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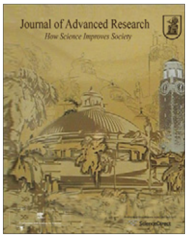

ORIGINAL ARTICLE

Power control algorithms for mobile ad hoc networks

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Abstract Power control algorithms are an important consideration in mobile ad hoc networks since they can improve network capacity and lifetime. Existing power control approaches in ad hoc network basically use deterministic or probabilistic techniques to build network topology that satisfy certain criteria (cost metrics), such as preserving network connectivity, minimizing interference or securing QoS constraints.

In this paper, we will provide a survey of the various approaches to deal with power control management in mobile ad-hoc wireless networks. We will classify these approaches into five main approaches: (a) Node-Degree Constrained Approach, (b) Location Information Based Approach, (c) Graph Theory Approach, (d) Game Theory Approach and (e) Multi-Parameter Optimization Approach.

We will also focus on an adaptive distributed power management (DISPOW) algorithm as an example of the multi-parameter optimization approach which manages the transmit power of nodes in a wireless ad hoc network to preserve network connectivity and cooperatively reduce interference. We will show that the algorithm in a distributed manner builds a unique stable network topology tailored to its surrounding node density and propagation environment over random topologies in a dynamic mobile wireless channel.

Introduction

The primary goal of the power control algorithm in mobile ad hoc networks is to achieve performance requirement such as network connectivity. Not only can they improve network capacity but also node's battery capacity. Thus, power control algorithm is an important consideration for mobile ad hoc networks.

Without a central node to administer power control, improving network topology with energy efficient communication is more challenging in ad hoc wireless networks. Further, if the ad hoc network is large consisting of thousands of nodes,

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collecting information from all the nodes and passing it to the concerned nodes lead to high overheads. Thus, distributed topology control algorithms that are asynchronous, scalable and localized are particularly attractive for ad hoc networks.

Further to simplify deployment and reconfiguration, the power control algorithm must adapt to the surrounding node density, mobility and the physical environment. Pradhan and Saadawi [1] show that the topology and performance of a mobile ad hoc network significantly depends on the surrounding physical environment and node mobility. Accordingly, Pradhan and Saadawi [2] make a strong argument for a distributed power control algorithm that develops a strongly connected network able to adapt to changing network conditions.

In this paper, we will provide a survey of various approaches to deal with power control management in mobile ad hoc networks. We will classify these approaches into Node-Degree Constrained Approach, Location Information Based approach, Graph theory approach, Game theory approach and Multi-Parameter Optimization approach. We will further present an example of a Multi-Parameter Optimization approach called DISPOW to preserve network connectivity, improve the network lifetime and cooperatively reduce interference. The generic network layer power management algorithm DISPOW, provides an energy efficient strongly connected network tailored to the surrounding node density, physical environment and node mobility. We will also provide analytical and simulation evaluation of DISPOW over the dynamic wireless channel.

Rest of the paper is organized as follows: 'Power Control Algorithms' surveys and attempts to classify the power control algorithm in mobile ad hoc networks. The DISPOW algorithm is also presented, analyzed and evaluated in 'Distributed power management algorithm, DISPOW'. 'Conclusion' section concludes this paper.

Power control algorithms

Existing power control approaches in the ad hoc network basically use deterministic or probabilistic techniques to build network topology that satisfies certain cost metrics, such as, preserving network connectivity, minimizing interference or securing QoS constraints.

Early approaches in power control techniques were mostly centralized and attempted to find a complete set of transmission power for the nodes with the purpose to minimize the total power consumption as shown by Kirousis et al. [3], Narayanaswamy et al. [4], Calinescu et al. [5] and Cheng et al. [6].

For an ad hoc network with a large number of nodes, it becomes difficult to calculate the optimal transmission range for all the nodes. Furthermore, collecting information of all the nodes and passing them to the concerned nodes lead to high overheads. Ad hoc networks, unlike cellular radio systems, do not have a central scheduler and, therefore, power control algorithms for ad hoc networks must be scalable and localized.

Power control algorithm approach to building network topology can mainly be summarized as follows:

Node-degree constrained approach

The degree of a node is defined as the total number of links it has with other nodes in the network. If $k(i)$ is the degree of node i in the network of N nodes, then the average node degree is

$$k_{\text{mean}} = \frac{1}{N}\sum_{i=1}^{N} k(i) \tag{1}$$

A node i of degree $k(i) = 0$ is isolated, i.e., it has no neighbors. Different nodes in the network can have different degrees and the minimum node degree of the network is given by

$$k_{\min} = \min_{\forall i \in N} k(i) \tag{2}$$

The Degree Distribution Function $P(k)$ of a network is defined as the probability that nodes in the network has exactly k neighbors.

Power control algorithms were initially proposed to preserve connectivity by selecting transmit power for nodes so that the nodes are connected with at least one neighbor. Algorithms proposed by Li et al. [7,8] and Wattenhofer et al. [9] provide a distributed approach on theoretical lower bound on node degree for network connectivity.

However, nodes with at least one neighbor make the network vulnerable to node and link failures. Networks can be made more robust by requiring each node to have at least a certain number, K, neighbors. Specifically,

$$k(i) \geqslant K \quad \forall \text{ node } i \text{ in } \{1, 2, \ldots, N\} \tag{3}$$

Such a network is said to be K-connected. If (K-1) nodes fail, the network is still connected. Algorithms, such as Local Information No Topology (LINT) and Local Information Link-State topology (LILT) proposed by Ramanathan and Rosales-Hain [10], collect routing information and adjust transmit powers of the nodes to maintain a desired number of neighbors for each node in the network.

A pair of nodes acting in such a distributed manner might develop an asymmetric link, meaning the link exists in only one direction. The link coming into the node from its neighbor is called the incoming link and the link from the node to its neighbor is called the outgoing link. This is a major drawback of these distributed attempts as most of the routing algorithms do not use asymmetric links to route packets. Additionally, such asynchronous links can be a major source of interference.

Algorithms such as Common Power (COMPOW) proposed by Kawadia and Kumar [11] overcome this problem by assigning a common power to all the nodes in the network to guarantee a lower bound node degree. This, however, requires that nodes communicate with each other to select a common transmit power leading to a significant increase in overhead. Such approaches are not scalable as the overhead increases with the size of the network. Blough et al. [12] goes further to select a common transmit power for all the nodes in the network such that the communication graph is connected with at least k-neighbors over a uniformly distributed network.

However, common power strategies depend on few nodes isolated in the network by physical location and environment. These isolated nodes might lead to unnecessarily high common node power causing inter-node interference in denser part of the network.

Location information based approach

Power control algorithm can benefit from location information of nodes in the network. Node equipped with directional antenna can utilize the geographical knowledge of their neighbors to significantly reduce interference in the network. This can lead to a considerable increase in network performance.

GPS systems were initially used to get location information of nodes in the network. However, fitting a GPS in every node might not be pragmatic for mobile ad hoc network because of its large delay in data acquisition and unavailability in certain conditions such as indoor environments. So, a localized technique of estimating the direction of the incoming signal from the Angle of Arrival (AoA) or Time Difference of Arrival (TDOA) at different elements of the antennas seems more feasible.

Nodes can have three types of directional antenna systems: the switched beam antenna system, the steered beam antenna system and the adaptive antenna system.

The switched beam antenna system has sets of M antennas capable of covering all directions as shown in Fig. 1. It consists of several highly directive fixed, pre-defined beams of width θ equal to $2\pi/M$ and a coverage area, A_s. Nodes are able to transmit through one, multiple, or all sectors at one time, thus capable of unicast, multicast or broadcast communications.

Based on switch beam antenna systems, a topology-control problem can be formalized as follows. Let us consider in a network of N nodes in an area A, each node is equipped with switched-beam antenna that consists of M sectors. Li et al. [13] proposes a Cone-Based Topology Control (CBTC) algorithm which takes advantage of this directional information by varying the transmission power of each node such that there is at least one neighbor in every cone of the angle, θ, centered at the node. It is further shown by Li et al. [14] that $\theta \leqslant 5\pi/6$ is necessary and sufficient condition to guarantee connectivity of the network. Further, Huang et al. [15] presents an implementation of Cone-Based Topology Control to maintain fewer and closer neighbors in different antenna sectors. These algorithms require every node to be capable of computing angle of arrival (AOA) or sector of arrival for its neighbor's location information.

Adaptive antenna systems consist of multiple antenna elements at the transmitting and/or receiving side of the communication link, whose signals are processed adaptively in order to exploit the spatial dimension of the mobile radio channel. Depending on whether the processing is performed at the transmitter, receiver, or both ends of the communication link, the adaptive antenna technique is defined as multiple-input signal-output (MISO), single-input multiple output (SIMO), or multiple-input multiple-output (MIMO).

Directional antenna has the potential of providing drastic improvement in the capacity and performance of ad hoc networks as shown by Huang et al. [16]. Ramanathan [17] shows that beam forming technique can significantly improve the throughput and decrease end-to-end delay in the network. Further attempts to use the directional antenna at every node to create low-interference and low-cost network topologies are presented by Kumar et al. [18] and Raman and Chebrolu [19]. Another algorithm proposed by Huang and Shen [20] attempts to adjust the power intensity independently in each direction of a multi-beam directional antennas to reduce the hop count in the network topology.

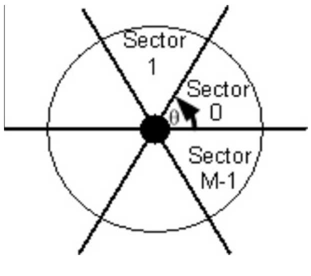


Fig. 1 Directive sector of a switched beam antenna system.

Graph theory approach

Graph theory mainly involves placing graphs with vertices as points in space and the edges as line segments joining select pairs of these points. It deals with ways to represent the geometric realization of graphs. Because of its inherent simplicity, graph theory has a very wide range of applications in topology control.

Graph theory optimization can be applied to ad hoc networks to build a topological graph G that minimizes some kind of cost function. The finite collection of nodes can be considered as the vertices of the graph. The wireless links between the nodes can be considered as the edges of the graph. Therefore, an ad hoc network can be represented by a topological graph G consisting of N set of nodes and L set of links.

If no loops and parallel links between the nodes are considered, the topological graph is considered to be simple. Further, a simple graph is said to be strongly connected if for each node u and v in $\{N\}$, there exists a path from u to v and from v to u.

A Relative Neighborhood Graph (RNG) T of the graph $G = (N, L)$ is defined as $T = (N, L')$ where there is a link between node u and node v if and only if there is no other node $w \in N$ that is closer to either u and v than the distance between u and v. Formally,

$$\max\{d(u,w), d(v,w)\} < d(u,v) \tag{4}$$

where $d(u, v)$ is the Euclidean distance between the two nodes. An example of the RNG on a random ad hoc network is shown in Fig. 2.

RNG is a subgraph of the Delaunay Triangulation (DT) and has been implemented in the topology control algorithm proposed by Cartigny et al., [21] to reduce the number of links between a node and its neighbors.

Another subgraph T of the graph $G = (N, L)$ without any cycles from node u to v is called a Tree. A tree is one of the most important kinds of topological graphs. A tree T is said to be a spanning tree of the graph G if it is a subgraph connecting all the nodes in the set $\{N\}$. The spanning tree can only be

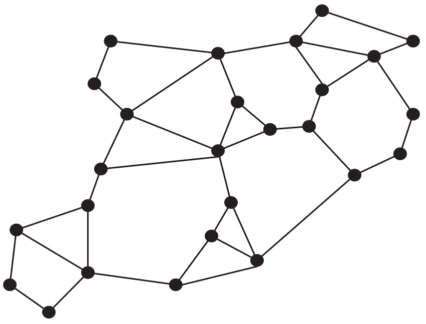


Fig. 2 Relative neighborhood graph (RNG) of a random ad hoc network.

defined for a connected graph as a disconnected graph does not have connected paths to every node in the network. In other words, a graph G that connects all the nodes without any circuits is its own spanning tree. If there are circuits in the graph G, then a spanning tree T can be obtained by deleting the edge until a connected circuit-free graph is reached.

A graph in which each edge is assigned a weight is known as a weighted graph. If the graph G is a weighted graph, then the weight of the spanning tree T is defined as the sum of the weights of all the braches in T. A weighted graph G can have different spanning trees of varying weight. However, the spanning tree with the smallest weight is called a shortest spanning tree or shortest-distance spanning tree or minimal spanning tree (MST). Fig. 3 shows an MST of a random ad hoc network. Li et al. [22] introduces a Local Minimum Spanning Tree (LMST) algorithm independently builds a MST for each node in the network keeping only one-hop on-tree nodes as neighbors.

The 1-connectivity tree might be cost-efficient but it is susceptible to link failures. To improve reliability, Local Tree-based Reliable Topology (LTRT) presented by Miyao et al. [23] adds the concept of Tree-based Reliable Topology (TRT) in LMST to guarantee K-edge connectivity.

Further, Zhang and Labrador [24] presents a MST based energy-aware topology control algorithm that considers node residual energy information known as Residual Energy Aware Dynamic (READ). Li et al. [25] and Moscibroda and Wattenhofer [26] present frameworks on developing low-interference topologies. Feng et al. [27] proposes the Minimum Interference Algorithm (MIA) that looks at interference between links and tries to minimize the overall interference in their network graph model. Another algorithm presented by Jia et al. [28] further builds a topology graph to meet QoS requirements such as end-to-end traffic and delay.

Game theory approach

If the nodes in the network can be considered as rational players with an intention to maximize their own objectives, then the power control algorithm for ad hoc wireless networks can be based on game theory. A game is a well-defined strategic form consisting of the following elements:

1. the set $n = \{1, 2, \ldots, N\}$ of players,
2. for every player $i \in N$, the set S_i of strategies (or choices) available to player i
3. the set of possible payoffs P

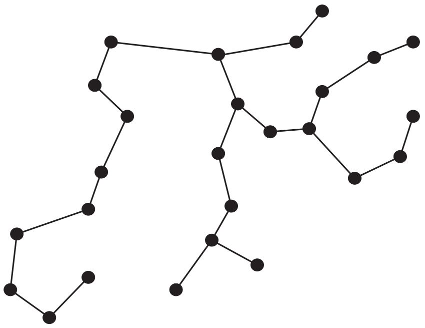


Fig. 3 Minimum spanning tree (MST) of a random ad hoc network.

It attempts to define and propose a solution or objective for a strategic situation where gains or payoffs of each node depends not only on its own decision but also on the decisions taken by other nodes in the network.

Based on the interdependence among the players, game theory is divided into non-cooperative and cooperative game theories. Cooperative game theory deals with situations where there are institutions that make agreements among the players binding. Players act together in different combinations with a common purpose to maximize payoff acceptable to all the players or coalitions of players satisfying some desirable properties.

In non-cooperative game theory, all the moves are available to the players and they make their decision independently based on those information. There are no contracts or agreements between the nodes because there is no external authority or institution to enforce them or communication between the nodes are not possible or allowed.

Non-cooperative game theory can be very useful in modeling and understanding multi-node power control problems characterized by their interdependency. Eidenbenz et al. [29] presents a framework for a utility-based topology control algorithm to encourage selfish nodes to work for members of a network when the network is established.

In a multi-player non-cooperative game, there can be a state known as the Nash Equilibrium, where no player can improve his or her payoff by unilaterally changing their strategy. Sun et al. [30] proves that a unique Nash equilibrium exists in a non-cooperative power control game where, each rational player tries to maximize its utility function. Komali et al. [31] also studies the Nash equilibrium properties of a non-cooperative topology control game with selfish nodes and evaluates the efficiency of the induced topology when nodes employ a greedy best response algorithm.

Multi-parameter optimization approach

Another approach is a dynamic multi-parameter optimization of different parameters, such as connectivity, interference and energy consumption of the network. We present a localized algorithm DISPOW in 'Distributed power management algorithm, DISPOW' that develops a strongly connected network topology in a completely distributed manner tailored to its surrounding node density and propagation environment. It will adapt to the changing network topology due to the node mobility and dynamic physical environment. DISPOW not only has a receiver-based interference model which attempts to lower inter-node interference but also has the capability of converting asymmetric link, which is a major source of concern, to symmetric link if required. It should be noted that DISPOW, by operating in a completely distributed manner, is scalable and readily applicable to large heterogeneous networks.

Distributed power management algorithm, DISPOW

In this algorithm, shown in Table 1, nodes periodically check their connectivity, interference level and battery power.

Problem definition

Let us define $P_{T_i}(t)$ and $\psi_i(t)$ as the transmitting power and connectivity of node i at time t in the network of N nodes in an area A. Then by definition, DISPOW selects

Table 1 Distributed power management algorithm (DISPOW).

```
DISPOW.Node
Set $P_{T_i} = P_{T_{\text{initial}}}$, compute $\psi_i$ and set timer = $\tau_{\text{ld}}$
If $\psi_i \leqslant \psi_{i_{\min}}$, then DISPOW.LowConnectivity
Else if $C_i < C_{i_{\text{critical}}}$, then DISPOW.CriticalBatteryLevel
Else if $\psi_i \leqslant \psi_{i_{\max}}$, then DISPOW.HighConnectivity
Compute connectivity degree, $\psi_{\text{DEG}_i} = \frac{\psi_i - \psi_{i_{\min}}}{\psi_{i_{\max}} - \psi_{i_{\min}}}$
If PowerDown_Request received, then
    DISPOW.PowerDown_Request
If PowerUp_Request received, then
    DISPOW.PowerUp_Request
If suffering from interference, then DISPOW.Interference
Sleep until timer expires
DISPOW.LowConnectivity
If $P_{T_i} = P_{T_{i\max}}$,, then calculate $P_{T_i} = P_{T_i} + \Delta P$ and
    set timer = $\tau_{\text{sd}}$
Else set timer = $\tau_{\text{ld}}$
If No Asymmetric link to itself, then
    broadcast PowerUp_Request and set timer = $\tau_{\text{md}}$
DISPOW.HighConnectivity
If $P_{T_i} = P_{T_{imax}}$,, then calculate $P_{T_i} = P_{T_i} - \Delta P$ and set
    timer = $\tau_{\text{sd}}$
Else set timer = $\tau_{\text{ld}}$
DISPOW.Interference
Broadcast PowerDown_Request
Set TTL and hop count
DISPOW.PowerUp_Request
If $\psi_{\text{DEG}_i}$ in high range, then calculate $P_{T_i} = P_{T_i} + \Delta P$ and
    timer = $\tau_{\text{sd}}$
Else set timer = $\tau_{\text{ld}}$
DISPOW.PowerDown_Request
If $\psi_{\text{DEG}_i}$ in high range, then calculate $P_{T_i} = P_{T_i} - \Delta P$ and
    timer = $\tau_{\text{sd}}$
Else set timer = $\tau_{\text{ld}}$
DISPOW.CriticalBatteryLevel
If $\psi_{\text{DEG}_i}$ in high range, then calculate $P_{T_i} = P_{T_i} - \Delta P$ and
    timer = $\tau_{\text{sd}}$
Else set timer = $\tau_{\text{ld}}$
```

$$P_{T_i}(t) \quad \forall \text{ node } i \text{ in } \{1,2,\ldots,N\}$$

subjected to the following four constraints:

1. The node should have at least minimum connectivity, ψ_{imin}, i.e. minimum acceptable number of neighbors with which the node has a bi-directional link at any time t.

$$\psi_i(t) \geqslant \psi_{i_{\min}}(t) \quad \forall \text{ node } i \text{ in } \{1,2,\ldots,N\} \tag{5}$$

2. For a packet from node j to node i to be correctly detected, signal to interference and noise ratio at node i, SINR_{ji}, must be greater than a threshold, γ_{th}

$$\text{SINR}_{ji}(t) = \frac{P_{ji}(t)}{P_0 + \sum_{\substack{k \in N \\ k \neq j}} P_{ki}(t)} \geqslant \gamma_{th} \quad \forall \text{ node } i \text{ in } \{1,2,\ldots,N\} \tag{6}$$

where T is the set of transmitting nodes causing interference, P_{ki} the received power levels from node k to node i and P_0 thermal noise.

The node should not transmit at such a high level that it causes interference to other nodes in the neighborhood. Specifically, the algorithm will try to reduce the total noise power P_{N_i} in node i, i.e.

$$\min P_{N_i} \quad \forall \text{ node } i \text{ in } \{1,2,\ldots,N\} \quad \text{where } P_{N_i} = P_0 + \sum_{\substack{k \in N \\ k \neq j}} P_{ki}(t). \tag{7}$$

If a node has high node connectivity, then it can probably afford to decrease its transmitting power P_T and still maintain acceptable ψ. Let $\psi_{i_{\max}}(t)$ be the maximum number of neighbors allowed, i.e. the upper acceptable connectivity threshold. This has an advantage of decreasing inter-node interference in the network.

$$\psi_i(t) \leqslant \psi_{i_{\max}}(t) \quad \forall \text{ node } i \text{ in } \{1,2,\ldots,N\} \tag{8}$$

3. The P_{T_i} for node i should be more than the minimum power level, $P_{T_{imin}}$, but less than the maximum power level, $P_{T_{imax}}$, defined by network and node power specifications.

$$P_{T_{imin}} \leqslant P_{T_i}(t) \leqslant P_{T_{imax}} \quad \forall \text{ node } i \text{ in } \{1,2,\ldots,N\} \tag{9}$$

4. The algorithm also tries to conserve node's battery capacity, $C(t)$, which is an important design consideration for mobile ad hoc networks. The algorithm will only allow the nodes to increase their P_T if their C is higher than the critical battery power level, C_{critical}.

$$C_i(t) \geqslant C_{i_{\text{critical}}} \quad \forall \text{ node } i \text{ in } \{1,2,\ldots,N\} \tag{10}$$

Now, if ψ_i is less than $\psi_{i_{\min}}$ for node i, it will attempt to improve its ψ_i by increasing P_{T_i}. It can only increase P_{T_i} if it is lower than $P_{T_{imax}}$. The node checks if there are any uni-directional links from other nodes. If there are, it will try to build bi-directional links with those potential neighbor nodes. It increases its P_{T_i} by an increment ΔP and checks after a short time delay, τ_{short_delay}. If there are no uni-directional links to the node, then the node can only create uni-directional link by increasing its P_{T_i}. Thus it's equally important for the potential neighbor to try to establish a link with it too. Hence, the node increases its P_{T_i} and broadcasts a *PowerUp_Request*. It then waits for medium time delay, τ_{medium_delay}, to check if it managed to set up any new link. Since it is trying to construct link with nodes that are not its neighbors, the maximum hop count for *PowerUp_Request* is set at 2. It should not be set too high because nodes transmitting at high P_{T_i}can interfere nearby nodes. Thus, it will eventually select the lowest P_{T_i}that will create bi-directional link.

Now if the node moves into a dense area, it can probably afford to decrease its P_T and still maintain acceptable network connectivity. This has an advantage of reducing inter-node interference in the network. So if ψ_i is higher than $\psi_{i_{\max}}$, it decreases its P_{T_i} and checks its ψ_i after τ_{short_delay}.

A node i will broadcast *PowerDown_Request* if it is suffering from interference. It sets the maximum hop count for the request to 2 to prevent forwarding overhead. It also sets *Request_TTL* (Time To Live) so that older requests are ignored.

If a node receives a *PowerDown_Request*, it will decrease its P_i if its ψ_i is in a higher acceptable range. When it changes its P_i, it checks its ψ_i after τ_{short_delay}. Otherwise, it sets the timer to long time delay, τ_{long_delay}, to avoid excessive calculations and overhead from frequent changes in P_i. If it receives a *PowerUp_Request*, it increases its P_i only if its ψ_i is in the lower acceptable range. It then waits for τ_{short_delay} to check its ψ_i. A node will forward other node's requests if they have a valid *Request_TTL* and hop count.

If at any instance the C_i is not sufficient, i.e. less than $C_{icritical}$, it will reduce its P_{T_i} to maintain $\psi_{i_{\min}}$. This has an effect of prolonging node battery and network lifetime.

Theoretical transmit power lower bound

Now modeling the wireless channel propagation model with the log-distance path loss and fading propagation model, for a receiver at a distance *d*.

For a correct reception of packet in a receiver at a distance of *d*, P_{T_i} should be enough to overcome the propagation loss and meet the receiver sensitivity, P_{rs}. Now modeling the wireless channel propagation model with the log-distance path loss and fading propagation model, P_{T_i} can be defined as

$$P_{T_i}\,\mathrm{d}B \geqslant P_{rs}\,\mathrm{d}B + P_L(d_0) + 10\eta\log(d) + L_{\mathrm{Fading}}. \tag{11}$$

If node density, ρ, is defined as the number of uniformly distributed nodes in a unit square area then the number of uni-directional neighbor of node *i* in its coverage area is given by

$$\psi_i = \pi\rho(\kappa P_{T_i})^{\frac{2}{\eta}} - 1. \tag{12}$$

Clearly, ψ directly depends on ρ, propagation environment (η) and P_T.

DISPOW adjusts node's P_T to maintain at least $\psi_{i_{\min}}$. Thus, the mathematical lower bound P_{T_i} to guarantee $\psi_{i_{\min}}$ is given in (9).

$$\text{Lower bound :}\quad P_{T_i} \geqslant \frac{1}{k}\left(\frac{\psi_{i_{\min}}+1}{\pi\rho}\right)^{\frac{\eta}{2}}. \tag{13}$$

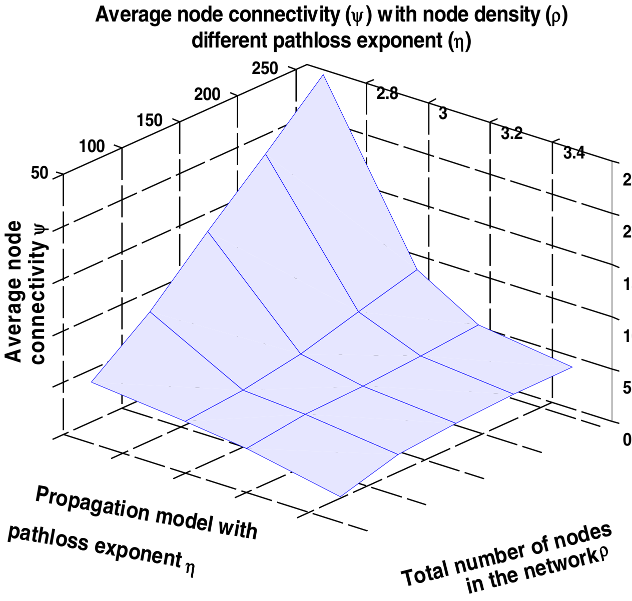


Fig. 4 Connectivity of nodes with DISPOW in the network depends on their surrounding node density and propagation environment.

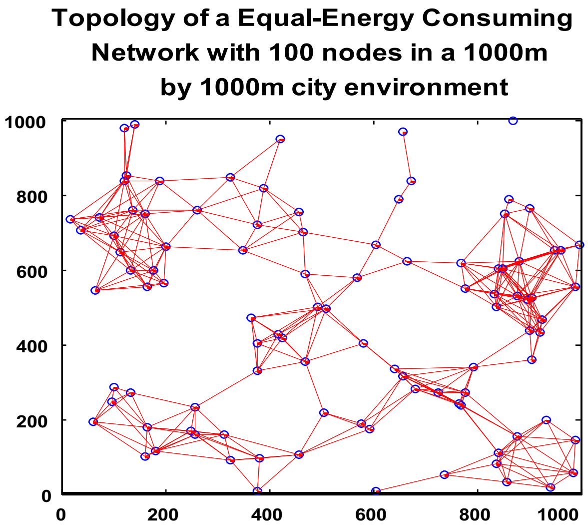
Therefore, it is clearly seen that a node can preserve its ψ by tailoring its P_T to ρ and the propagation environment. For example, in a city environment, characterized by path loss exponent of 3.2, a node can adjust its P_T between its $P_{T_{\min}}$ and $P_{T_{\max}}$ to maintain its ψ between 2 and 14.

Fig. 4 highlights the variation in parameter used by routing protocol because of node distribution, node mobility, dynamic nature of wireless channel and environment. DDISPOW adapts to its surrounding environment and provides strongly connected reliable.

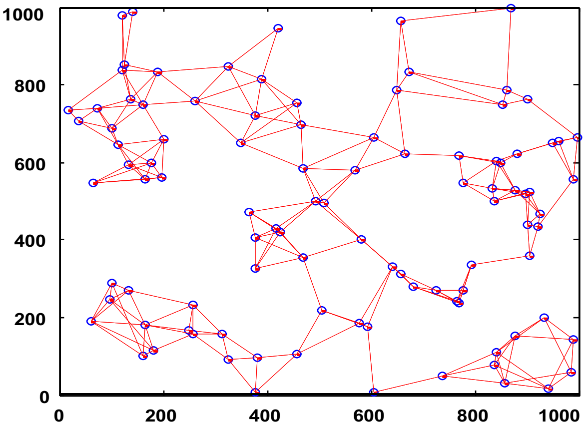
Simulation results

The performance of DISPOW on a dynamic network of 100 nodes distributed over a 1000 m by 1000 m urban area, such as a city characterized by no LOS path and multipath effects, is evaluated through simulations carried out in MATLAB and OPNET network simulator.

Fig. 5 shows topology of a random equal energy consuming network with common P_T and with DISPOW. As clearly seen from Fig. 5a, the common node power scheme leads to denser



a) with common power level



b) with DISPOW Algorithm

Fig. 5 Network topology with power control, with DDISPOW and equal energy consuming network with common node power.

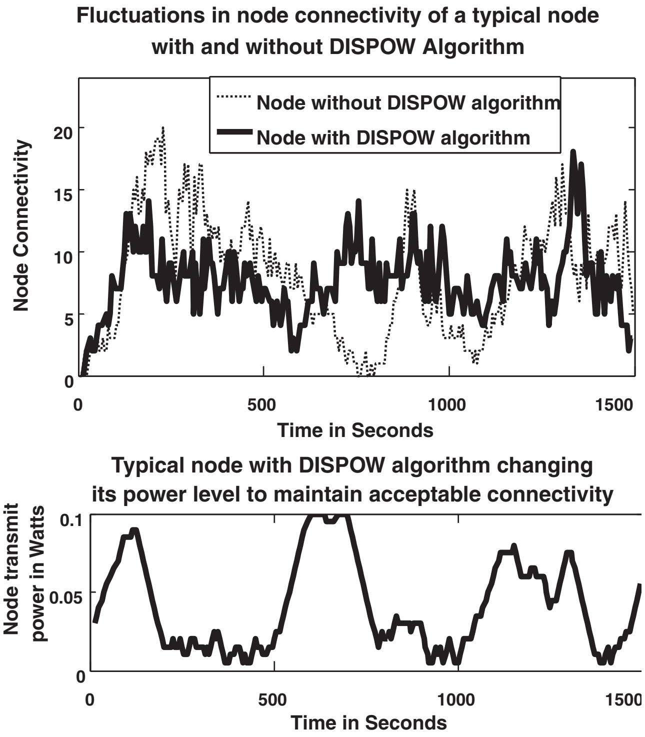


Fig. 6 Fluctuation of connectivity of a typical node and how DISPOW algorithm selects its power level to maintain acceptable connectivity.

clusters but more importantly it leaves out to sparsely connected nodes even some totally disconnected from the network. However with DISPOW, it is clear that every node individually selects P_T that satisfies the parameters of the algorithm. It is interesting to note that two-third of the nodes have their P_T less than the average P_T and only about one-tenth of the nodes have $P_{T_{\max}}$. Further, DISPOW algorithm yields a 32% reduction in average total interference in an equal energy consuming network.

Fig. 6 shows that ψ of a typical node initially increases to 20 and then steadily decreases as it moves to a low ρ area even becoming zero (i.e. the node is totally disconnected) around 700–800 s during the simulation. It is clearly seen that ψ severely fluctuates during simulation and the node may even become completely disconnected from the network.

Conclusion

Power control algorithm basically uses deterministic or probabilistic techniques to build network topology. Node degree, thus becomes an important parameter of a connected network. Therefore, many topology control schemes evaluate their effectiveness by studying the degree of nodes in the network.

We have classified power control algorithm based on their approaches. Node-degree constrained approach provides a mechanism to provide a theoretical lower bound on node degree to build network topology. Algorithm based on location information attempts to benefit from geographical location of nodes using directional antenna. Another approach is to build a network graph that minimizes some kind of cost function. Yet another approach is to model the interaction among the nodes in the network using game theory to maximize their own objectives.

We also presented an example of the multi-parameter optimization approach algorithms, DISPOW, which adaptively manages nodes' power in a dynamic wireless ad hoc mobile network to preserve the network connectivity, conserve energy consumption and reduce interference cooperatively. DISPOW builds a stable strongly connected network tailored to its surrounding node density and propagation environment. It is also shown that DISPOW adapts better to the changes in the network due to node mobility and dynamic wireless channel variations.

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