topologia utworzona przez algorytm IRA4MN

The values of the used spatial density used here are mean values of the possible spatial density. Considering the XTC graph for given topology (see Fig. 6), we can see the sparser graph. Nevertheless, it retains some inference paths. Using the IRA4MN algorithm, we see that our algorithm generates the best graph (see Fig. 7). It preserves all optimal paths and loses a large number of interference paths. In comparison, the results are better than for the XTC graph.

Figure 8 displays the values of our metric for the various topologies of the communication graph. As seen from this figure, the total path interference coverage (TotalPathInterfCov) of all the topologies remains below 5 in the case of the XTC graph, and below 4 for the IRA4MN graph. We can see that the IRA4MN algorithm performs better than the XTC algorithm with respect to this metric.

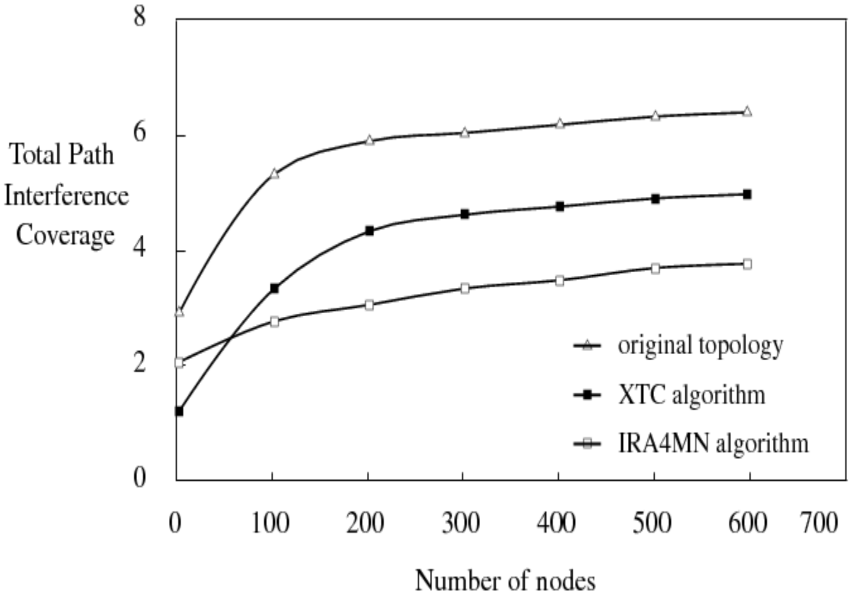

Fig. 8. The Total Path Interference Coverage for the XTC and IRA4MN algorithms in dependence of the number of nodes

Rys. 8. Suma pokrycia zakłóconych węzłów dla algorytmów XTC, IRA4MN w zależności od liczby węzłów

The running time of the IRA4MN algorithm is polynomial. We observed that in practice the running time of the algorithm is comparable to the most elementary heuristics

5. Conclusions

We showed that the direction neighbor coverage is a fundamental approach to topology control as it reduces interference in mobile ad hoc and sensor networks. In contrast to most other studies in this field we looked at the interference of entire paths in the direction of movement in the network. We proposed new interference metrics in relation to mobile network interference.

We also presented a new topology control algorithm, called IRA4MN that can produce an energy-spanning graph with reduced interference. We compared it with the XTC algorithm. It was evident that the IRA4MN algorithm performs better in the case of average edge interference Moreover, the majority of the paths in the mobile network had low interference.

In our future work we will use this algorithm as a tool in dynamic channel allocation strategies and control policies for mobility nodes in a mobile ad hoc and sensor network.

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Recenzent: Dr hab. inż. Andrzej Kwiecień, prof. Pol. Śląskiej

Wpłynęło do Redakcji 26 września 2008 r.

Omówienie

W pracy sformułowano model zakłóceń radiowych w ruchomych sieciach sensorowych i ad hoc. Obszary zakłóceń są w nim określone przy użyciu krawędzi grafu nieskierowanego (rys. 3). Dla potrzeb modelowania ruchomych sieci sensorowych i ad hoc zdefiniowano pokrycie skierowanego sąsiada w postaci stożka $a\widehat{u}b$ (rys. 4). Jest on połączeniem pokrytego obszaru węzłów *w* oraz *v*, gdzie węzeł *v* jest osiągalny przez *u* dzięki ruchowi. Przedstawiony w pracy algorytm IRA4MN redukuje obszar zakłóceń radiowych w ruchomych sieciach sensorowych i ad hoc. Jego działanie w pierwszej fazie polega na konstrukcji grafu Gabriela dla tego rodzaju ruchomych sieci, a następnie na rozpięciu na nim grafu o minimalnej energii dla transmisji komunikatu. W drugiej fazie, dzięki wykorzystaniu zdefiniowanego wcześniej pokrycia skierowanego sąsiada dla danego węzła, zastąpiono w nim te węzły, dla których istnieje mniejsze pokrycie skierowanego sąsiada. W badaniach symulacyjnych wykazano, że dla ruchomych sieci sensorowych i ad hoc suma pokrycia zakłóconych węzłów dzięki algorytmowi IRA4MN charakteryzuje się mniejszą liczbą węzłów, niż ma to miejsce w przypadku użycia algorytmu XTC, znanego z literatury i stosowanego w tego rodzaju rozwiązaniach. Oznacza to zmniejszenie zakłóceń w ruchomych sieciach sensorowych i ad hoc.

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