ADAPTIVE POWER MANAGEMENT ALGORITHM IN MOBILE AD HOC NETWORK

by

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Abstract

DISTRIBUTED POWER MANAGEMENT ALGORITHM IN MOBILE AD HOC NETWORK

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This thesis addresses the importance and the necessity of distributed power management algorithms that adapts to the changing physical environment and network topology in Mobile Ad Hoc Network (MANET). Ad hoc networks are a self-organizing systems formed by the cooperating nodes within a communication range. Routing protocols are responsible for enabling nodes in ad hoc network to communicate with each other over an error prone wireless channel. A key component that achieves and maintains connectivity between the nodes in the network is the power control algorithm. However, without a central node to administer the power control, building network topology is more challenging in wireless ad hoc networks. Further, if the ad hoc network is large consisting of thousands of nodes, then collecting information from all the nodes and passing it to the concerned nodes lead to high overheads. Thus, distributed power control algorithms that are asynchronous, scalable and localized are particularly attractive in MANET.

We propose a distributed power management algorithm (DISPOW) that adaptively manages the transmit power of nodes in MANET to preserve network connectivity. It builds a unique stable topology in a completely distributed manner tailored to its surrounding non-uniform node density and propagation environment. However, a node in order to be strongly connected can

increase its power indiscriminately causing interference. Also, asymmetric links developed by distributed algorithm are a major source and interference and most of the routing algorithms do not use them to route packets. DISPOW with a receiver-based interference model not only co-operatively reduces inter-node interference but also convert asymmetric links to symmetric links if required. The adaptive optimization algorithm is shown to provide robust strongly-connected network with improved performance.

Another proposed algorithm, distributed power management algorithm with directional antenna (DDISPOW), highlights the benefits of using directional antenna with power control algorithms. Smart antenna techniques can increase channel utilization and be an effective technique in reducing interference in a network.

To demonstrate the performance and capability of the proposed algorithms, DISPOW and DDISPOW, we have evaluated them in a realistic ad hoc network through theoretical and simulation analyses. Modeling the complex propagation and fading losses a signal experiences over a dynamic wireless channel is an integral part of a realistic ad hoc network. It affects the connectivity and stability of a network and crucial parameters of different protocols. Traditional disk propagation model, free space propagation model or the 2 ray model do not model the realistic physical environment where there are several multi-paths of similar strength and the propagation range is limited by batteries. Additionally, interference from other nodes in multi-user system acts as noise and can be more significant than background thermal noise. A multi-user wireless networks are generally interference-limited rather than noise-limited.

Therefore, the log-distance path loss model, random log-normal shadowing model and the Rayleigh fading model is used to model the wireless channel in different environment such as a city or an open area. Analyzing the performance of the network over a city and a rural environment led to two distinctly different results. Higher attenuation and degradation of wireless links in urban environment induced longer packet delay and more overheads and consequently lower throughput. Further, node mobility introduces additional fading and frequent changes in topology. This change in topology has to be reported throughout the network increasing routing overheads. Thus, it is crucial for power control algorithms in a mobile wireless network to adjust and adapt to the dynamic topology and physical environment.

A comparative study of the proposed distributed algorithm with common power strategies in literature illustrates the superior network performance of DISPOW and DDISPOW. The algorithms effectively maintain network connectivity and reduce inter-node interference. They alleviate the dependency of common power strategy on few nodes that are isolated in the network because of their physical location and surrounding network environment. Detail analyses show that DISPOW and DDISPOW are energy efficient and significantly improve the performance of wireless networks.

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Acronyms

AAS	Adaptive Antenna System
AoA	Angle of Arrival
AODV	Ad hoc On-demand Distance Vector
APRL	Any Path Routing without Loops
BER	Bit Error Rate
BTS	Base Transceiver Station
CBTC	Cone-Based Topology Control
CEDAR	Core Extraction Distributed Ad Hoc Routing
COMPOW	Common Power
DDISPOW	Distributed Power Management Algorithm with Directional Antenna
DISPOW	Distributed Power Management Algorithm
DSR	Dynamic Source Routing
DT	Delaunay Triangulation
LILT	Local Information Link-State topology
LINT	Local Information No Topology
LMST	Local Minimum Spanning Tree
LOS	Line of Sight
LTRT	Local Tree-based Reliable Topology
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MIA	Minimum Interference Algorithm
MIMO	Multiple-Input Multiple-Output

MISO	Multiple-Input Signal-Output
MPR	Multipoint Relay
MST	Minimal Spanning Tree
NCR	Normalized Convergence Rate
ODMRP	On-Demand Multicast Routing Protocol
OLSR	Optimized link-state routing Protocol
PCMA	Power Control Multiple Access
QoS	Quality of Service
READ	Residual Energy Aware Dynamic
RNG	Relative Neighborhood Graph
RWMM	Random Waypoint Mobility Model
SIMO	Single-Input Multiple-Output
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
STARA	System- and Traffic-dependent Adaptive Routing Algorithm
TC	Topology Control
TDOA	Time Difference of Arrival
TRT	Tree-based Reliable Topology
ZHLS	Zone-based Hierarchical Link State
ZRP	Zone Routing Protocol

Chapter 1

Introduction

Ad hoc networks are a self-organizing systems formed by co-operating nodes with a communication range to from an infrastructure-less networks. They can be rapidly deployed anywhere and anytime where is very attractive for tactical communication.

One of the key components required for communication in such network is a routing protocol. Larger number of nodes spread in the environment with limited resources such as bandwidth makes routing packets in ad hoc networks extremely challenging. The routing protocol has to find the path from source node to the destination node through intermediate nodes used as multi-hop relays to route packets minimizing routing overheads. The routing protocol should be designed to tackle the erroneous wireless channel and the resource constraints in the network.

The key component that achieves and maintains connectivity between the nodes in the network is the power control algorithm. Without a central node to administer power management similar to cellular networks, improving network topology with energy efficient communication is more challenging in ad hoc wireless networks.

The dynamic wireless channel places fundamental limitations on the performance of the ad hoc networks. A signal propagating through wireless channel experiences path loss which limits its range. The signal also goes through reflection, diffraction scattering. Due to multiple reflections, the signal can propagate through different paths of varying lengths before reaching the destination node. This several versions of the signal give rise to multi-path fading. The path loss and fading effects determines the quality of a communication link. Since the metrics such as available bandwidth or delay experienced by the packet is taken into consideration while routing the packet, the propagation model is an important consideration in modeling ad hoc wireless network.

1.1 Ad hoc routing protocol

The routing protocol is responsible for exchanging the route information and finding a feasible path to a destination based on metrics such as hop count and delay. It must be able to use limited resources such as bandwidth and battery power. The routing protocol must also be adaptive to the frequent topology changes caused by the mobility of nodes. Due to the frequent changes in the network topology, maintaining consistent topological information at all the nodes involves more control overhead. The increase in control overhead means more bandwidth wastage. The routing protocol must also keep the number of packet collisions to a minimum by limiting the number of messages broadcasted by the nodes in the network.

Routing protocols for ad hoc wireless networks can be classified into several types based on criteria such as information organization and update mechanism. Protocols are generally divided into proactive or table-driven routing protocols, reactive or on-demand routing protocols and hybrid routing protocols.

1.1.1 Proactive or table-driven routing protocol

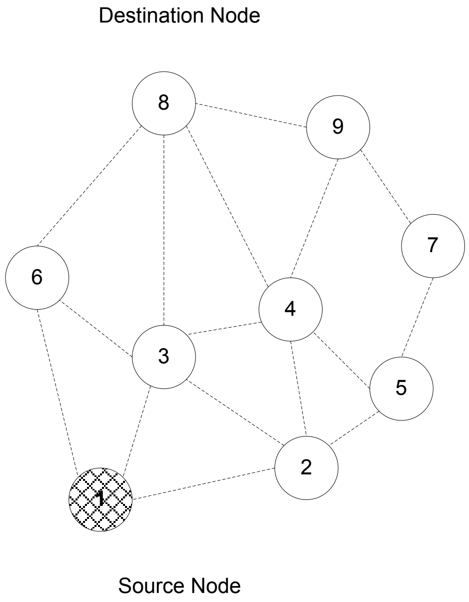
In proactive or table-driven routing protocols, every node maintains the topology information of the network in the form of routing tables by exchanging routing information at fixed intervals. Routing information is generally flooded in the whole network to maintain the global topology information in the form of routing tables at every node. In order to maintain consistent and accurate network status information, these node routing tables are frequently updated. These tables are routinely exchanged between neighbors to keep up-to-date view of the network topology. The tables are also forwarded if a node observes a significant change in the local topology.

Whenever a node requires a path to a destination, it runs an appropriate path-finding protocol based on the topology information it maintains in its routing table. The routes to all the destinations are readily available at every node at all times. This has an advantage of minimizing delay in obtaining a route when initiating traffic to a destination. Also, reachability of the destination can be quickly determined.

An example of protocol routing protocol is the Dynamic Destination-Sequenced Distance-Vector Routing Protocol (DSDV). In DSDV, ever node maintains a routing table that lists all available destinations, the number of hops to reach the destination and the sequence number assigned by the destination node. The nodes exchange the routing table periodically or when a significant change occurs in the network topology. So, the update is both time-driven and event-driven.

The routing table for the source node, node 1, in an ad hoc network of 9 nodes is shown in figure 1-1. If the source node has to send a packet to node 9, it looks up the routing information such as the next node and distance to the destination in its routing table.

However, maintaining routing tables in every node of the network can consume significant network resources. The updates due to broken links can lead to a heavy control overhead during high mobility. Even a network with small number of highly mobile nodes or a large network of low mobile nodes can completely choke the available bandwidth. This type of protocols suffers from an excessive control overhead. The control overhead is proportional to the number of nodes in the network. Thus, these routing protocols might not be scalable in a highly dynamic ad hoc wireless network with little bandwidth.



Destination	Next Node	Distance	Sequence No
2	2	1	18
3	3	1	24
4	3	2	54
5	2	2	82
6	6	1	38
7	2	3	148
8	3	2	104
9	3	3	204

Figure 1-1 Routing table and route establishment in Dynamic Destination-Sequenced Distance-Vector Routing Protocol (DSDV).

1.1.2 Reactive or On-demand routing protocol

Unlike the protocol routing protocols, nodes do not have to maintain or update any routing information in reactive or on-demand routing protocol. When a node needs to communicate with another node in the network, it executes a path-finding process and exchanges routing information. So, the routes are created as and when needed. The route remains valid till the destination is reachable or until the route is no longer needed.

This type of protocols mainly consists of a route discovery process and a route maintenance process. When a source node needs a route to the destination node, it broadcasts a *route_request*. The intermediate nodes record the link it receives and re-broadcasts it. When the request reaches the destination, a *route_reply* is sent back to the source through the appropriate intermediate nodes. The *route_reply* essentially consists of information on several routes to the destination node. The source then can select one of these routes based on metrics such as hop-count or latency.

In order to ensure that the *route_request* reaches the destination, it must be disseminated throughout the network. Flooding the network with *route_request* messages leads to the unnecessary overhead as it is highly redundant. Each node can receive the *route_request* multiple times and the request can propagate far beyond the destination. Also, since the nearby nodes will receive and re-broadcast the message at roughly the same time, contention of the communication channel and collision can be a very common problem.

Many techniques such as adding random delay to re-broadcast to reduce collision, using a sequence of hop-limited *route_request* or using probabilistic re-broadcasting methods can improve the efficiency of the flooding techniques. However, with probabilistic re-broadcasting technique, there is a chance that the request might not reach the destination node.

The route maintenance process deletes failed routes and re-initiates route discovery in case of topology change. If an end-to-end failure detected, then a discovery process must be reinitiated at the source node. If a hop failure is detected, then a localized route discovery might be able to repair broken links.

An example of on-demand routing protocol is the Dynamic Source Routing Protocol (DSR). When a source node needs to send a packet to a destination node, it first broadcasts the *route_request* as shown in figure 1-2. The broadcasted *route_request* reaches the destination node. The destination node then sends a *route_reply* through the path the broadcasted *route_request* took.

In a resource-constrained dynamic network, the cost of maintaining unneeded routing information is a serious problem. Reactive protocol eliminates the need to periodically flood the network with route information. However, connection setup delay is higher that proactive protocols as routes are not readily available and has to be setup. Route latency is, thus, variable than a constant time table lookup. The route overhead associated with route setup is generally directly proportional to the path length. Route discovery process can be both expensive and unpredictable.

1.1.3 Hybrid routing protocol

Hybrid routing protocols are a compromise between the proactive and the reactive routing protocols. The node maintains network topology information up to a certain number of hops. Zone Routing Protocol (ZRP), Zone-based Hierarchical Link State (ZHLS) routing protocol and Core Extraction Distributed Ad Hoc Routing (CEDAR) protocol are some examples of hybrid routing protocols.

1.2 Power control algorithm

Existing power control approaches in 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 [1], [2], [3] and [4].

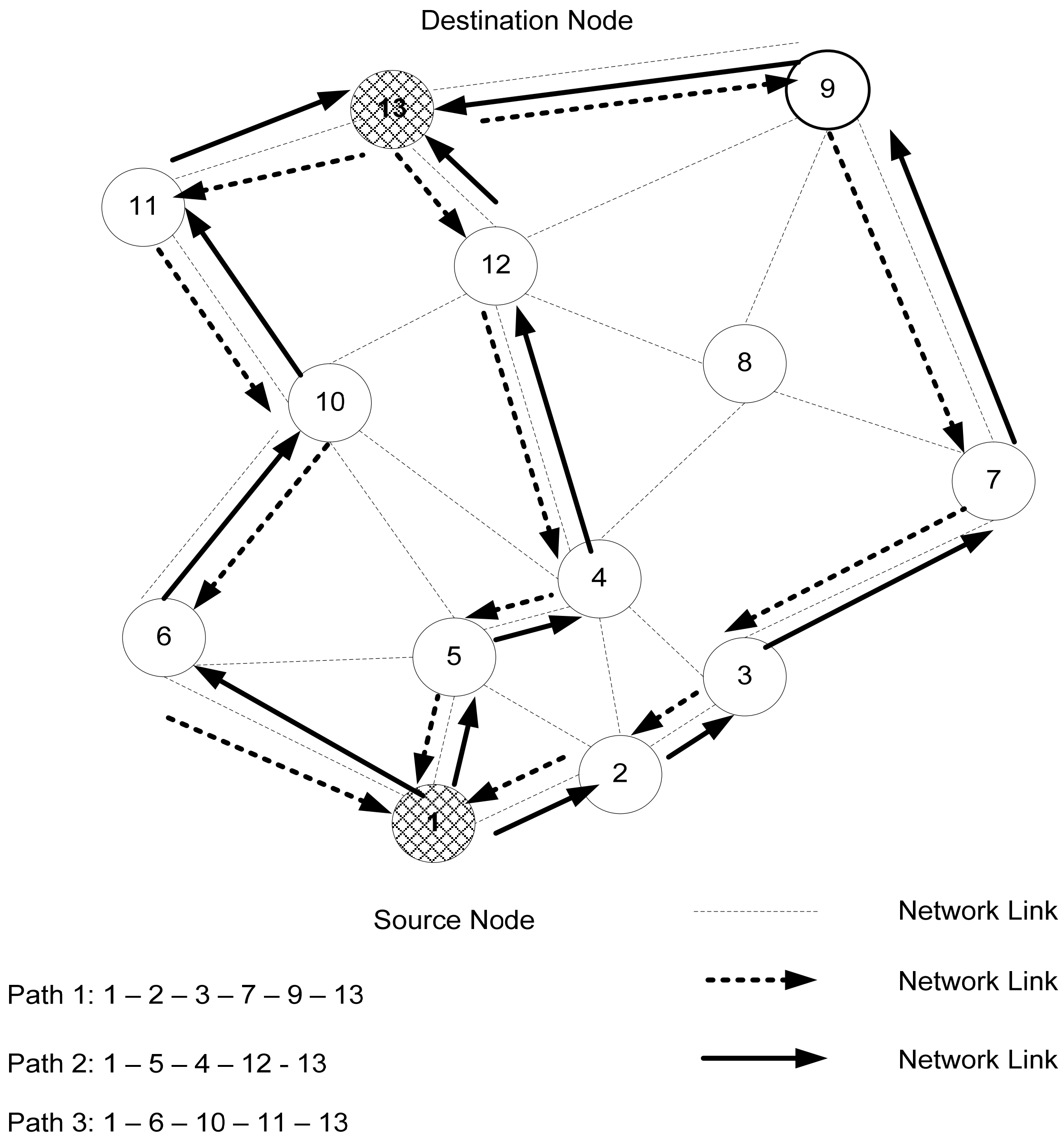


Figure 1-2 Route establishment process in Dynamic Source Routing Protocol (DSR).

For an ad hoc network with a large number of nodes, it becomes difficult to calculate optimal transmission ranges for all the nodes. Furthermore, collecting information of all the nodes and passing them to the concerned nodes leads 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:

1.2.1. Node-degree constrained approach

The degree of a node is defined as the total number of neighbors or its number of links. If k(i) is the degree of node i in the network of N nodes, then the average node degree is

$$\mathrm{k_{mean}} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{k(i)} \tag{1.1}$$

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

$$\mathrm{k_{min}} = \min_{\forall\, \mathrm{i} \in \mathrm{N}} \mathrm{k(i)} \tag{1.2}$$

The Degree Distribution Function P(k) of a network is defined as the probability of nodes in the network that 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 in [5], [6] and [7] 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,

$$\mathrm{k(i)} \geq \mathrm{K} \quad \forall \ \text{node } \mathrm{i} \text{ in } \{1, 2, \dots, \mathrm{N}\} \tag{1.3}$$

Such network is said to be K-connected. If (K-1) nodes fail, the network is guaranteed to be still connected. Algorithms such as Local Information No Topology (LINT) and Local Information Link-State topology (LILT) proposed in [8] collected routing information and adjusted transmit powers of the nodes to maintain a desired number of neighbors for each node.

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 incoming link and the link from the node to its neighbor is called outgoing link. This is a major drawback of these distributed attempts as most of the routing algorithms do not use asymmetric link to route packets. Additionally, such asynchronous links can be a major source of interference.

Algorithms such as Common Power (COMPOW) in [9] 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. Ref [10] 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.

1.2.2. Location information based approach

Power control algorithm can benefit from location information of nodes in the network. Nodes equipped with directional antenna and geographical knowledge of their neighbors can lead to significant decrease in interference. This can lead to a considerable increase in network performance. With the availability of directional information of nodes in the network, recent research has tried to utilize the benefits of directional antennas.

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 coverage area, A_s. Nodes are able to transmit through one, multiple, or all sectors at one time, thus creating unicast, multicast or broadcast communications respectively.

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. A Cone-Based Topology Control (CBTC) algorithm in [11] 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 in [12] that $\theta \leq 5\pi/6$ is necessary and sufficient condition to guarantee connectivity of the network. Further, Ref. [13] 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.

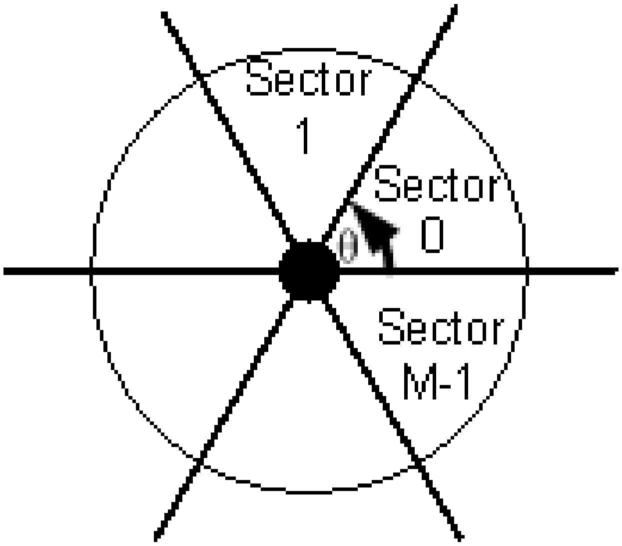


Figure 1-3 Directive sector of a switched beam antenna system

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 [14]. It is shown in [15] that beamforming technique can significantly improve the throughput and decrease end-to-end delay in the network. Further attempts to use directional antenna at every node to create low-interference and low-cost network topologies are presented in [16] and [17]. Another algorithm proposed in [18] attempts to adjust the power intensity independently in each direction of a multi-beam directional antennas to reduce hop count in the network topology.

1.2.3. 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, any 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. A simple graph is called 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 the nodes u and v if and only if there is no other node w ∈ N that is closer to either u and v than the distance between u and v. Formally,

$$\max\{\mathrm{d}(\mathrm{u},\mathrm{w}),\mathrm{d}(\mathrm{v},\mathrm{w})\} < d(u,v) \tag{1.4}$$

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 Figure 1-4.

RNG is a subgraph of the Delaunay Triangulation (DT) and has been implemented in topology control algorithm [19] 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 graph. 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 defined for a connected graph as disconnected graph doesn't 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 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). Figure 1-5 shows a MST of a random ad hoc network. A Local Minimum Spanning Tree (LMST) algorithm, introduced in [20], independently builds 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) in [21] adds the concept of Tree-based Reliable Topology (TRT) in LMST to guarantee K-edge connectivity.

Further, a MST based energy-aware topology control algorithm that considers node residual energy information known as Residual Energy Aware Dynamic (READ) is presented in [22]. Also, MAC layer approaches in [23] and [24] attempt to reduce power consumption by selecting energy-efficient routes to the destination. Another MAC protocol in [25] selects different power levels for RTS-CTS and DATA-ACK packets to conserve energy. Power Control Multiple Access (PCMA) protocols in [26] and [27] select transmit power per packet basis to provide framework for collision-avoidance. However, these approaches usually need multiple channels and might not be practical for implementation.

Other algorithms presented in [28] and [29] provide frameworks on developing low-interference topologies. The Minimum Interference Algorithm (MIA) in [30] looks at interference between links and tries to minimize the overall interference in their network graph model. Another algorithm presented in [31] further builds a topology graph to meet QoS requirements such as end-to-end traffic and delay.

1.2.4. 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 and sensor 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,…,N} of players
2. for every player i ϵ N, the set S_i of strategies (or choices) available to player i
3. the set of possible payoffs P

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

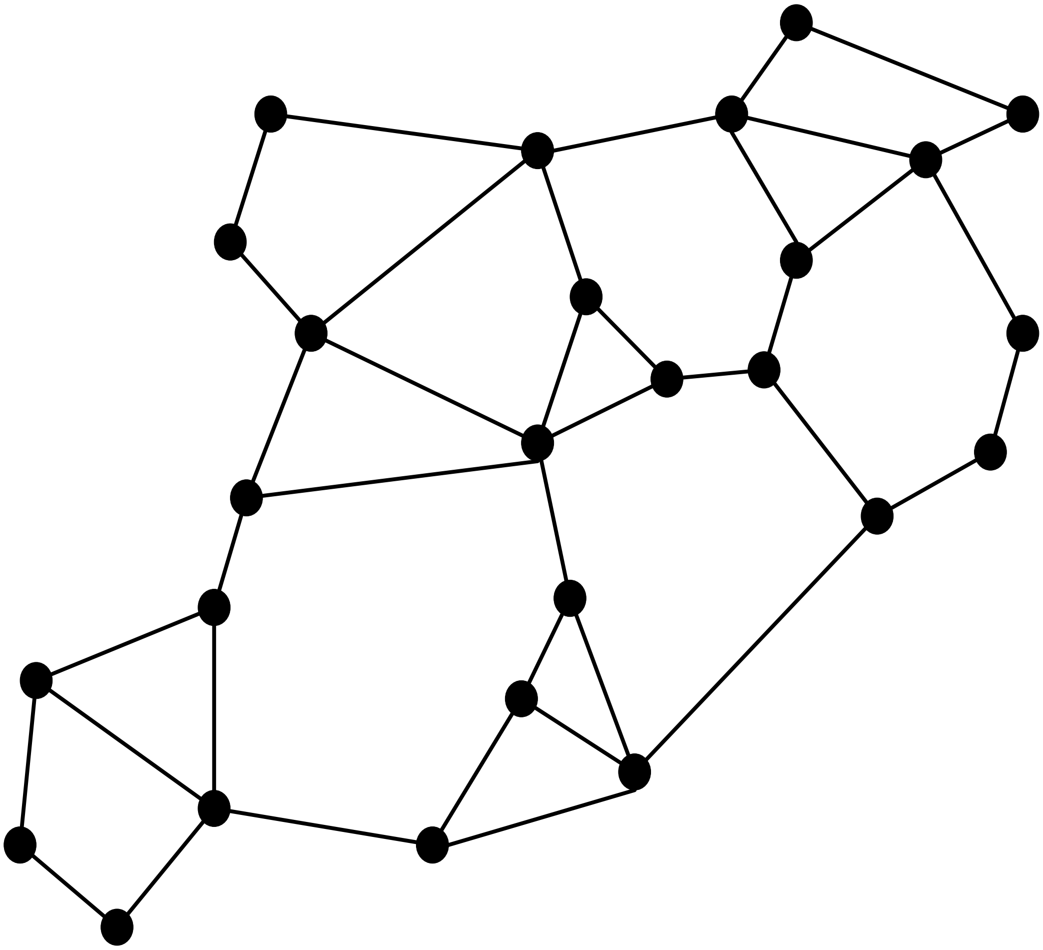


Figure 1-4 Relative Neighborhood Graph (RNG) of a random ad hoc network

Based on the interdependence among the players, game theory is divided into non-cooperative and cooperative game theory. 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.

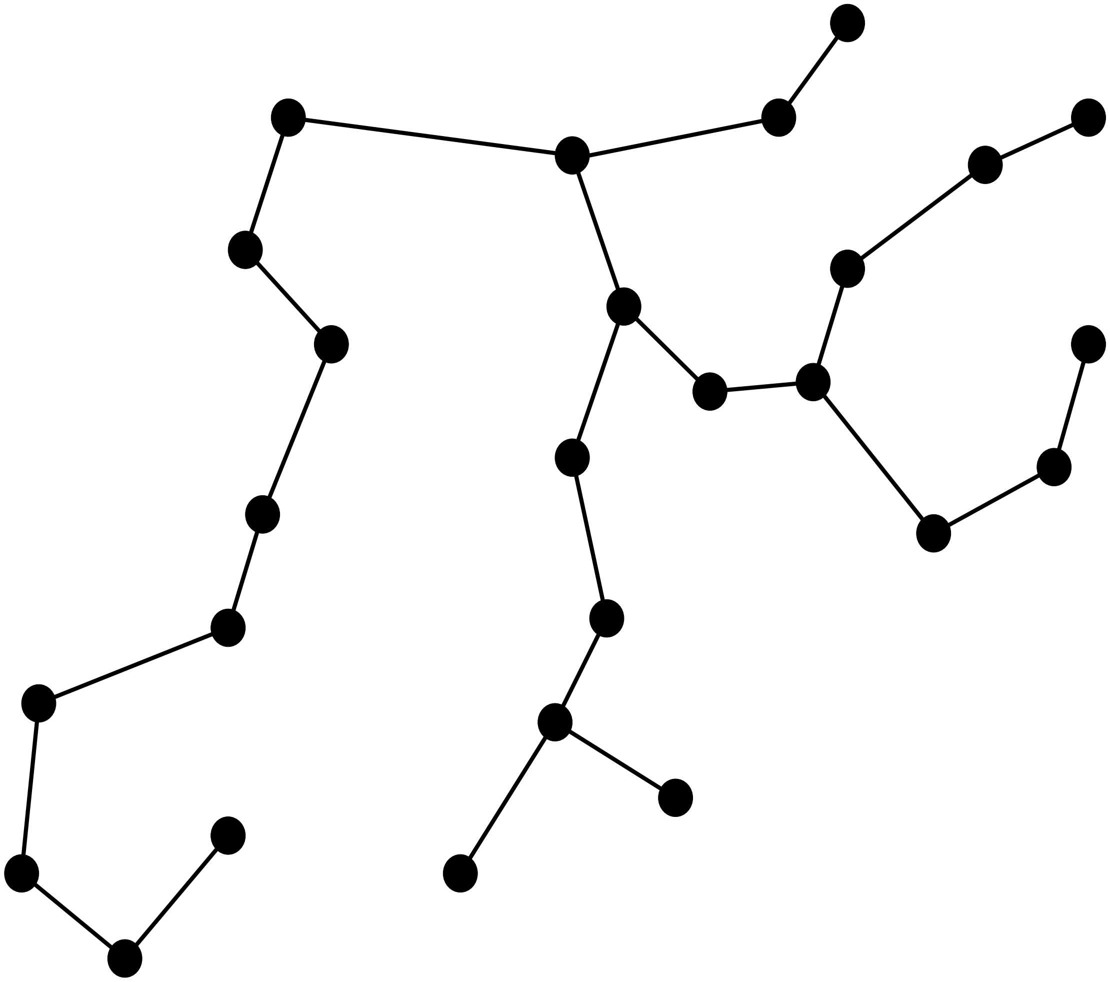


Figure 1-5 Minimum Spanning Tree (MST) of a random ad hoc network

Non-cooperative game theory can be very useful in modeling and understanding multi-node power control problems characterized by their interdependency. Ref. [32] 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 where no player can improve his or her payoff by unilaterally changing their strategy known as the Nash Equilibrium. Ref. [33] proves that a unique Nash equilibrium exists in a non-cooperative power control game where each rational player tries to maximize its utility function. Ref. [34] 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.

1.2.5. Multi-Parameter Optimization Approach

Another approach is a dynamic multi-parameter optimization of difference parameters such as connectivity, interference and energy consumption of the network. Two localized Distributed Power Management Algorithm (DISPOW) and Distributed Management Algorithm with Directional Antenna (DDISPOW), presented in Chapter 3 and 4, develop a strongly connected network topology in a completely distributed manner tailored to its surrounding node density and propagation environment.

1.3 Power control algorithm

The dynamic nature of wireless channel places fundamental limitations on the performance of wireless communication systems. Propagation model predicts the average received signal strength at a given distance for the transmitting node. This prediction of mean signal strength is useful in estimating the coverage of the transmitting node and characterizes signal strength over large transmitting receiving node distances. The main propagation models used in modeling wireless networks are as follows:

1.3.1 Disk propagation model

The disk propagation model is the simplest propagation model where the signal propagates to a certain distance and no more [35] and [36]. It does not take the path loss or fading loss present in the wireless channel into consideration.

1.3.2 Free space propagation model

Free space propagation model are used to predict the signal strength at the receiving node when there is a clear line-of-sight path between the transmitting and the receiving node [37]. The predicted signal strength decreases with increasing distance between the transmitting and receiving nodes. If d is the distance between the transmitting node and the receiving node, then the free space power received by the receiver is given by the Friis free space equation [38],

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2\, d^2 L_{system}} \tag{1.5}$$

where,

P_t : trasmitting power

d : $distance\ between\ the\ transmitting\ and\ receiving\ node$

λ : $wavelength$

G_t: gain of transmitting antenna

G_r: gain of receiving antenna

L_{system} : system loss factor

The equation shows that the receiving power falls off as the square of the separation distance. The signal attenuation is defined as a ratio between the transmitting power and the receiving power. The path loss, assuming unit system loss factor, is given by the following

$$PL(dB) = 10\log\frac{P_t}{P_r} = -\,10\log\left(\frac{G_t\,G_r\,\lambda^2}{(4\,\pi)^2\,d^2}\right) \tag{1.6}$$

The Friis free space model to predict the receiving power is only valid for distance, *d*, in the far-field or the Fraunhofer region of transmitting antenna.

1.3.3 Two-ray propagation model

The two-ray propagation model considers both the direct and a ground reflected propagation path between the source and the destination node as shown if the figure 1-6 [39] and [40]. The predicted signal strength at the receivers, P_r, from this model can be expressed as:

$$P_r(d) = \frac{P_t G_t G_r {h_t}^2\, {h_r}^2}{d^4} \tag{1.7}$$

$where,$

$P_t: transmitting\ power$

$G_t: gain\ of\ the\ transmitting\ antenna$

$G_r: gain\ of\ the\ receiving\ antenna$

$h_t: height\ of\ the\ transmitter$

$h_r: height\ of\ the\ receiver$

$d: distance\ between\ the\ transmitting\ and\ receiving\ node$

This model, even though, reasonably accurate for predicting the large scale signal strength over a distance of several kilometers for radio system, is not suitable for ad hoc network where there are several multi-paths of similar strength and the propagation range is limited by transmission power of the nodes [39] and [41].

1.3.4 Log-distance path loss model

The average large-scale path loss of the propagation signal between the transmitting node and the receiving node separated by a distance of *d* can be expressed as a function of distance and the path loss exponent, *n*, as given by the following equation [38] and [39]:

$$P_L(dB) = P_L(d_0) + 10\,n\,log\left(\frac{d}{d_0}\right)$$

where,

d_0: reference distance (1.8)

$P_L(d_0)$: reference path loss at d_0

d: $distance\ between\ the\ transmitting\ and\ receiving\ node$

n: $path\ loss\ exponent$

The path loss exponent indicates the rate at which the path loss increases with distance. The value of the path loss exponent depends on the specific propagation environment.

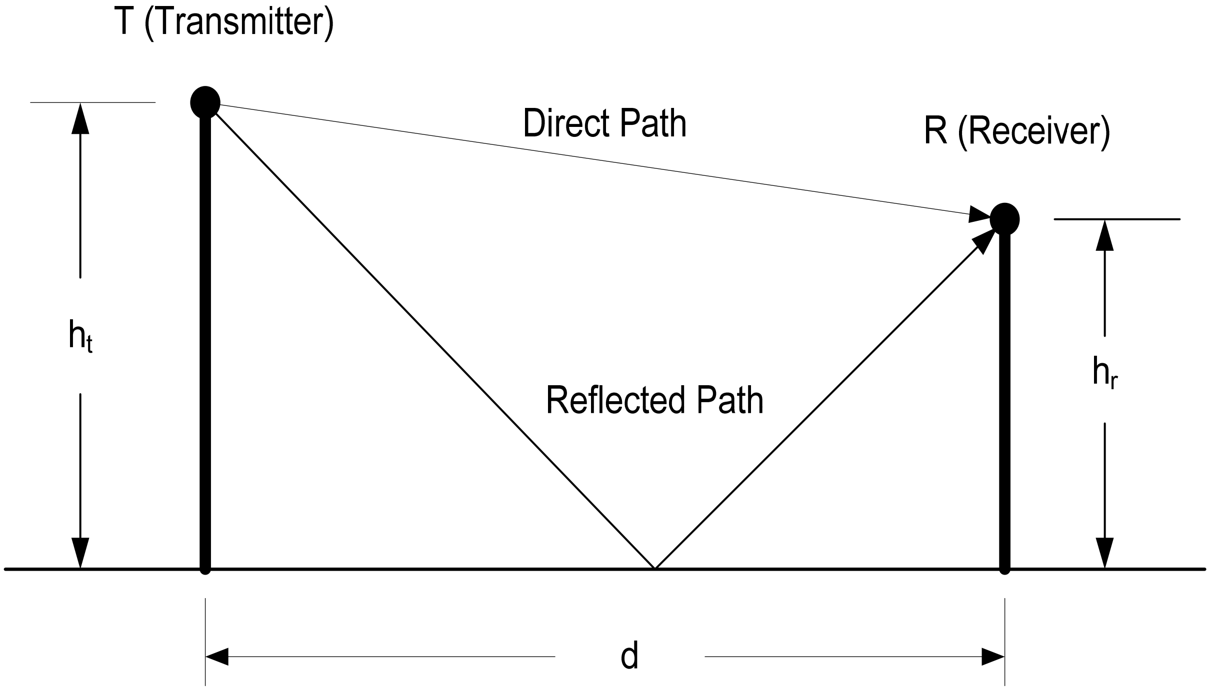


Figure 1-6 Two-ray ground reflection propagation model

1.3.5 Log-normal shadowing model

The surrounding environment clutter may be vastly different at two different locations for the same separation distance. This leads to a very different received signal from the one predicted by the log-normal path loss model. It has been determined by empirical approach that the path loss at a particular location is random and distributed log-normally about a mean distance dependent value clearly visible in the following expression [42],

$$
\begin{aligned}
& P_L(d)dB = \overline{P_L(d)} + X_\sigma \\
& where, \\
& \quad \overline{P_L(d)}: mean\ path\ loss\ at\ distance\ d \\
& \quad X_\sigma: zero - mean\ guassian\ distributed\ random \\
& \qquad\qquad variable\ with\ standard\ deviation\ \sigma
\end{aligned}
\tag{1.9}
$$

The log-normal distribution describes the random shadowing effects which occur because of different levels of clutter on the propagation path. Thus, the model is statistically defined by the path loss exponent, n, and the standard deviation of log-normal shadowing, σ.

1.3.6 Fading loss model

The presence of reflecting objects and scatterers such as building and trees give rise to different version of the signal. This signal traveling through different paths, multipath waves, reaches the receiver at different times. These then combines in the receiving antenna to give a resultant signal which can vary widely in amplitude and phase, depending on the distribution of the intensity and relative propagation time of the different versions of the signal. The relative movement between the nodes also introduces a frequency spreading phenomenon known as Doppler Effect.

Chapter 2

Impact of Physical Propagation Environment on Ad Hoc Network Routing Protocols

The impact of physical propagation model on the performance of ad-hoc network routing protocol are analyzed in this chapter. The impact of different propagation environments on a typical routing protocol such as OLSR is presented through simulation results. It will be shown that the network degrades and the average delay and routing packet overhead significantly increase in a higher attenuating environment.

2.1. Motivation

Propagation model estimates the propagation and fading loss experienced by the signal. We will model the random shadowing effects and multipath fading with log-normal shadow model and rayleigh fading model. The loss affects the Signal and Noise Ratio (SNR) and the Bit Error Rate (BER) of a communication link. This in turn determines the available bandwidth, the stability of the link and the node transmitted signal coverage. Therefore, the performance of a routing protocol significantly depends on the propagation model as it takes these parameters as its routing metrics.

Most of the simulation models in ad hoc network implement the disk propagation model [35] and [36]. This model does not take the physical channel condition at all. Free space propagation model which predicts signal strength of a Line of Sight (LOS) path, has also been implemented for ad hoc network simulation [37]. However, this model is generally not applicable for scenarios where there are obstacles such as buildings, trees or any other physical obstructions.

References [40] and [39] used two-ray propagation model in their simulation work. Several simulations have also implemented empirical or statistical propagation models such as Okumura or Hata model [43].

These models, however, do not model realistic physical environments for ad-hoc network simulation. We select log-distance path loss model, log-normal shadowing model and Rayleigh fading propagation model to model the path loss and fading loss in a realistic dynamic wireless channel.

2.2. Wireless propagation model

Propagation model generally predicts the average received signal strength at a given distance from a transmitting node. This prediction of mean signal strength is useful in estimating the coverage of the transmitting node and characterizes signal strength over larger transmitting receiving node distances. It can also characterize the rapid fluctuation of the received signal strength. So, a propagation model can be used to estimate the received power of the transmitting signal at the receiving node. SNR is defined as the ratio of power of the receiving signal to the noise power at the receiver. If the SNR and subsequently BER are acceptable, the link can be selected for routing packets. The SNR or the BER determines the quality of the link and eventually the different metrics used for the routing protocol. Thus, the propagation model becomes an important consideration during the simulation.

Most of the simulation done in ad hoc network uses the trivial disk propagation model, the free space propagation model or the two-ray propagation model. Although several empirical or statistical propagation models for path loss such as Okumura model or Hata model are well documented in literature, they are limited to frequencies below 2 GHz and generally used in cellular network. Since ad hoc network operates in higher frequency range, these models cannot be used in simulation.

We select log-distance path loss model as described in chapter 1.3.4 where the average path loss of the propagating signal is given by

$$P_L(dB) = P_L(d_0) + 10\, n \, log\left(\frac{d}{d_0}\right) \tag{2.1}$$

where,

d_0: reference distance

$P_L(d_0)$: reference path loss at d_0

d: $distance\ between\ the\ transmitting\ and\ receiving\ node$

n: $path\ loss\ exponent$

The random shadowing effect at the receiver is modeled by the log-normal shadowing model and is defined by the following equation,

$$P_L(d)dB = \overline{P_L(d)} + X_\sigma \tag{2.2}$$

$where,$

$P_L(d)dB$: $fading\ loss\ at\ distance\ of\ d$

$\overline{P_L(d)}$: $mean\ path\ loss\ at\ distance\ d$

X_σ: $zero - mean\ guassian\ distributed\ random\ variable\ with\ standard\ deviation\ \sigma$

Also the presence of reflecting objects and scatterers such as buildings and trees gives rise to different version of signal wave. The waves travelling through different paths reach the receiver at different times. These multi-path waves then combine at receiving antenna to give a resultant signal which can vary widely in amplitude and phase, depending on the distribution of the intensity and relative propagation paths.

The mobility of a user not only changes the distance between the node affecting the path loss but also fading experienced by the signal. The Random Waypoint Mobility Model (RWMM) [44] is used to model the node's mobility in the simulation.

In this mobility model, a node selects a destination randomly within a roaming area and moves towards it at a speed uniformly distributed between predefined minimal and maximum set value. Once the node reaches that destination it stops for a predefined pause time and then selects another destination randomly and moves towards it. This node mobility behaviour is repeated for the duration of the simulation.

Rayleigh fading is used to model this small-scale fading and doppler Effect in this paper. This multipath fading loss has a rayleigh distribution with probability density function given by equation (2.3).

$$p(d) = \begin{cases} \frac{d}{\sigma^2} exp\left(-\frac{d^2}{2\sigma^2}\right) & (0 \leq d \leq \infty) \\ 0 & (d < 0) \end{cases} \tag{2.3}$$

$where,$

σ^2 : time − average power of the recevide signal

So, a propagation model can be used to estimate the received power of the transmitting signal or SNR at the receiving node. SNR is defined as the ratio of power of the receiving signal to the noise power at the receiving signal to the noise power at the receiver. If the SNR and subsequently BER are acceptable, the link can be selected for routing protocols. But, in reality, in multi-user system the interference from other nodes also acts as noise and can be more significant than background thermal noise. We will, therefore, model the wireless network as interference-limited rather than noise-limited and consider Signal to Interference and Noise Ratio (SINR) given by equation (2.4) to determine the BER of a communication link [45]. Here N_i represents both the thermal noise and the interference.

$$SINR(\gamma) = P_{PL}(dB) - P_L(dB) - P_F(dB) - N_I \tag{2.4}$$

The SINR or the BER determines the quality of the link and eventually the different metrics used for the routing protocol.

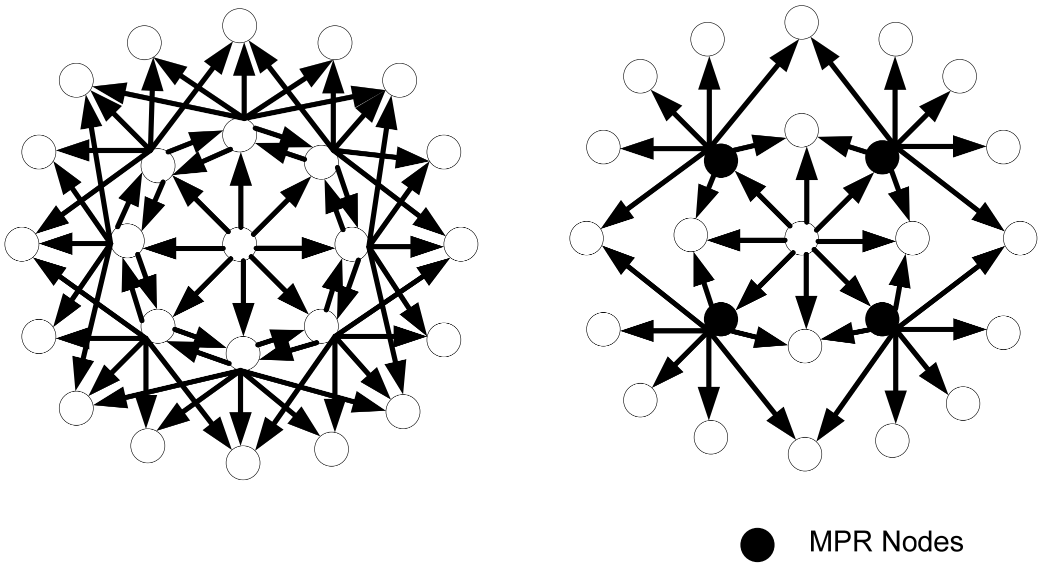
2.3. Optimized link-state routing (OLSR) Protocol

OLSR is a proactive table driven protocol which optimizes the classic link state protocol by using only selected nodes called Multipoint Relay (MPR) to advertise links in the network [46]. It has routing information immediately available when needed and provides hop-by-hop routing.

Each node in the network selects a set of nodes, MPRs, in its symmetric 1-hop neighbourhood which may retransmit its messages. MPRs are selected in such a manner that every node in the node’s two-hop neighbourhood has a bidirectional link with it. Only MPRs are allowed to advertise the links by periodically broadcasting Topology Control (TC) messages [47]. Neighbours, who are not selected as a MPR, receive and process the broadcast messages but do not retransmit broadcast messaged received.

A node updates its MPR set whenever it detects a new bidirectional link or a breakage of the existing bidirectional link in its two-hop topology. Therefore the selection of the MPR set significantly affects the performance of OLSR.

Compared to classical flooding mechanisms, where every node forwards each message received, this technique of using MPR substantially reduces the message overhead. This is clearly evident in figure 2-1. In the network running OLSR protocol, source selects only 4 nodes as MPRs. Since only these MPRs forward the message, the overhead is far lesser than in network with classical flooding mechanism. The smaller the set of MPR the lesser the control traffic overhead resulting from the routing protocol.



Network with classical flooding mechanism

Network with OLSR routing protocol

Figure 2-1 Classical flooding mechanism and flooding in OLSR

The HELLO message maintains the local link and neighbourhood information in the network and serves the common purpose of local topology discovery. A node must perform link sensing on each interface in order to detect links with other neighbour nodes and to advertise its entire symmetric 1-hop neighbours. It also contains the list of nodes that has a bidirectional link and of the neighbours whose transmissions were received in the recent past but with whom bidirectional links has not yet been confirmed. This is used in selecting MPRs from its 1-hop neighbours. HELLO packet therefore serves three independent tasks of link sensing, neighbour detection and MPR selection signalling.

In order to build the topology information of the network, the MPRs flood the TC message to all the nodes. This topology information derived from link sensing and neighbour detection is used to construct routes in the network. In order to provide sufficient information to enable routing, a node must at least disseminate links between itself and the nodes in its MPR selector set. The TC messages are sent regularly within a certain refreshing period to help each node calculate and maintain a routing table.

The routing table allows nodes to route their data to its destination node in the network. So it is kept up to date through periodic message exchange. It is also recalculated if changes are detected in its link set or if a link is created or removed in its two-hop neighbourhood.

2.4. Simulation model

The performance of ad hoc routing protocol such as OLSR in different environments is studied here through a series of simulations carried out in OPNET network simulator.

The network consists of 100 nodes distributed in a 1000 meter by 1000 meter area. All the nodes are configured with OLSR routing protocol and IEEE 802.11 MAC protocol. Each node, transmitting at 30 mW, generates traffic of 1 kbps with an average packet size of 1024 bits. The simulations are done over two distinctly different environments: open_environment characterized by open space or plain area with a LOS path, and city_environment with no LOS path but multiple versions of the signal with many obstacles such as buildings and trees in the propagation path. These open_environment and city_environment are modelled by log-distance path loss model with path-loss exponents of 2.0 and 3.2 respectively. RWMM is used to model the node's mobility with minimum speed of 0 m/s and maximum speed of 1, 5, 10, 15 and 20 m/s.

In accordance with the 802.11 standard, a link in this paper is defined as acceptable or good if the power of the signal in the receiving node is greater than the threshold value of -95.0 dBm. If the power level of the signal in the receiving node falls below the threshold, the link is considered bad and is discarded. Only the good links are considered when routing the packets through the network.

The simulation parameters used in this simulation are listed in table 2-1.

2.5. Network throughput, delay and routing performance

The metrics that are considered in this simulation to evaluate the performance of the OLSR routing protocol are discussed below.

Average traffic delay defines the average time taken by a data packet to reach its destination. It is calculated by subtracting the time at which the packet is transmitted by the source node to the time at which the data arrives in the destination node. This includes all the possible delays caused by node's processing time, queuing delays, retransmission delay at the MAC layer and propagation time. Queuing is often the prominent delay especially when the network is congested.

Figure 2-2 shows the average network delay experienced in the open_environment and city_environment. The average delay experienced in the city_environment is found to be more than three times higher compared to the open_environment.

Throughput of a network expresses its ability to deliver packets and is defined as the total number of data delivered during the simulation time. The throughput of the network, as can clearly be seen from figure 2-3, is about 18% less in city_environment than in open_environment.

Figure 2-4 shows the average number of hops needed to successfully deliver packets in the network. The average number of hops to deliver packet in city_environment was about one-third more than that in open_environment.

The higher average delay, lower throughput and higher number of hops needed experienced in city_environment is due to a much weaker signal received in nodes. The higher attenuation of the signal limits the propagation range, thus degrading the quality of the link and lowering the network connectivity.

Table 2-1. Simulation parameters

Simulator	**OPNET**
Propagation Model	Log-distance Path Loss Model
MAC Protocol	IEEE 802.11
Carrier Frequency	2.4 GHz
Network Area	1000m x 1000m
Number of Nodes	100
Simulation Time (sec)	100
Data Streams	Exponential
Inter arrival Packet time (sec)	1
Packet Size (bits)	1024
Transmitting Power (mW)	30
Reception Power Threshold (dBm)	- 95.0
HELLO Interval (sec)	2.0
TC Interval (Sec)	5.0
Mobility Model	Random Waypoint Mobility Model (RWMM)
Maximum speed of nodes (m/s)	1, 5, 10, 15, 20
Minimum speed of nodes (m/s)	0
pause time (sec)	0

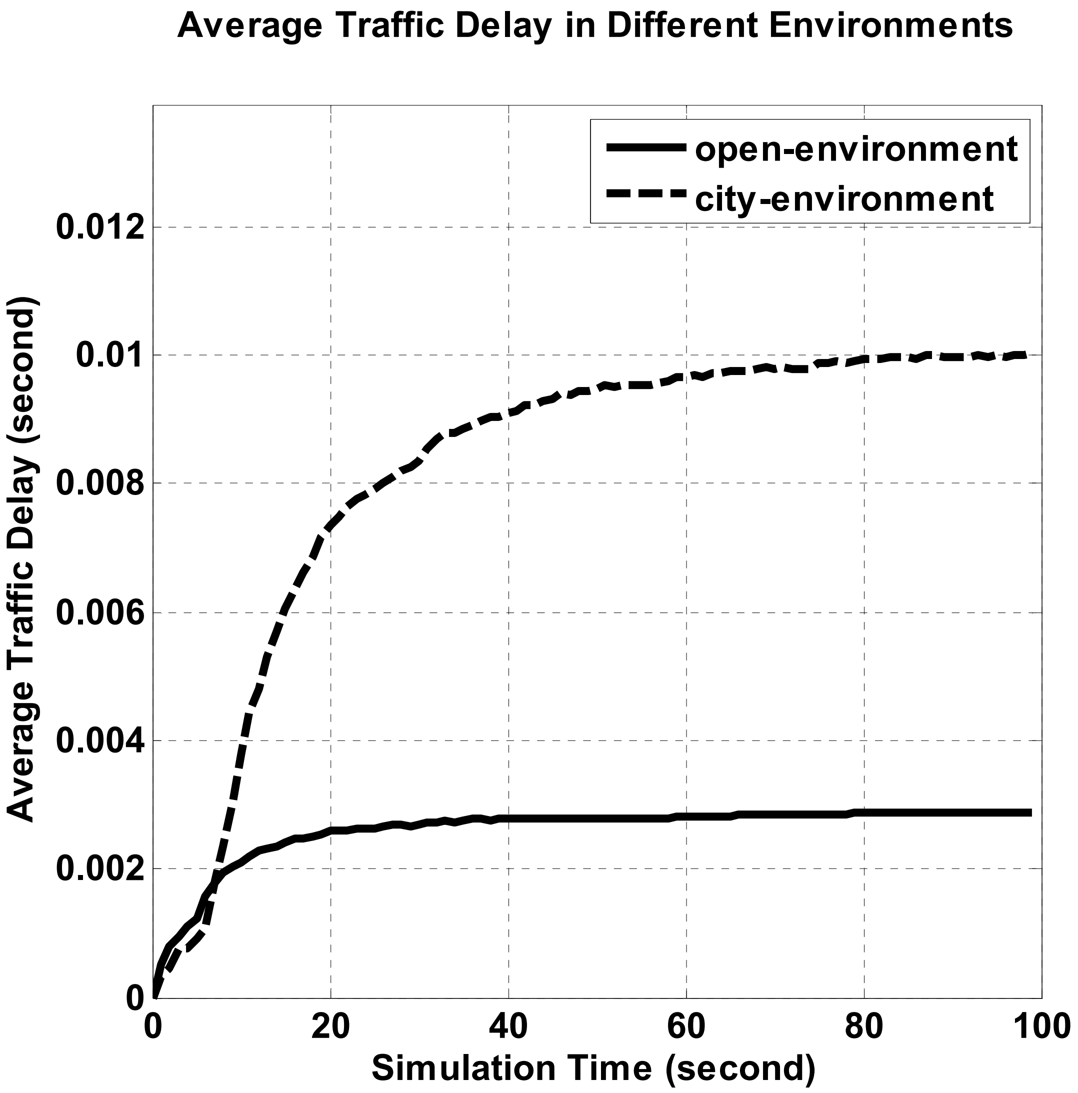


Figure 2-2 Average traffic delay in open_environment and city_environment

MPRs of a node are selected from its neighbour node such that every node in its two-hop neighbourhood has a bidirectional link with the node. Figure 2-5 shows that 70% of the nodes are selected as MPR in open_environment. The number of MPR increased to 82% in the city-_environment. This increase is due to the decrease in the number of acceptable links between the nodes. Lower connectivity between the nodes means that the minimum number of intermediate nodes the source node has to go through to reach its 2-hop neighbours is higher. Hence, the number of MPRs increases in the city_environment because of lower network connectivity.

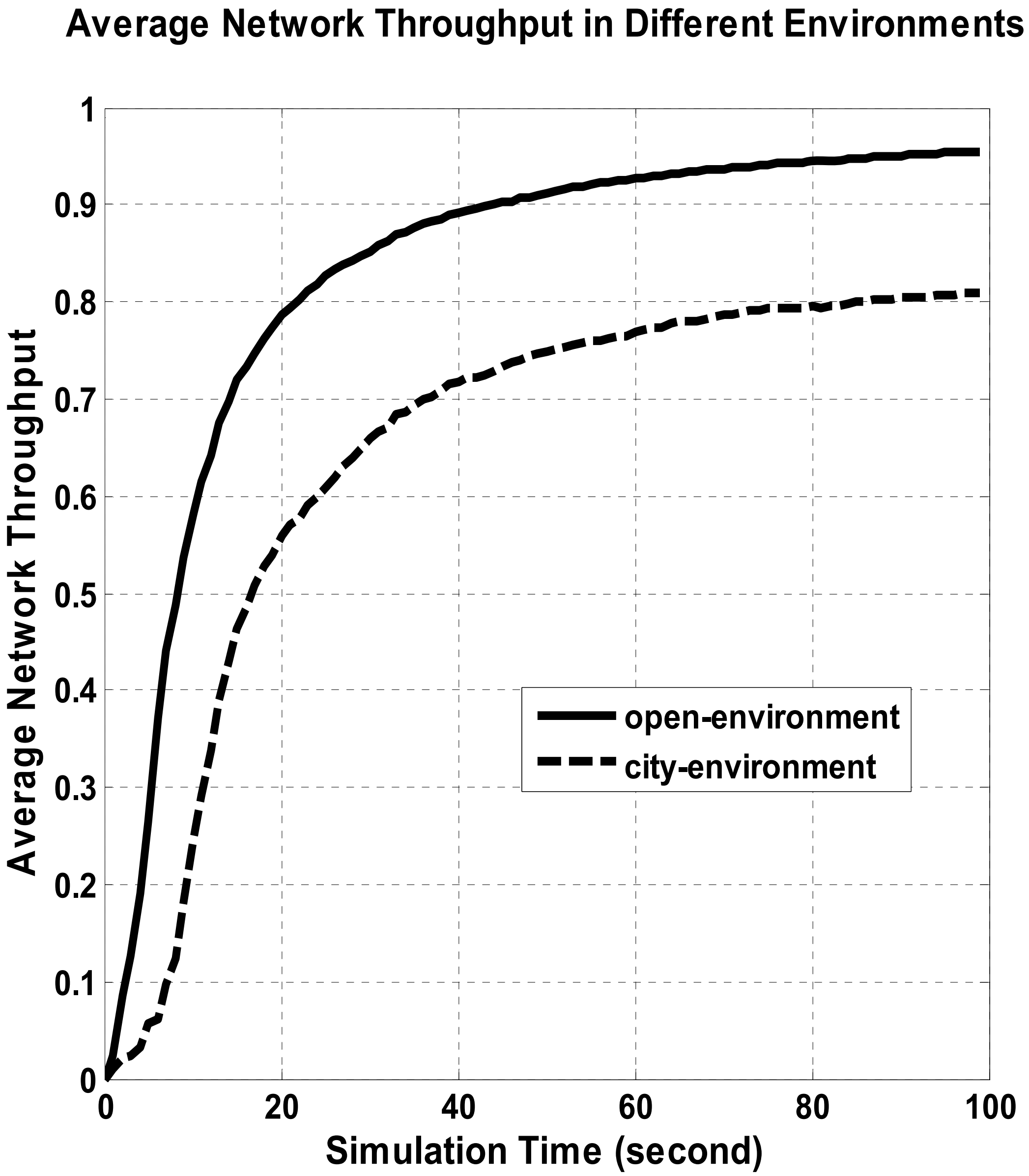


Figure 2-3 Average network throughput in open_environment and city_environment

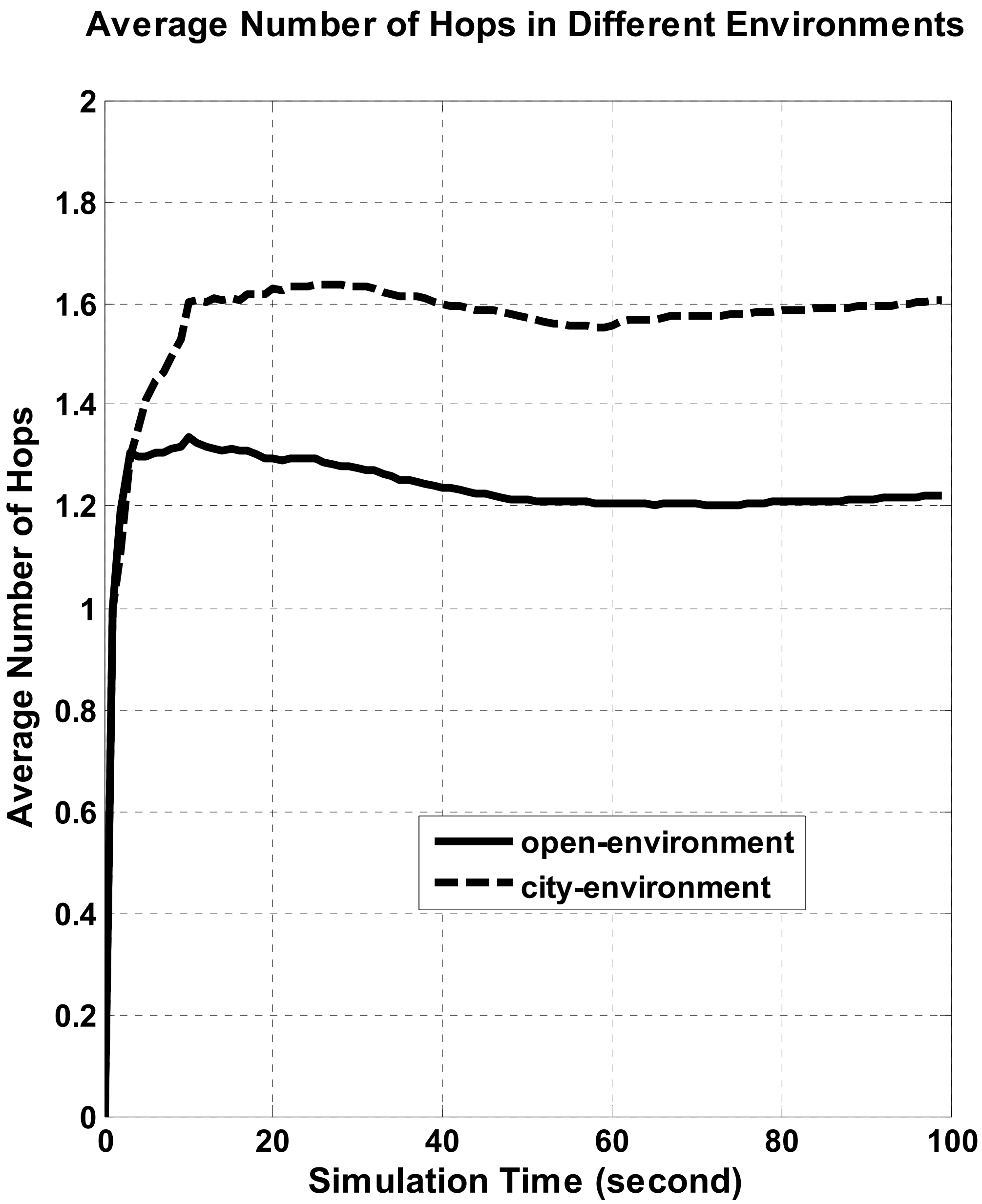


Figure 2-4 Average Number of Hops in open_environment and city_environment

Nodes, which are selected as MPRs, broadcast and forward the TC messages to build the topology information of the network. The average number of TC packets broadcasted in the city-_environment, as shown in figure 2-6, is about 15% higher than that in the open_environment. This is because there is a higher percentage of a node selected as a MPR in city_environment compared to the open_environment. Since only MPRs are allowed to send and forward TC packets, the number of TC packets sent and forwarded is higher in city_environment.

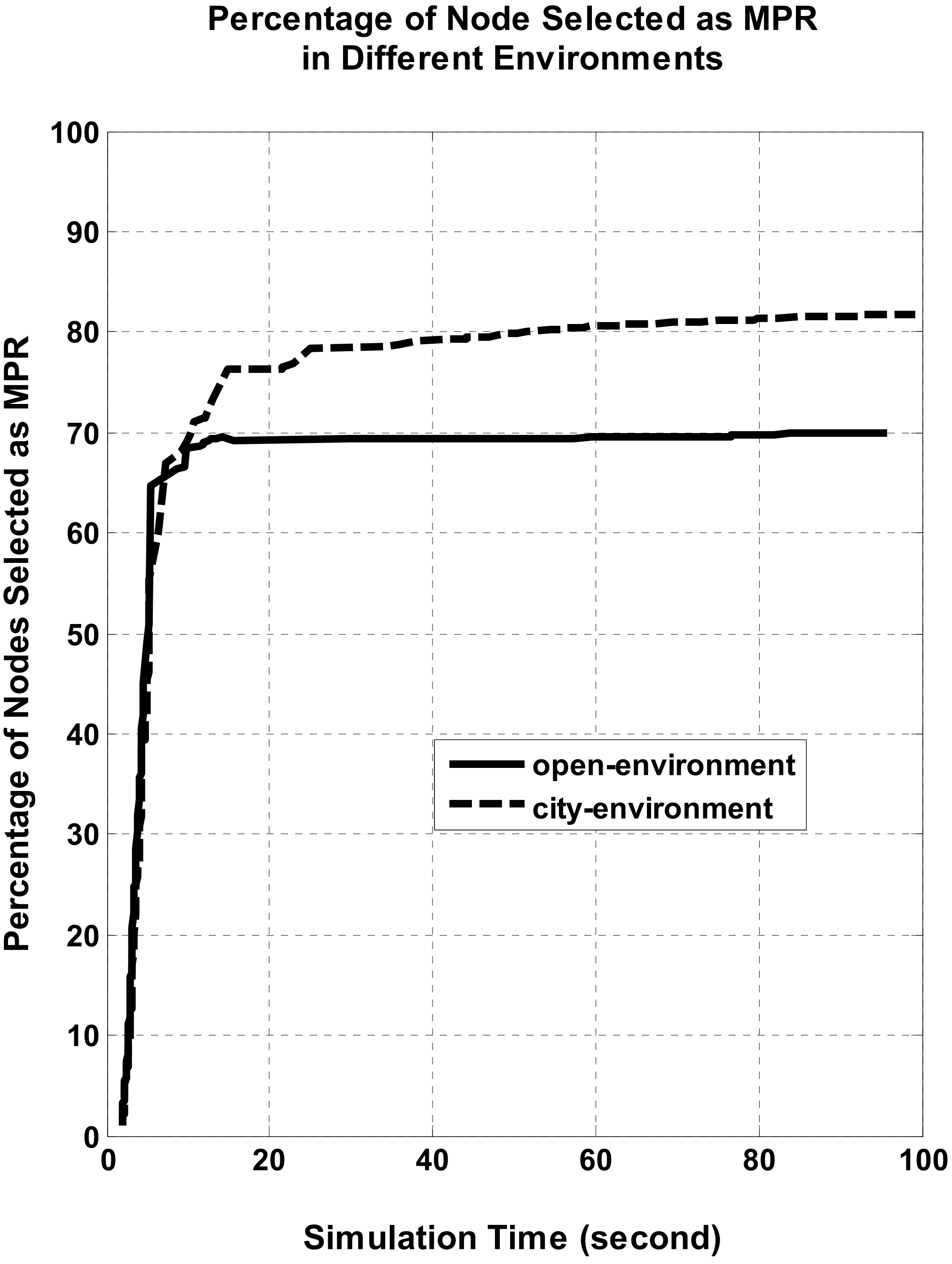


Figure 2-5 Percentage of nodes selected as MPR in open_environment and city_environment

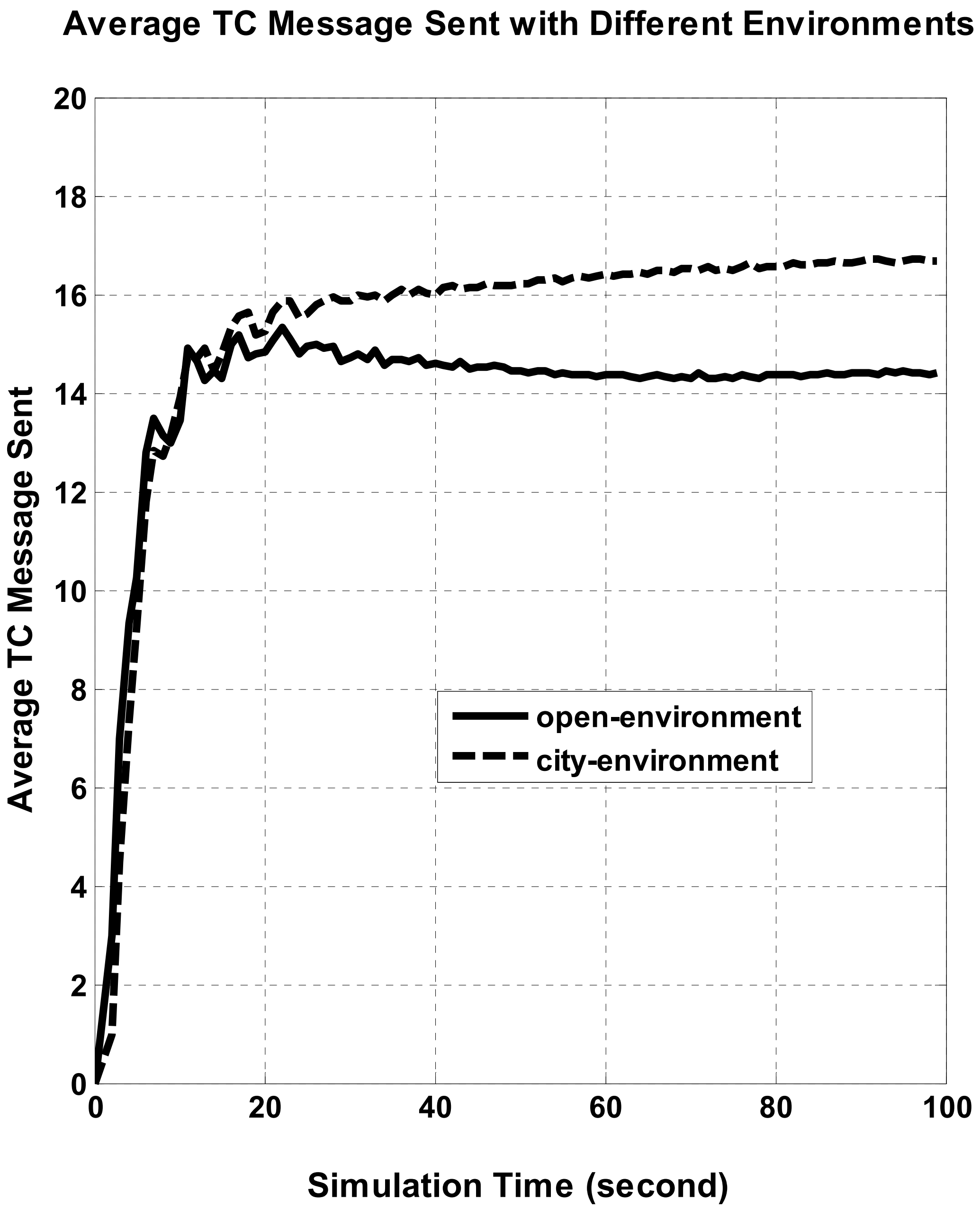


Figure 2-6 Average total TC message generated in open_environment and city_environment

The routing overhead packets of OLSR routing protocol are the HELLO packets and the TC packets generated and replicated. The number of routing overhead packets sent is higher for city_environment compared to open_environment as seen in figure 2-7. The increase in MPR, and thus the number of TC messages broadcasted and forwarded, explains the increased routing traffic overhead of OLSR in city_environment compared to open_environment.

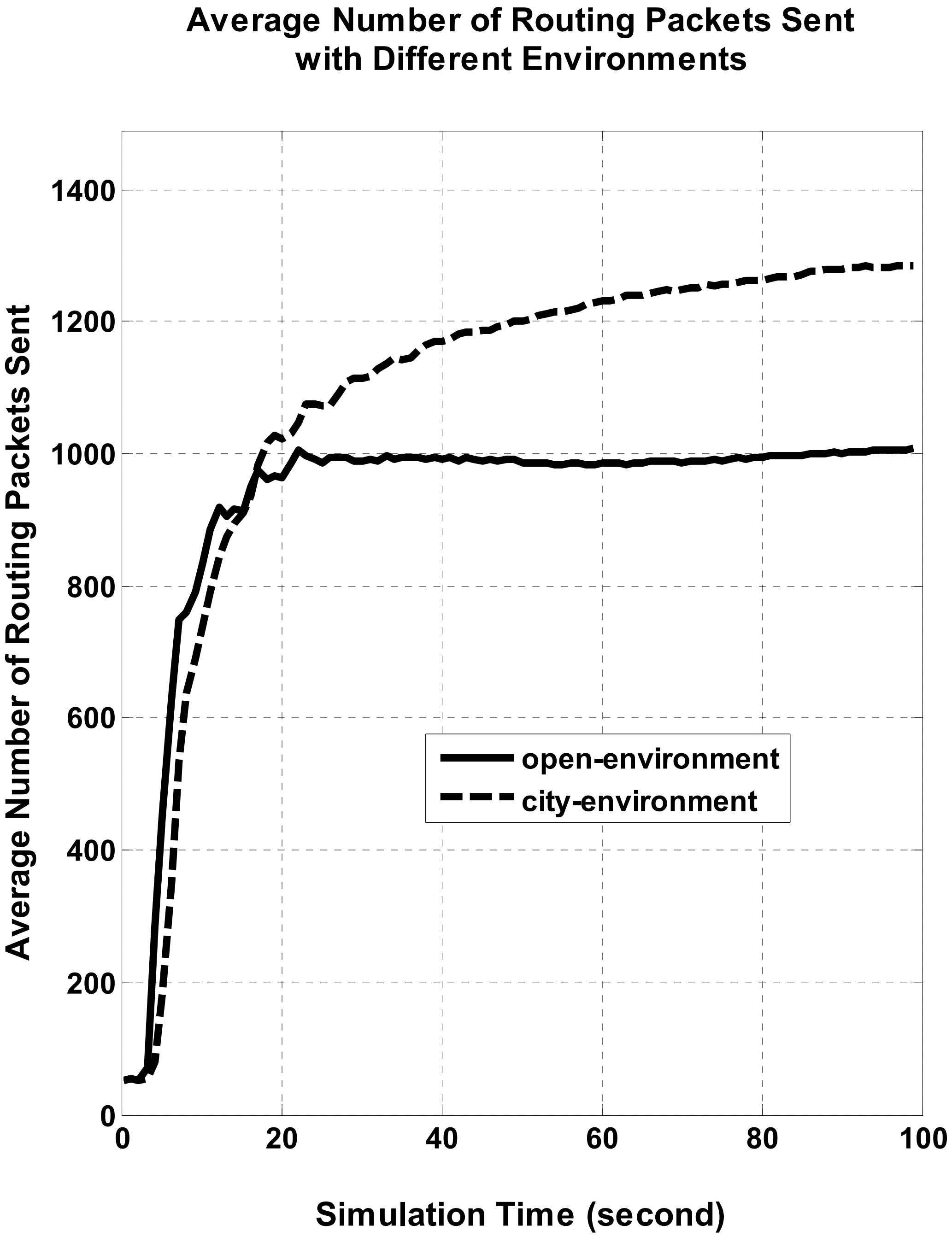


Figure 2-7 Average routing overhead packets sent in open_environment and city_environment

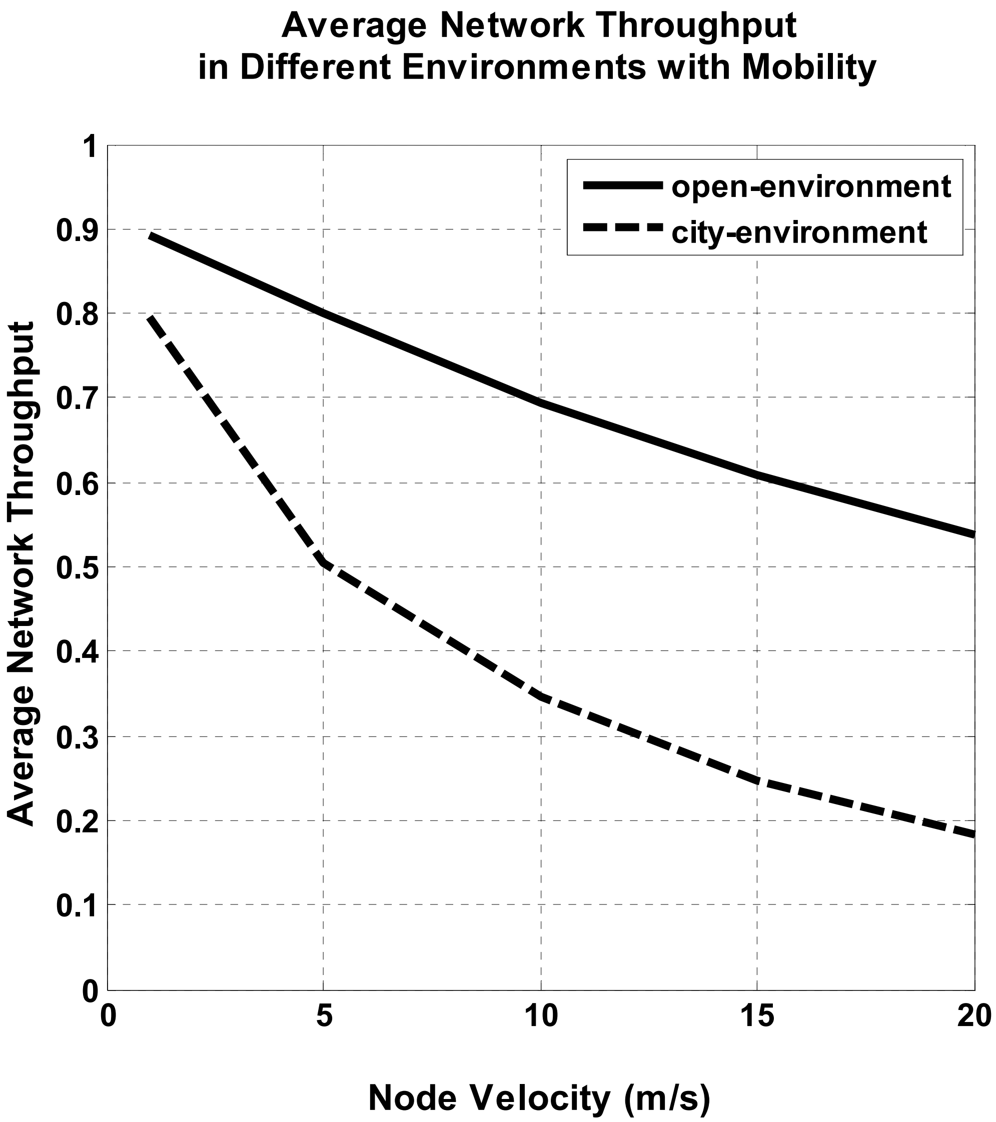


Figure 2-8 Average network throughput in open_environment and city_environment with node mobility

Further with increase in node's mobility, the probability of link breakage increases, and thus the throughput of the network decreases as seen in figure 2-8. Also, figure 2-9 shows that the percentage of nodes selected as MPR also increases with node's mobility as fading and probability of link breakage increase. With the increase in MPRs and frequent changes in the topology, higher number of TC messages is flooded throughout the network which is clearly seen in figure 2-10. Therefore, percentage of nodes selected as MPR and number of TC messages increase with node mobility.

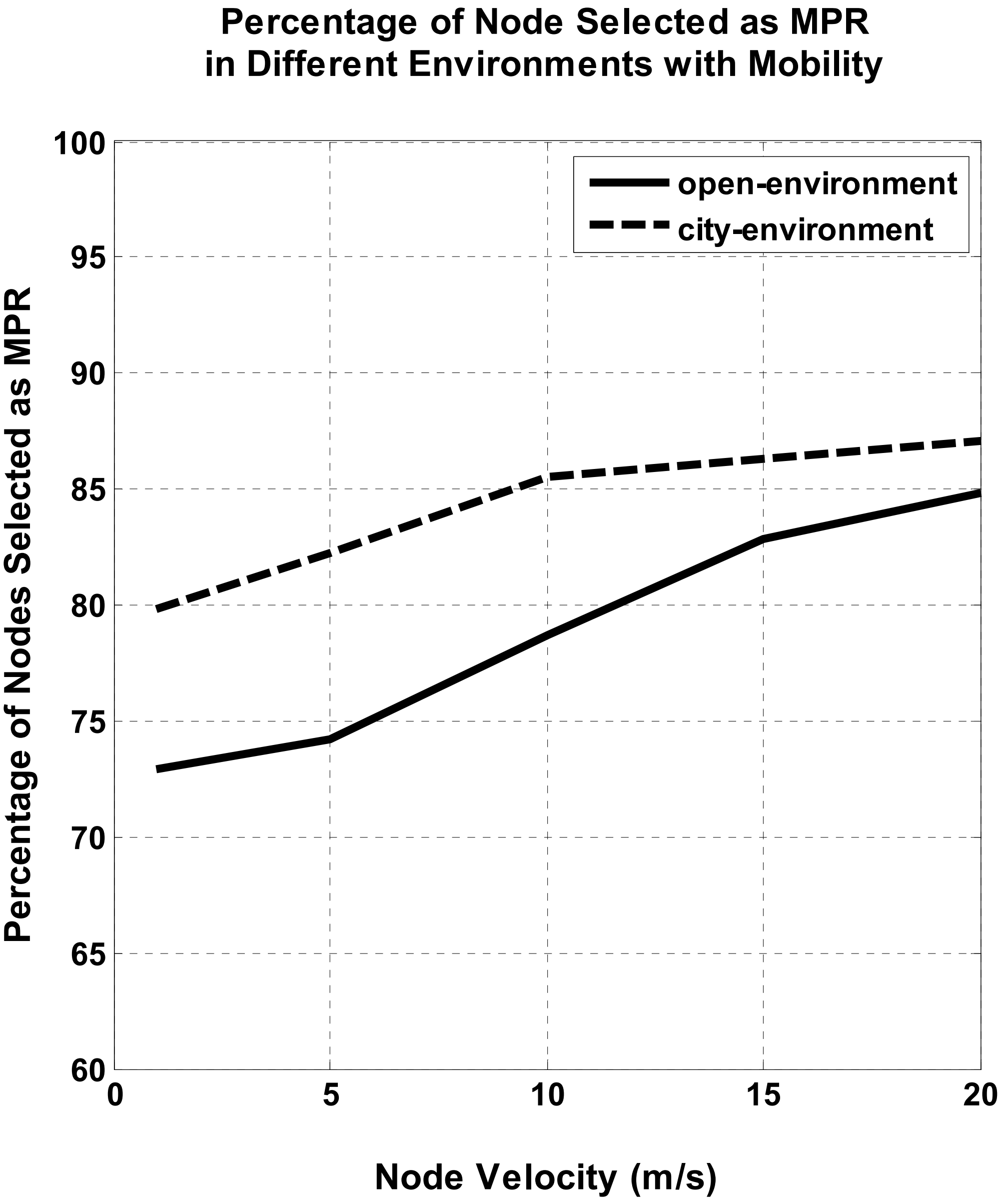


Figure 2-9 Percentage of nodes selected as MPR in open_environment and city_environment with node mobility

2.6. Conclusion

Propagation model which represents the propagation and fading losses that a signal experiences over a wireless channel is an integral part of a realistic ad hoc network simulation. It affects the metrics the routing protocol uses to route the data packets. We choose OLSR as a typical routing protocol for simulations to verify this concept.

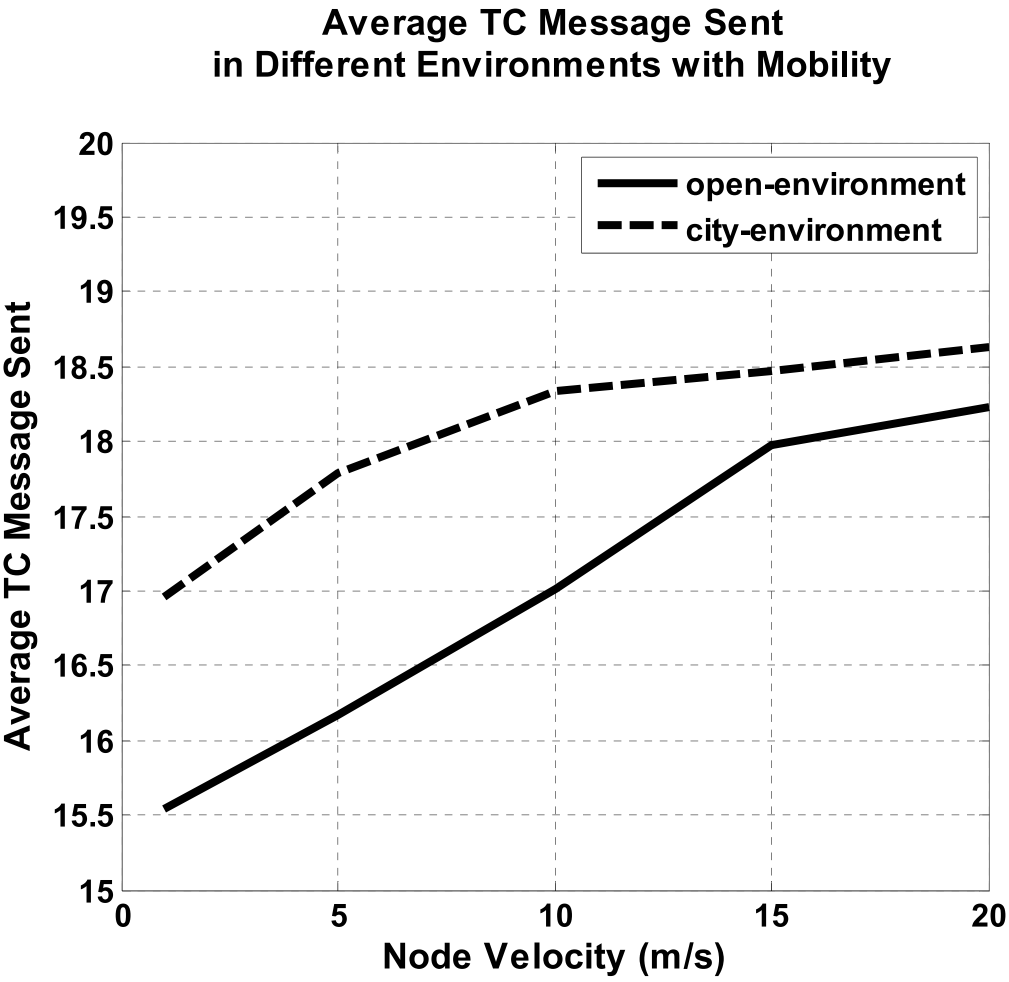


Figure 2-10 Average total TC message sent in open_environment and city_environment with node mobility

Simulation on performance of routing algorithm over open_environment and city-_environment has lead to two distinctly different outputs. Higher attenuation of signal in city_environment compared to open_environment limits the communication range of the nodes and degrades the quality of the wireless links. As a result, a higher packet delay and a lower throughput are observed in city_environment. This decrease in connectivity of the nodes increases the number of nodes that must be selected as MPRs. As the nodes selected as MPRs only broadcast and forward the TC packets, increase in MPRs leads to higher TC packets being flooded into the network thus increasing the routing packet overhead.

Further in both the environments, node mobility introduces additional fading of the signal and frequent changes in topology. Therefore throughput of a network significantly decreases as the node's mobility increases. This change in topology has to be reported throughout the network via control packets. Also, the number of MPRs selected also increases with mobility and therefore the number of control packets increases in the network.

Chapter 3

Adaptive Distributed Power Management Algorithm (DISPOW)

The adaptive Distributed Power Management (DISPOW) algorithm is presented here. The algorithm builds a unique stable network topology tailored to its surrounding node density and propagation environment in a dynamic mobile wireless channel. It will be shown that the algorithm stabilized node connectivity over the dynamic network environment and even prevents nodes from being completely disconnected from the network. It will also be shown that DISPOW reduces interference and routing overheads providing a shorter packet delay and improving network throughput.

3.1. Motivation

Power control algorithms have been studied primarily as a way to improve energy efficiency. They are an important consideration in Mobile Ad Hoc Network (MANET) because they can improve network capacity and node’s battery capacity. Without a central node to administer power management, building network topology is more challenging in wireless ad hoc networks. Further, if the ad hoc network is large consisting of thousands of nodes, then collecting information from all the nodes and passing it to the concerned nodes lead to high overheads.

Also majority of the existing power control algorithms employ a common power strategy that assigns equal power to all the nodes in the network to achieve some performance requirements. However, common power strategy depends on few nodes isolated in the network by physical location and environment. These isolated nodes might lead to unnecessarily high common node power level causing inter-node interference in denser parts of the network.

Additionally, reference [48] shows that the network topology and the performance of the routing protocol significantly depend on the dynamic physical environment and node mobility. Thus, there is also an inherent need for a power control algorithm to adapt to the surrounding node density, mobility and the physical environment. Therefore, power control algorithm for MANET must be adaptive, scalable and distributed.

We propose a novel dynamic multi-parameter optimization approach 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 because of node mobility and dynamic physical environment. This is notably beneficial because mobility aware topology control algorithm has been shown to provide robust network topology [49]. In addition to building strongly connected robust networks, DISPOW also focuses in developing low energy consumption and interference topologies. It limits node’s transmit power and functionality if its battery capacity deteriorates to a critical level to extend its lifetime. Topology control algorithms in [28] and [29] have presented frameworks on developing low-interference topologies. DISPOW has a receiver-based interference model which attempts to reduce inter-node interference. It also alleviates the main drawback of distributed approach by cooperatively converting asymmetric link to symmetric link if required. Thus, DISPOW operates in a completely distributed manner and is scalable and readily applicable to large heterogeneous networks.

The proposed algorithm DISPOW will be evaluated through analysis and simulation over a dynamic wireless channel. The propagation model is used to determine the Signal to Noise Ratio (SNR) and the Bit Error Rate (BER) of a communication link. In reality, multi-user networks are interference-limited rather than noise-limited. Interference from other nodes in the network can be more significant than background noise. Therefore, we will consider Signal to Interference and Noise Ratio (SINR) to determine the BER of a communication link. SINR and BER, in turn, determine the available bandwidth, stability of the link, error probabilities, and thus the number of retransmissions and signal coverage area.

3.2. Adaptive Distributed Power Management (DISPOW) Algorithm

The proposed adaptive distributed power management algorithm (DISPOW) that manages node transmit power to provide strongly connected network and minimize inter-node interference in the network.

3.2.1 Problem Definition

Consider a network of N nodes in an area A. If $P_{T_i}(t)$ and $\psi_i(t)$ represent the transmitting power and connectivity of node i in the network at time t respectively, then we need to select

$$P_{T_i}(t) \quad for\ node\ i\ \forall\ 1, 2, 3, \ldots\ldots, N$$

subject to the following four constraints:

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

$$\psi_i(t) \geq \psi_{i_{min}}(t) \quad for\ node\ i\ \forall\ 1, 2, 3, .., N \tag{3.1}$$

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}.

$$\begin{gathered} SINR_{ji}(t) = \frac{P_{ji}(t)}{P_0 + \sum_{\substack{k \epsilon T \\ k \neq j}} P_{ki}(t)} \geq \gamma_{th} \\ for\ node\ i\ \forall\ 1, 2, 3, .., N \\ where, \\ P_{ji}: Received\ power\ level\ from\ node\ j\ to\ node\ i \\ T: set\ of\ transmitting\ nodes\ causing\ interference \\ P_{ki}: Received\ power\ level\ from\ node\ k\ to\ node\ i \\ P_0: thermal\ noise \end{gathered} \tag{3.2}$$

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 total noise power P_{N_i} in node i, i.e.

$$\begin{gathered} min\ P_{N_i} \quad for\ node\ i\ \forall 1, 2, 3, .., N \\ where\ P_{N_i} = P_0 + \sum_{\substack{k \epsilon \mathcal{N} \\ k \neq j}} P_{ki}(t) \quad . \end{gathered} \tag{3.3}$$

A node that 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.

$$\psi_i(t) \leq \psi_{i_{max}}(t) \quad for\ node\ i\ \forall\ 1, 2, 3, .., N \tag{3.4}$$

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.

$$P_{T_{imin}} \leq P_{T_i}(t) \leq P_{T_{imax}} \quad for\ node\ i\ \forall\ 1, 2, 3, \dots, N \tag{3.5}$$

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, $C_{critical}$.

$$C_i(t) \geq C_{i_{critical}} \qquad for\ node\ i\ \forall\ 1, 2, 3, \dots, N \tag{3.6}$$

3.3.2. Relationships of Node Connectivity with Node Density, Transmit Power and Physical Network Environment

This section highlights the dependency of node connectivity ψ on node density ρ and physical network environment with path loss exponent, η. It also shows how a node can achieve certain ψ by changing its transmitting power P_T. The sensitivity analysis provides suitable range for the algorithm parameters.

Now, let us select node i as a reference node. We will model the wireless channel with the log-distance path loss propagation model. A wireless channel also suffers from random fading losses. The reasons for selecting these propagation models are discussed in Section IV. The propagation loss at the receiver d meter away from node i is given by

$$P_L dB = P_L(d_0)\ dB + 10\, \eta\ log(d) + L_{Fading} \tag{3.7}$$

where L_{Fading} is the fading loss due to shadowing and rayleigh fading effects and η is the propagation path loss exponent. $P_L(d_0)$ is the reference path loss at d_0 usually measured at 1 meter.

For a correct reception of packet, P_{T_i} should be enough to overcome the propagation loss and meet the receiver sensitivity, P_{rs}. It should be noted that in accordance with the 802.11 standard, a link in this paper is defined as acceptable or good if the power of the signal in the receiving node is greater than the P_{rs}. The P_{rs} can be calculated based on channel bandwidth, modulation and coding scheme used. The effects of carrier sense thresholds in topology control algorithms are analyzed in [50]. Then from (3.7) we have

$$P_{T_i}dB \geq P_{rs}dB + P_L(d_0)\ dB + 10\eta\ log(d) + L_{Fading}. \tag{3.8}$$

For simplicity, we are going to ignore fading loss in (3.8). The impact of fading channel on topology control algorithms are analytically presented in [51]. Simplifying (3.8), we get

$$\begin{aligned} & d\ \leq \sqrt[\eta]{\kappa\, P_{T_i}} \\ & where, \\ & P_{T_i} is\ the\ transmit\ power\ of\ node\ i\ in\ W \\ & \kappa = 10^{-(P_{rs}\ dB + P_L(d_0)\ dB)/10} \end{aligned} \tag{3.9}$$

Hence for a random node l to receive the packet successfully from node i, transmitting with an omni-directional antenna, node l must be in the coverage area of node i defined by a circle of radius d as given by (3.9).

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

$$\psi_i = \pi \, \rho \left(\kappa \, P_{T_i}\right)^{\frac{2}{\eta}} - 1 \, . \tag{3.10}$$

Clearly, ψ directly depends on ρ and also on P_T. It increases steadily with more nodes in the network as evident in figure 3-1. Also, ψ depends on the node's physical network environment through the propagation parameter η. This dependency of number of neighbors a node has on the propagation environment is shown in figure 3-2.

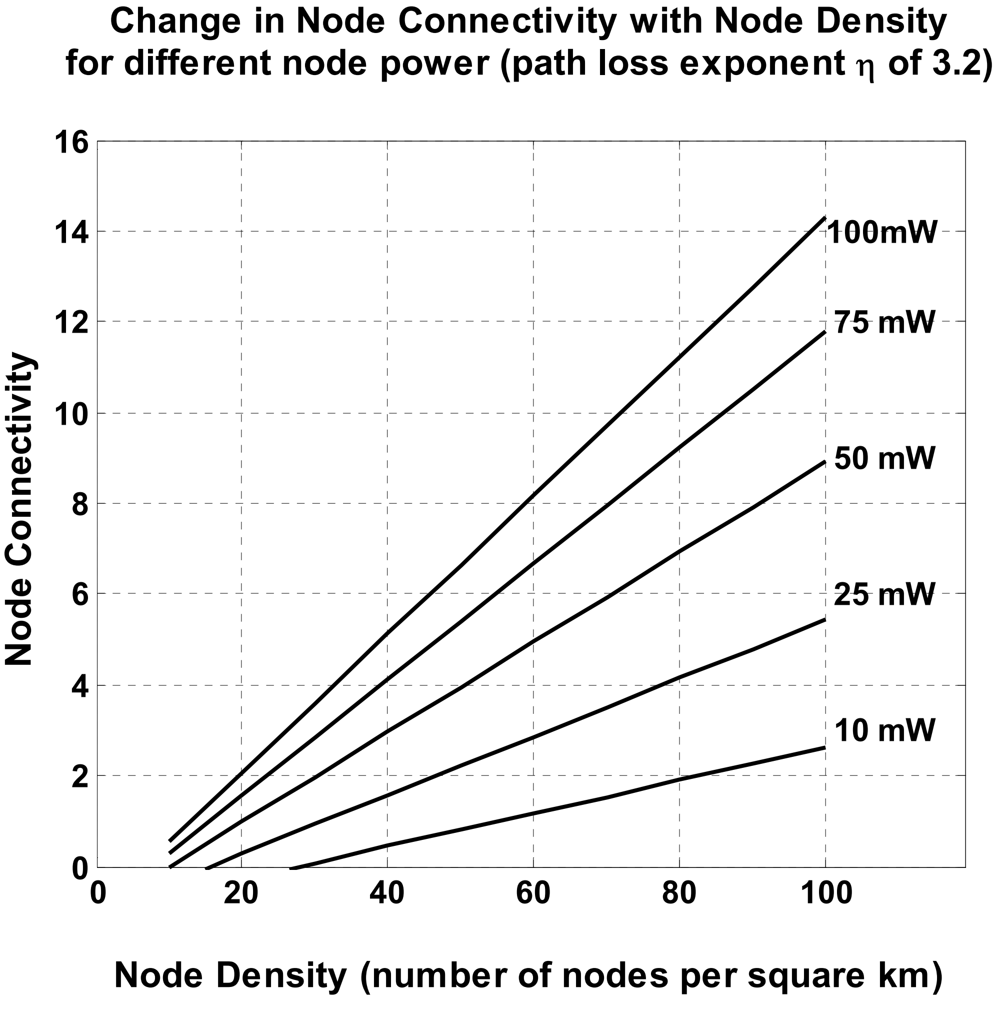


Figure 3-1 Change in node connectivity with node density for different node power

DISPOW adjusts node's P_T to maintain at least ψ_{min}. Thus, the mathematical lower bound P_{T_i} to guarantee $\psi_{i_{min}}$ is given in (3.11).

Lower bound: $$P_{T_i} \geq \frac{1}{\kappa}\left(\frac{\psi_{i_{min}}+1}{\pi\,\rho}\right)^{\frac{\eta}{2}} \tag{3.11}$$

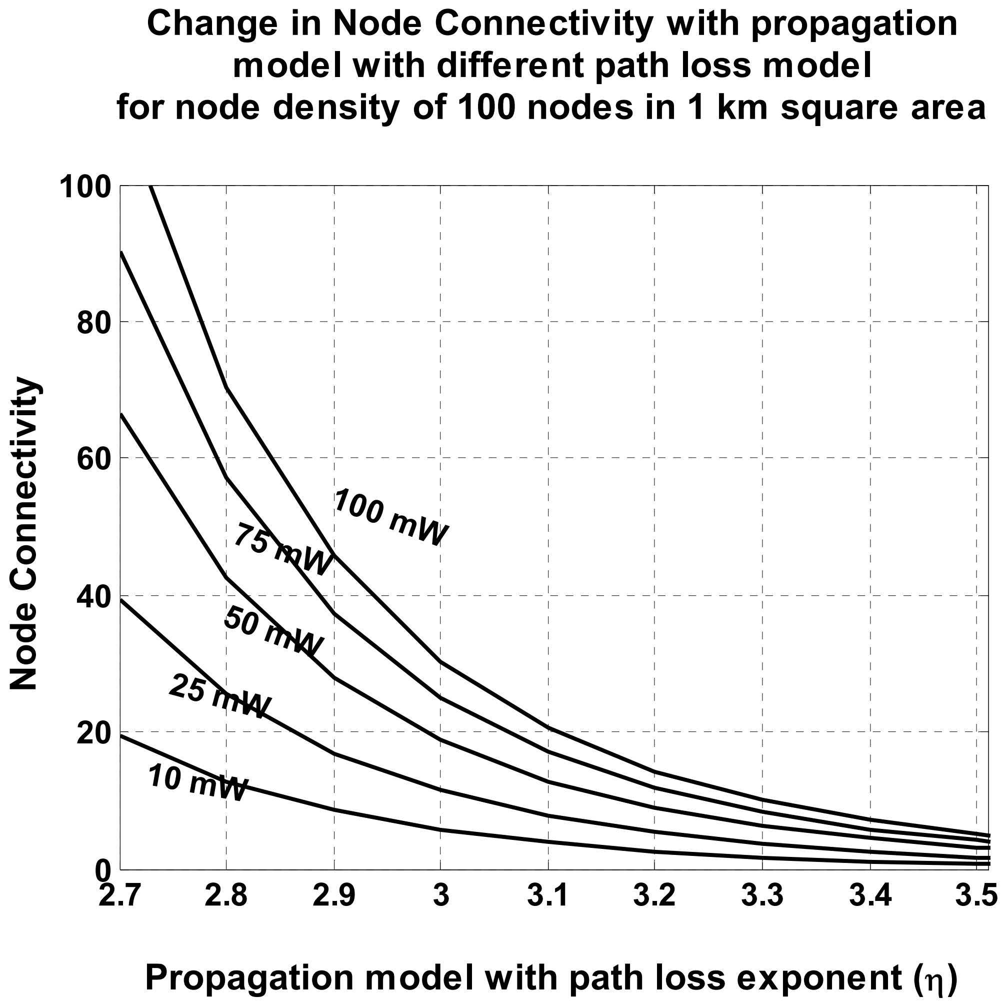


Figure 3-2 Dependence of node connectivity on propagation model with different path loss exponent η

Figure 3-3 shows how a node can maintain ψ by tailoring its P_T to the surrounding ρ and 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_{Tmin} and P_{Tmax} to maintain ψ between 2 and 14.

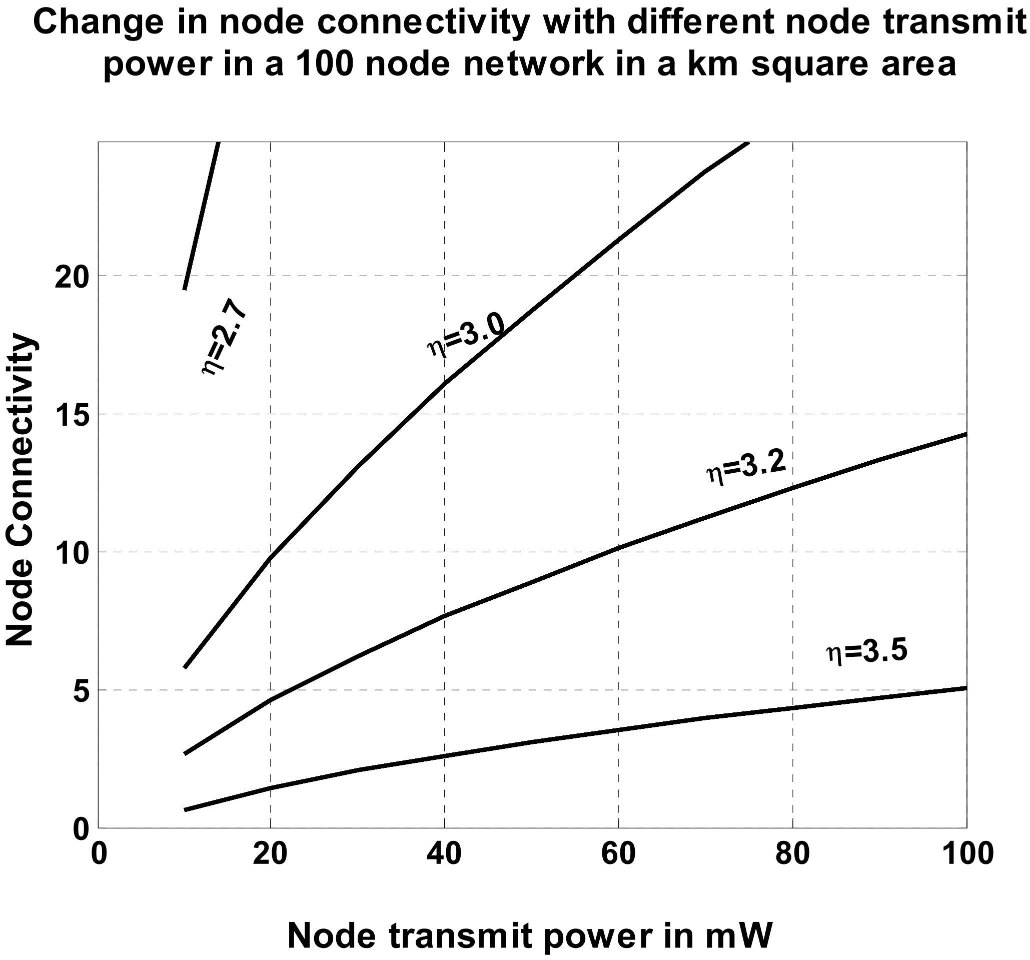


Figure 3-3 Effect in node connectivity by changing its transmit power in different propagation environments

A node i can increase its P_{T_i} by an increment, ΔP, in an attempt to build links with other nodes that are already not its neighbor. Similarly, the node i can also decrease its P_{T_i} with ΔP possibly losing links with some of its neighbors and still maintain at least minimum connectivity, $\psi_{i_{min}}$.

The consequent change in ψ_i because of these power level updates can be evaluated from (3.10) as

$$\Delta\psi_i = \pi\,\rho\,\kappa^{\frac{2}{\eta}}\left[\left(P_{T_i} \pm \Delta P\right)^{\frac{2}{\eta}} - \left(P_{T_i}\right)^{\frac{2}{\eta}}\right]. \tag{3.12}$$

Thus, ψ change significantly depends on ρ and η as evident in figure 3-4. It is interesting to note that, with ΔP of 5mW, $\Delta\psi$ is not even one neighbor in higher attenuating environment. Figure 3-4 clearly shows that $\Delta\psi$ also depends on the initial node power P_T . An adaptive power increment or decrement scheme with a certain probability of connectivity change will be more suitable. It is clearly evident that a node can effectively select its ψ by adjusting its P_T with respect to its surrounding ρ and attenuating propagation environment.

However, nodes can increase P_T indiscriminately and might end up interfering each other thus severely reducing network performance. DISPOW will keep the total interference level below a threshold, Γ_{inf}, so that a transmitting node i does not overwhelm nearby nodes. Simplifying from (3.3) and (3.8), we have

$$P_T\,dB \;\leq\; \Gamma_{inf} dB + 10n\log d + P_L(d_0)\,dB + \;P_0\;dB. \tag{3.13}$$

Given a specific ρ, the necessary BER for the wireless propagation environment and the P_{rs}, the interference threshold level Γ_{inf} can be roughly estimated.

Actual implementation of this model requires nodes to process the SINR of each transmitted packet. The SINR determines the BER of the signal depending on the wireless channel, modulation and coding schemes used. Thus, the simulation model in this paper considers the

SINR and the BER over the dynamic wireless channel when determining the link error probability and number of successful transmissions.

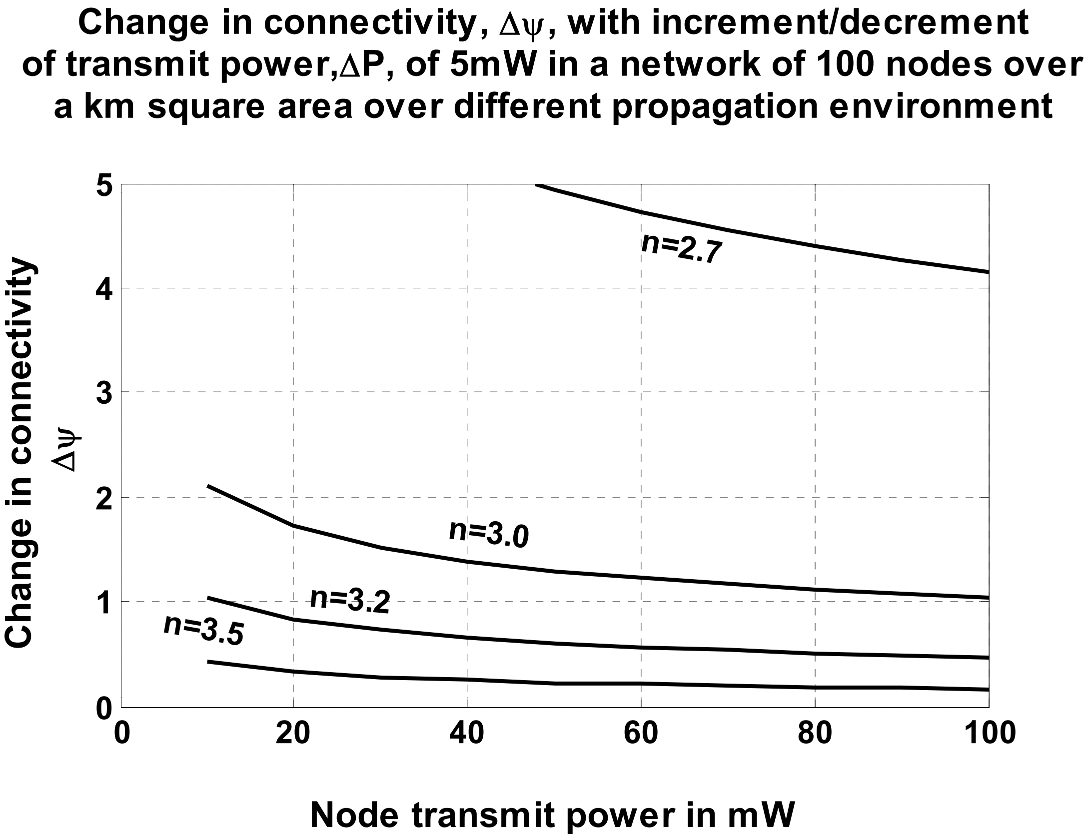


Figure 3-4 Change of connectivity with power increment or decrement over different propagation environments

3.3.3. The Proposed Algorithm, DISPOW

In the proposed algorithm, nodes continuously check their connectivity ψ, interference level from other nodes and their battery power C as shown in table 3-1. We assume that each node has no knowledge of other node's P_T.

Table 3-1. The Adaptive Distributed Power Management Algorithm (DISPOW)

DISPOW.Node

```
Set $P_{T_i} = P_{T_{initial}}$, compute $\psi_i$ and set timer=$\tau_{long\_delay}$
If $\psi_i \leq \psi_{i_{min}}$, then DISPOW.LowConnectivity
Else if $C_i < C_{i_{critical}}$, then DISPOW.CriticalBatteryLevel
Else if $\psi_i \leq \psi_{i_{max}}$, then DISPOW.HighConnectivity
Compute Connectivity Degree, $\psi_{DEG_i} = \frac{\psi_i - \psi_{i_{min}}}{\psi_{i_{max}} - \psi_{i_{min}}}$
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
```

For any node i, if its connectivity ψ_i is less than $\psi_{i_{min}}$ 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. Through a series of control messages exchanged or flooded in the network, a node can decipher if a neighbor has a symmetric or an asymmetric link to itself as listed in table 3-2.

If there are asymmetric links to the node, 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 to potential neighbors by increasing its P_{T_i} . Thus it's equally important for the potential neighbors 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 a 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 with potential neighbor nodes.

Table 3-2. DISPOW – Low connectivity

DISPOW.LowConnectivity

```
If $P_{T_i} < P_{T_{imax}}$, then calculate $P_{T_i} = P_{T_i} + \Delta P$ and
    set timer=$\tau_{short\_delay}$
Else set timer=$\tau_{long\_delay}$
If No Asymmetric link to itself, then
    broadcast PowerUp_Request and set timer=$\tau_{medium\_delay}$
```

Now if the node *i* moves into a dense area, it can probably afford to decrease its $P_T$as listed in table 3-3 and still maintain acceptable network connectivity. This has an advantage of reducing inter-node interference in the network. So if $\psi_i$is higher than $\psi_{i_{max}}$, it decreases its P_{T_i} and checks its ψ_i after τ_{short_delay}.

Table 3-3. DISPOW – High Connectivity

DISPOW.HighConnectivity

```
1. If $P_{T_i} > P_{T_{imin}}$ , then calculate $P_{T_i} = P_{T_i} - \Delta P$ and set
2.     timer=$\tau_{short\_delay}$
3. Else set timer=$\tau_{long\_delay}$
```

A node *i* will broadcast *PowerDown_Request*, as listed in table 3-4, if it suffers from interference greater than the threshold, Γ_{inf}. 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.

Table 3-4. DISPOW - Interference

DISPOW.Interference

```
1. Broadcast PowerDown_Request
2. Set TTL and hop count
```

Table 3-5 shows how a node reacts to receiving *PowerUp_Request* and *PowerDown_Request* from other nodes in the network. If a node receives a *PowerDown_Request*, it will decrease its P_T if its ψ_i is in a higher acceptable range. When it changes its P_T, 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_T. If it receives a *PowerUp_Request*, it increases its P_T only if its ψ_{DEG_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.

Table 3-5. DISPOW – *PowerDown/PowerUp* Request

DISPOW.PowerUp_Request

```
If $\psi_{DEG_i}$ in lowrange, then calculate $P_{T_i} = P_{T_i} + \Delta P$ and
    timer=$\tau_{short\_delay}$
Else set timer=$\tau_{long\_delay}$
```

DISPOW.PowerDown_Request

```
If $\psi_{DEG_i}$ in highrange, then calculate $P_{T_i} = P_{T_i} - \Delta P$ and
    timer=$\tau_{short\_delay}$
Else set timer=$\tau_{long\_delay}$
```

If at any instance node's battery capacity C_i is not sufficient, i.e. less than $C_{i_{critical}}$, it will reduce its P_{T_i} to maintain $\psi_{i_{min}}$ as listed in table 3-6. This has an effect of prolonging node battery and network lifetime.

Table 3-6. DISPOW – Critical battery level

DISPOW.CriticalBatteryLevel

```
If $\psi_{DEG_i}$ in highrange, then calculate $P_{T_i} = P_{T_i} - \Delta P$ and
    timer=$\tau_{short\_delay}$
```

```
3. Else set timer=$\tau_{long\_delay}$
```

It should be noted that the algorithm gives higher priority to achieve the lowest required connectivity and energy efficiency.

The list of main notations used is summarized in Table 3-7.

Table 3-7. Main Notations

N	Number of nodes in the network
A	Area of the network
$P_{T_i}(t)$	Transmitting power of node *i* at time *t*
ΔP	Transmit power increment/decrement
$\psi_i(t)$	Connectivity of node *i* at time *t*
ψ_{DEG_i}	Connectivity degree of node *i* specifying level of connectivity in an
$SINR_{ji}(t)$	Signal to Interference and Noise Ratio for a packet from node *j* to
P_{ki}	Received power level from node *k* to node *i*
$C_i(t)$	Battery capacity of node *i* at time *t*
P_L	Propagation loss at the receiver
ρ	Node density
η	Log-distance path loss model path loss exponent
d	Propagation distance between transmitting node and receiving node
L_{Fading}	Fading loss due to shadowing and rayleigh fading effects

3.4. Simulation Results

The performance of DISPOW on a dynamic network of 100 nodes randomly distributed over a 1000 meter by 1000 meter urban area, such as a city characterized by no LOS path and multipath effects, is evaluated through simulations on a complete system model in OPNET network simulator [52]. Additionally, extensive simulations conducted in MATLAB reinforced the results presented here.

We have conducted numerous simulations and sensitivity analysis in section III to find the upper and lower bound of the DISPOW algorithm parameters. In this paper, we have selected typical values for $P_{T_{imin}}$ and $P_{T_{imax}}$ at 5 mW and 100 mW. Node i can select the P_T between $P_{T_{imin}}$ and $P_{T_{imax}}$ at an increment ΔP of 5 mW. The time delays: τ_{short_delay}, τ_{medium_delay}, and τ_{long_delay} are set to 5, 10 and 15 seconds. These selections of time delays not only give nodes enough time to adjust to their new topology, but also do not overload the network with overhead. It should also be noted that the time delays are statically distributed around their mean value. This prevents simultaneous P_T change of all the nodes in the network and also gives node opportunity to react to P_T changes of its surrounding nodes.

All the nodes are configured with Optimized Link State Routing (OLSR) protocol, IEEE 802.11 MAC protocol and TCP traffic. Each node always has a packet of average size 1024 bits to send. OLSR is a proactive table driven protocol which optimizes the classic link state protocol by using only selected nodes called Multipoint Relay (MPR) to advertise links in the network [46].

3.4.1. Wireless Propagation Model

For the wireless propagation model, we will select an urban environment such as a city characterized by no LOS path and multipath effects due to many obstacles such as building and trees in the propagation path.

We will select log-distance path loss model with a path loss exponent η typically between 2.7 and 3.5 to model this physical environment. Random log-normally distributed fading due to surrounding environment clutter is modeled by log-normal shadowing model.

The performance of DISPOW will be evaluated over a dynamic pedestrian environment with nodes moving randomly with speed between 0 to 3 m/s with Random Waypoint Mobility Model (RWMM) [44]. It should be noted that the algorithm can also function seamlessly on network with highly mobile nodes. The small-scale fading will be modeled by the rayleigh fading model. The reasons behind selecting these wireless propagation models are discussed in [48].

Propagation model represented by (3.7) determines the Signal to Noise Ratio (SNR) at the receiving node. We will model the multi-user network as interference-limited rather than noise-limited and consider Signal to Interference and Noise Ratio (SINR) to determine the BER of a communication link. The SINR or the BER determines the quality of the link, the error probability and whether it can be selected for routing packets.

3.4.2. Network Topology

Figure 3-5 shows a topology of a random network without topology control with a common P_T of 5 mW. As clearly seen the network topology has few connected clusters. DISPOW builds a topology as shown in figure 3-6a on the initial network in figure 3-5. Detail analysis of connectivity distribution in the network shows that 11% of the nodes were disconnected in the initial network, figure 3-5. However with DISPOW, none of the nodes were disconnected from the network. Every node individually selects P_T that satisfies the parameters of the algorithm. Node power levels were distributed between the minimum and the maximum power rating as shown in figure 3-7 with an average P_T of 32 mW. It is interesting to note that two-thirds of the nodes have their P_T less than the average P_T and only about one-tenth of the nodes has $P_{T_{max}}$.

Further, figure 3-6b shows the network topology with a common node power of 32 mW (average P_T from DISPOW) i.e. with equivalent total energy consumption. Comparing figure 3-6a and figure 3-6b, it is clear that the common node power scheme leads to denser clusters. More importantly it leaves out sparsely connected nodes even some of them totally disconnected from the network. Without a well distributed power control mechanism, nodes nearby interfere with each other. Table 3-8 lists the average total interference level in figure 3-6a and figure 3-6b. Clearly, DISPOW algorithm yields a 32% reduction in average total interference compared with common power level in an equal energy consuming network.

Table 3-8. Average Interference Level in Equal Energy Consuming Network

Without DISPOW Management Algorithm	-73.23 dBm	
With DISPOW Management Algorithm	-74.96 dBm	32.86% less

Evaluating the performance of DISPOW over 100 random network topology, it is also clear from figure 3-8 that the average P_T increases with increasing attenuating environment. The average P_T also increases as ψ_{min} increases. Detailed analysis of power distribution shows that in low attenuating propagation environment most of the nodes have P_T less than the average P_T.

It is the few nodes in the network that are physically isolated that raise the total node power in the network.

3.4.3. Adapting to the Dynamic Network Topology

Figure 3-9 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 to 800 seconds during the simulation. It is clearly seen that ψ severely fluctuates during simulation and the node may even become completely disconnected from the network.

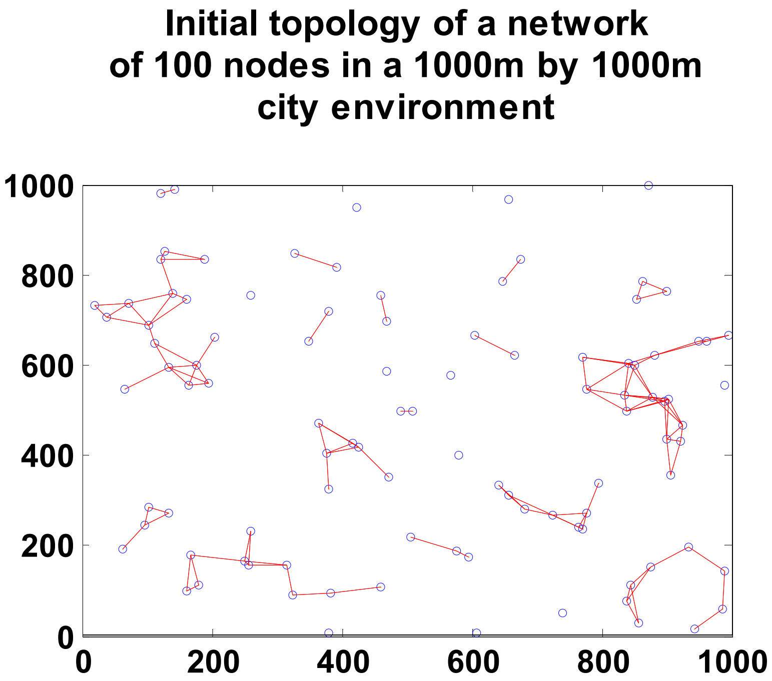
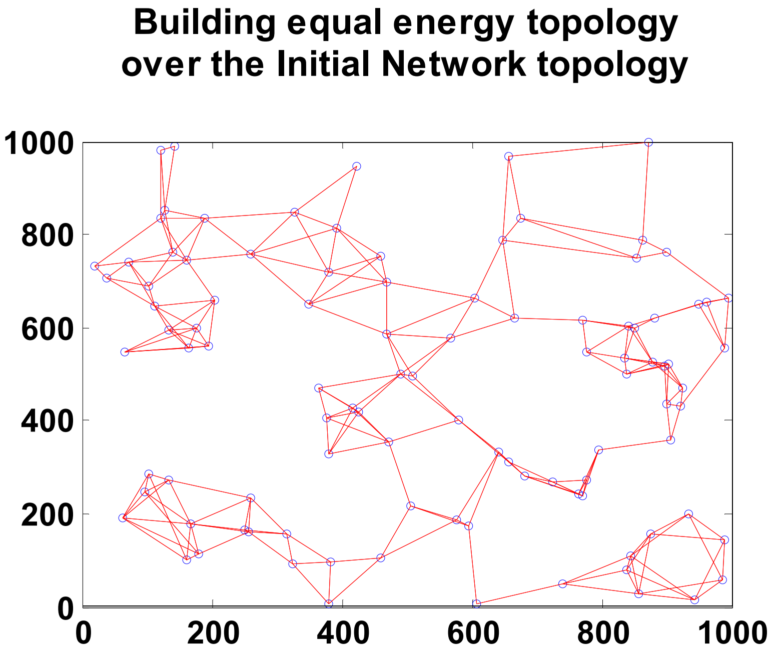
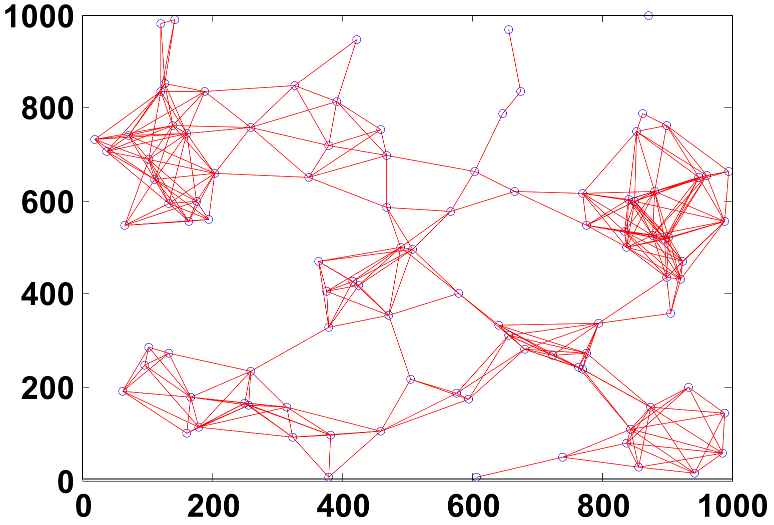


Figure 3-5 Initial topology of a network with 100 nodes randomly distributed over 1000m by 1000m city environment.



a) with DISPOW Algorithm



b) with common power level

Figure 3-6 Building equal energy network topology over the initial network topology with DISPOW and with common node power.

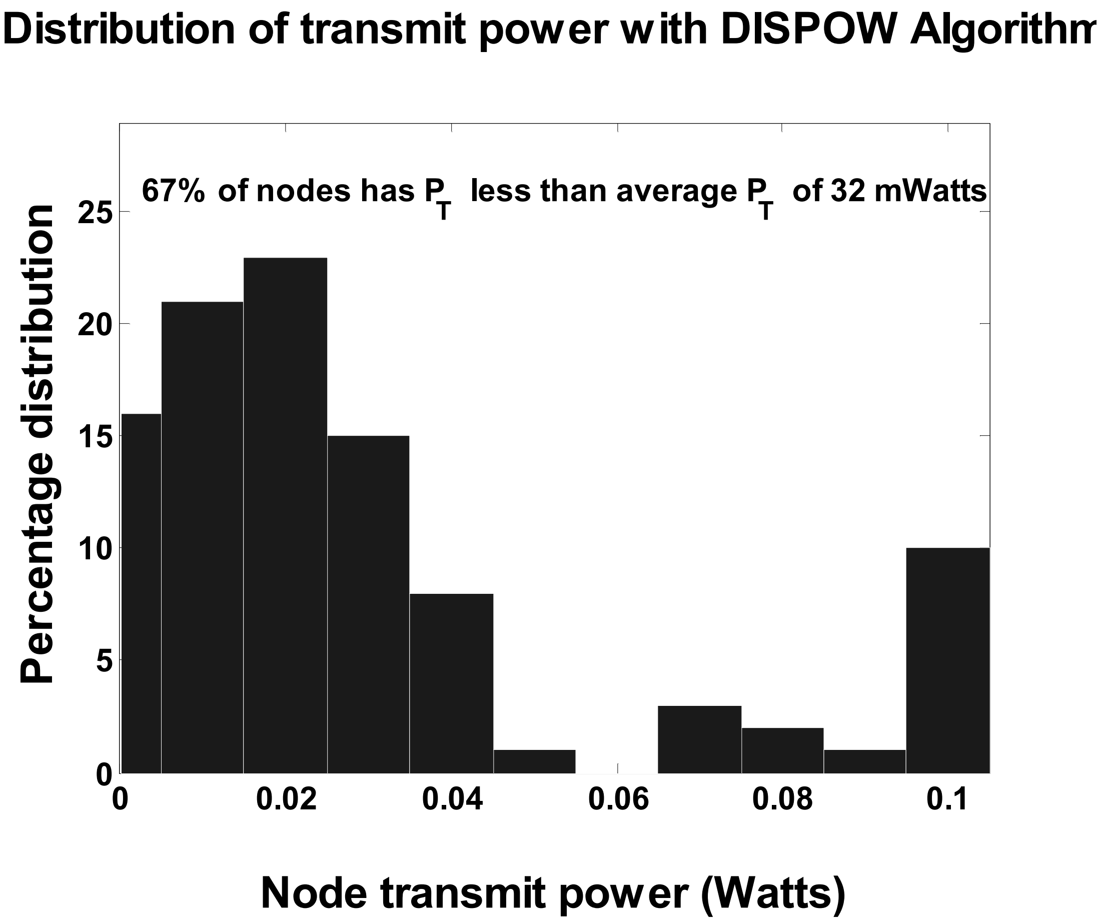


Figure 3-7 Distribution of transmit power of nodes in the network with DISPOW algorithm.

However with DISPOW, the same node initially decreases its P_T to 5 mW, as seen in figure 3-10, still maintaining acceptable ψ and reducing interference to its neighbors. Similar to the earlier scenario, the node moves to an area with low density around 700 seconds and starts loosing links with its neighbors. However, DISPOW realizes that ψ has decreased below the threshold and starts increasing its P_T as can be seen in figures 3-9 and 3-10. The node does not even get disconnected from the network at any point during the simulation.

Throughout the simulation, nodes without DISPOW were found to be totally disconnected with an average time of 2% compared to less than 0.1% of the time for nodes with DISPOW.

From the distribution of node connectivity in the network, seen in figure 3-11, it is clear that DISPOW maintains acceptable node connectivity instead of almost an even connectivity distribution from 0 to 20 for a network. It even prevents nodes, to a certain extent, from becoming disconnected from the network.

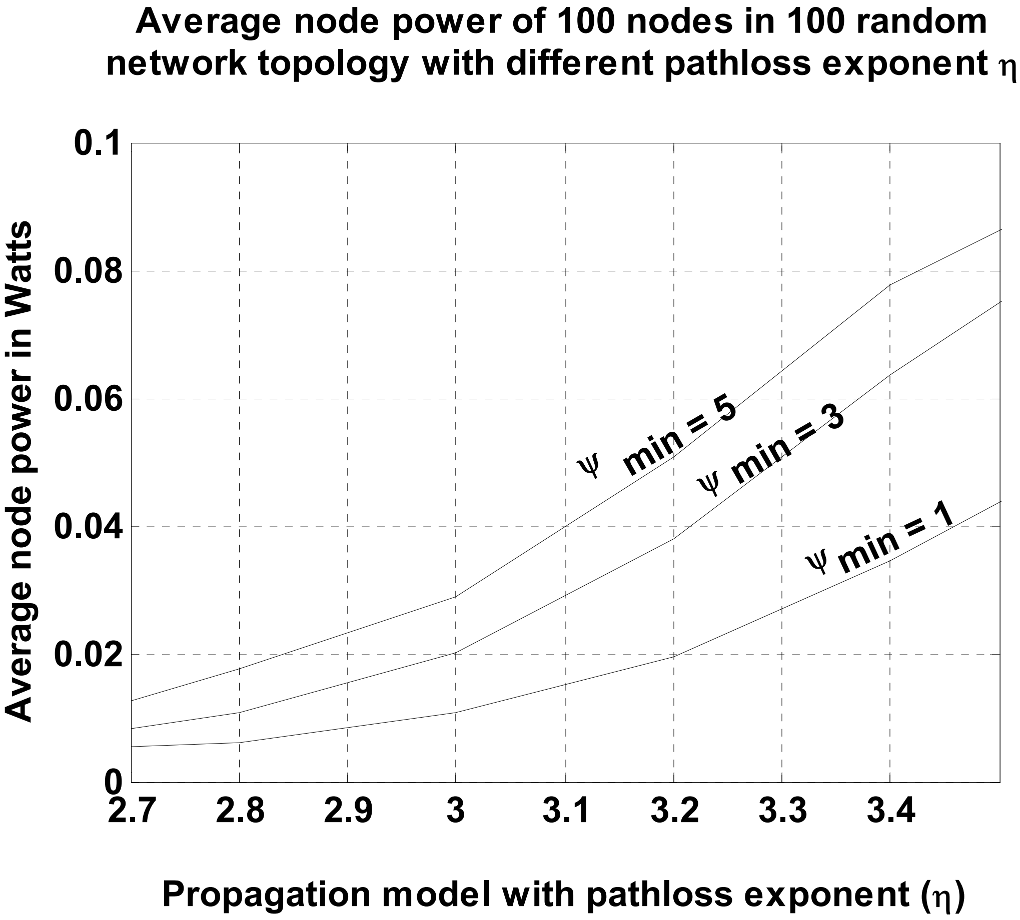


Figure 3-8 Average node power over different propagation environment

Detailed analysis of node power distribution, as shown in figure 3-12, demonstrates that approximately 57% of the nodes have their power level less than the initial power level of 15dBm. Only 7% of the nodes in low density area have their power level at its highest power level, $P_{T_{max}}$.

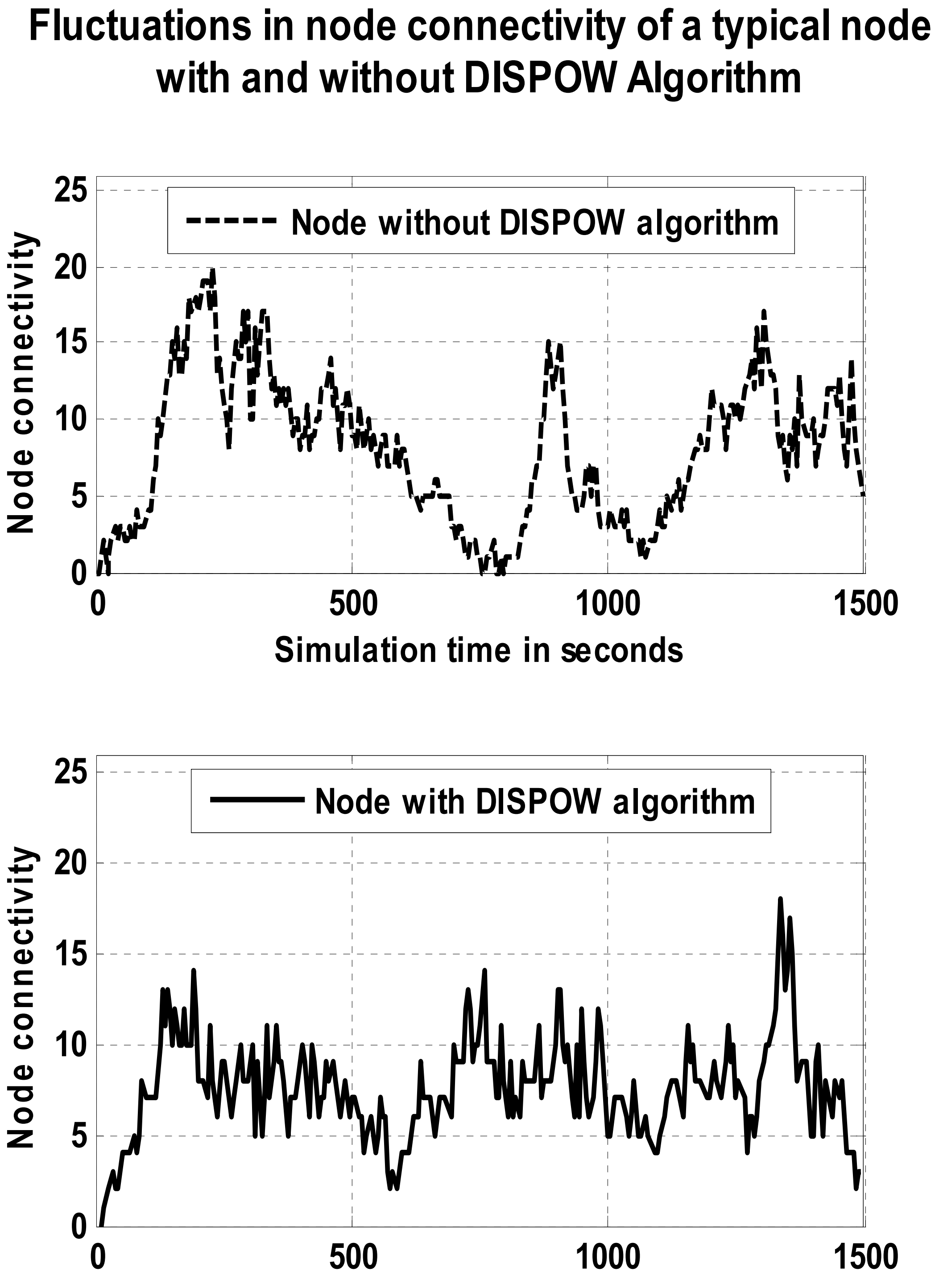


Figure 3-9 Fluctuation of connectivity of a typical node with and without DISPOW algorithm

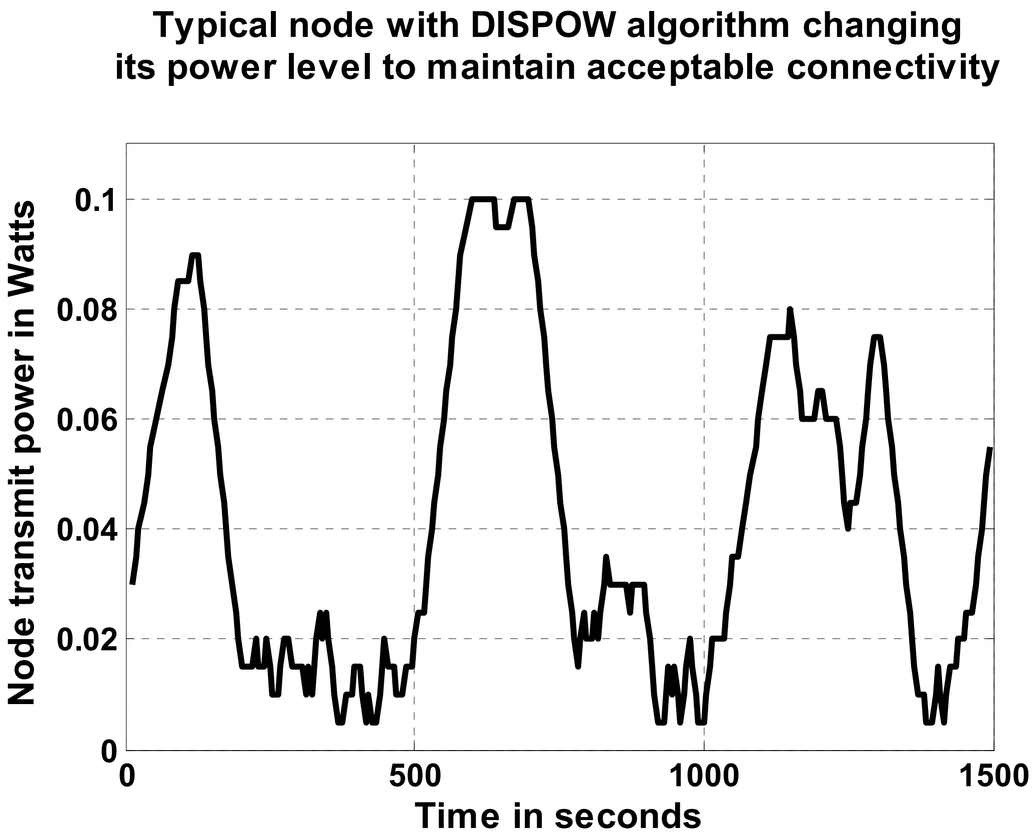


Figure 3-10 How node changes its transmit power to maintain connectivity with DISPOW algorithm

3.4.4. Network throughput, Packet Delay and Routing Overhead

Figures 3-1 to 3-6, 3-9 and 3-10 highlight the variation in routing parameters because of node distribution, node mobility, the dynamic nature of wireless channel and the physical environment. It is clearly seen in figure 3-9 that routing protocol with DISPOW reduces ψ and network topology fluctuations. DISPOW adapts much better to the changes in ρ, physical environment and node mobility thus reduces the average number of topology and neighborhood changes. It, therefore, provides strongly connected reliable network thereby reducing routing overhead by an average of 25%. This leads to shorter, better quality and stable routes; and therefore a 37% improvement on data packet throughput and about 12% lower average packet delay. The throughput, packet delay and routing overhead with and without DISPOW algorithm are listed in Table 3-9. It should be noted that the request power control packets sent between the nodes in the network are included within the periodic routing control packets.

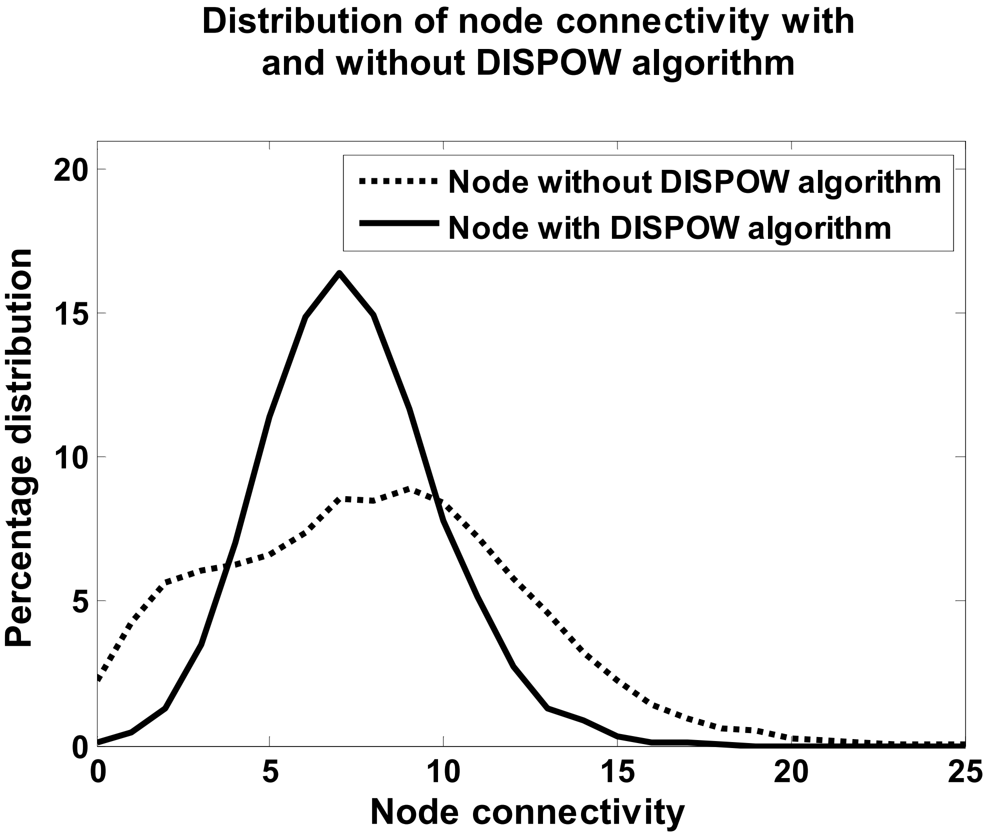


Figure 3-11 Distribution of connectivity of nodes in the network with and without DISPOW algorithm

3.4.5. Convergence and Stability of DISPOW

Running DISPOW over a network topology for sufficient time guarantees a stable solution with a level of confidence. Since P_T is incremented by $\pm\Delta P$ and is confined between $P_{T_{min}}$ and

$P_{T_{max}}$, the number of P_T steps $n_{St}(\Delta P)$ is $\left(P_{T_{max}} - P_{T_{min}}\right)/\Delta P$. Now, let us define Normalized Convergence Rate (NCR) as

$$NCR = \frac{n(\mathrm{T})}{n_{St}(\Delta P)} \tag{3.14}$$

$where,$

$n(\mathrm{T})$: $number\ of\ P_T\ steps\ needed\ to\ reach$
$steady\ state\ power\ levels\ for\ all\ the\ nodes$
$in\ topology\ \mathrm{T}.$

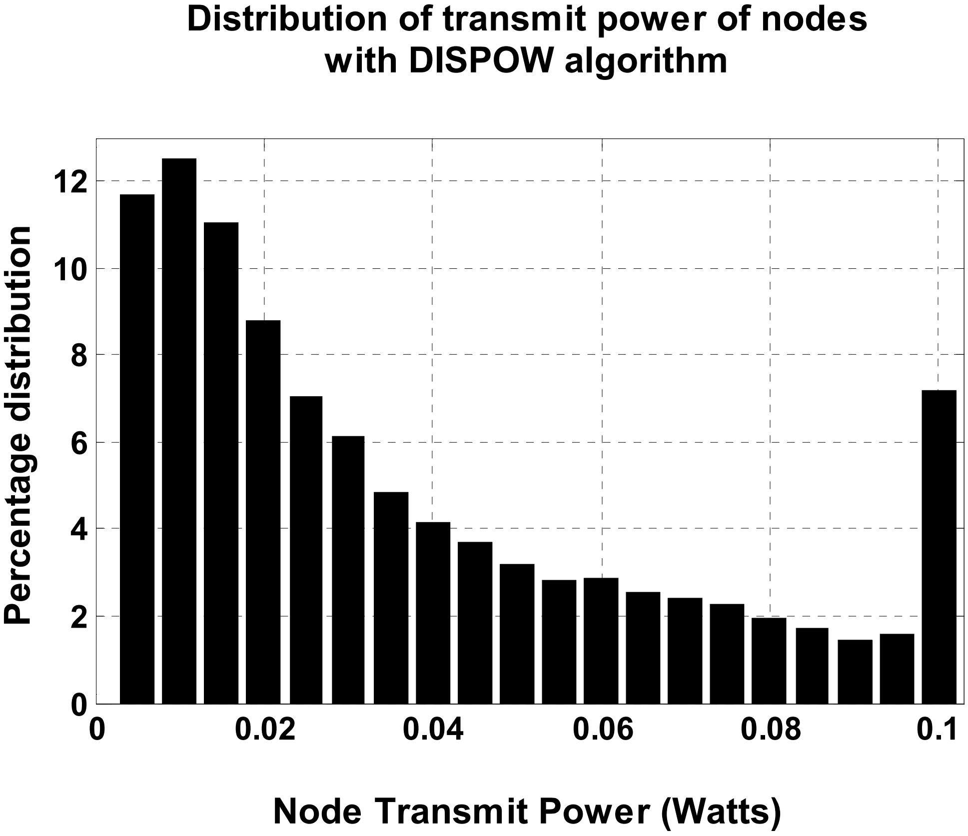


Figure 3-12 Distribution of transmit power of nodes in the network with DISPOW algorithm.

Basically $n(\mathrm{T})$ represents number of P_T changes across all nodes in the network until there are no further changes in any nodes within the network. Average NCR with ΔP of 10 mW over 100 random network topology is almost consistent at approximately 0.65 over ψ_{min} of 1 to 10 as seen in figure 3-13. Further, NCR was found to be lower at 0.55 with a shorter ΔP of 5 mW. It is clear that the algorithm converges, with almost a constant NCR, to a steady network topology with approximately same number of steps.

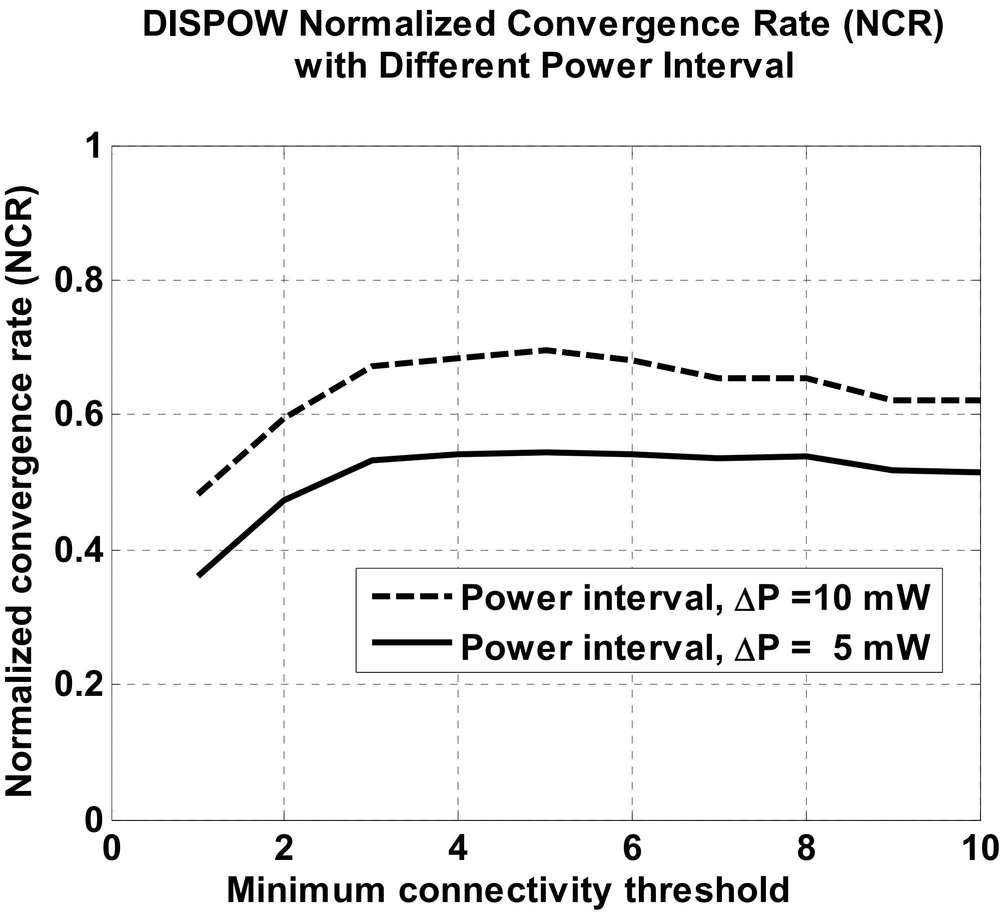


Figure 3-13 Normalized Convergence Rate (NCR) of DISPOW algorithm with power intervals, ΔP, of 5 mW and 10 mW.

3.4.6. Comparing with Common Node Power Strategy

We will compare the performance of DISPOW with our implementation of COMPOW (COMmon POWer) protocol [9] on OLSR routing protocol over 100 random network topologies.

COMPOW protocol aims to operate all nodes at a common power level which is chosen to be the smallest power level at which the network is connected. Strongly connected networks are also guaranteed by DISPOW with adequate power thresholds. COMPOW, however, leads to unnecessarily high common node power because of few isolated nodes in the network. This is the reason why the average node power with COMPOW is much higher than DISPOW as clearly seen in figure 3-14. An energy efficient power control algorithm will unquestionably increase the lifetime of the network. Further analysis of P_T distribution (for n=3.2) with DISPOW shows that about three-fourths of the nodes have P_T less than the average P_T. An increased average P_T inherently implies an increase in inter-node interference. In addition to that, common power needed to connect isolated nodes can cause high interference in a denser part of the network. Thus, the average node interference with COMPOW is much higher than that with DISPOW as seen in figure 3-15. It is also interesting that the node interference increases with ψ_{min}. It decreases in a higher attenuating environment as the higher attenuated propagating signal causes less inter-node interference.

Table 3-9. Throughput, Packet Delay and Routing Overhead

	DISPOW Management Algorithm		
	Without	With	
Throughput	243.09 kbits/sec	333.82 kbits/sec	37.32% increase
Packet delay	7.45 sec	6.53 sec	12.35% reduction
Routing overhead	610.54 kbits/sec	456.62 kbits/sec	25.21% reduction

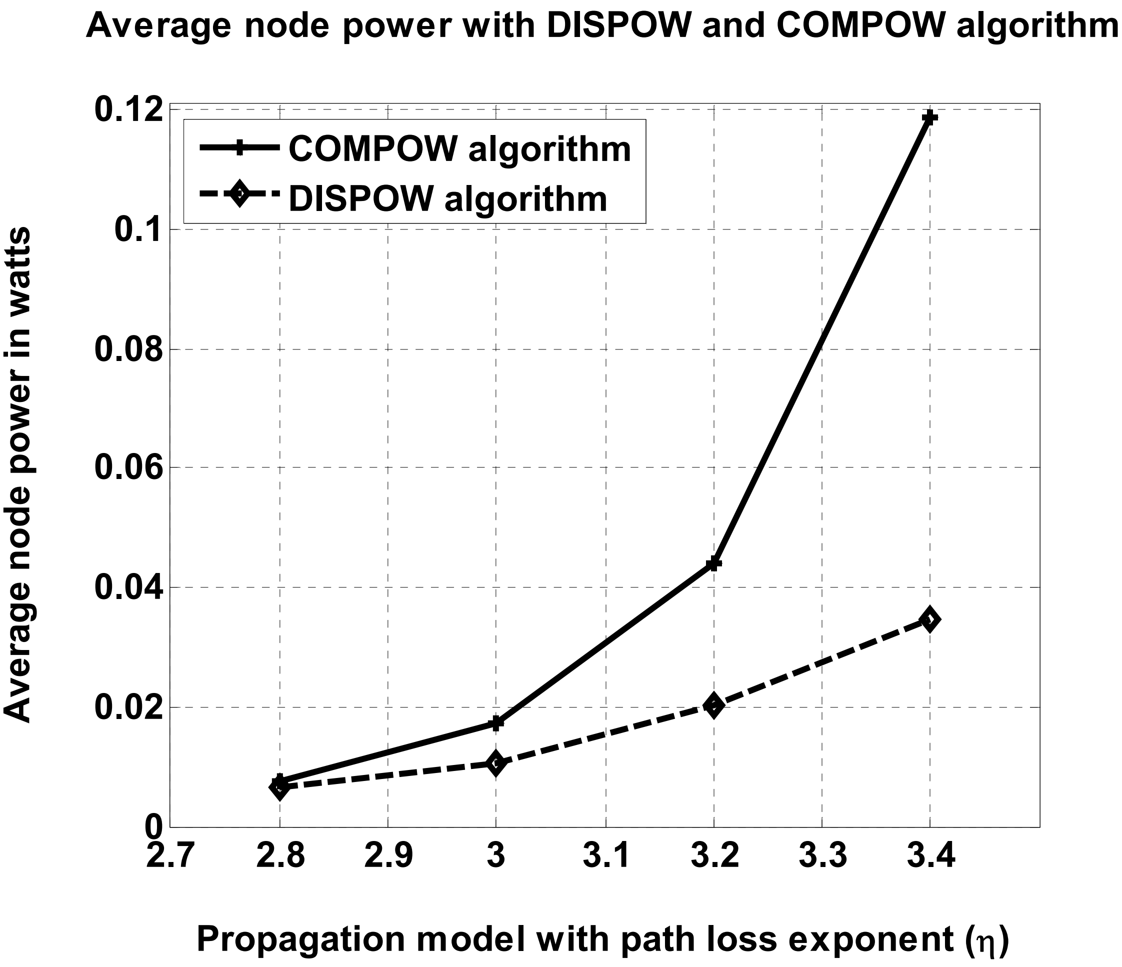


Figure 3-14 Average node power with COMPOW and DISPOW algorithms.

This reinforces the earlier argument that few nodes isolated by physical location and environment significantly dominate common power strategies.

3.5. Conclusion

DISPOW is a localized asynchronous generic algorithm that adaptively builds a stable network tailored to its surrounding node density and propagation environment. Topology of an equal energy consuming network without DISPOW algorithm leads to denser clusters that gives rise to inter-node interference and more importantly leaves isolated nodes totally disconnected from the network. Detailed analysis shows how more than two-thirds of the nodes with DISPOW have lower power level than the average power level in the network. It is the few isolated nodes that require high power level and are mainly responsible for raising the energy consumption of a network. By increasing node power, we inevitably increase interference in the network. However in the same network, DISPOW with a receiver-based interference model actually has lower interference than common power control.

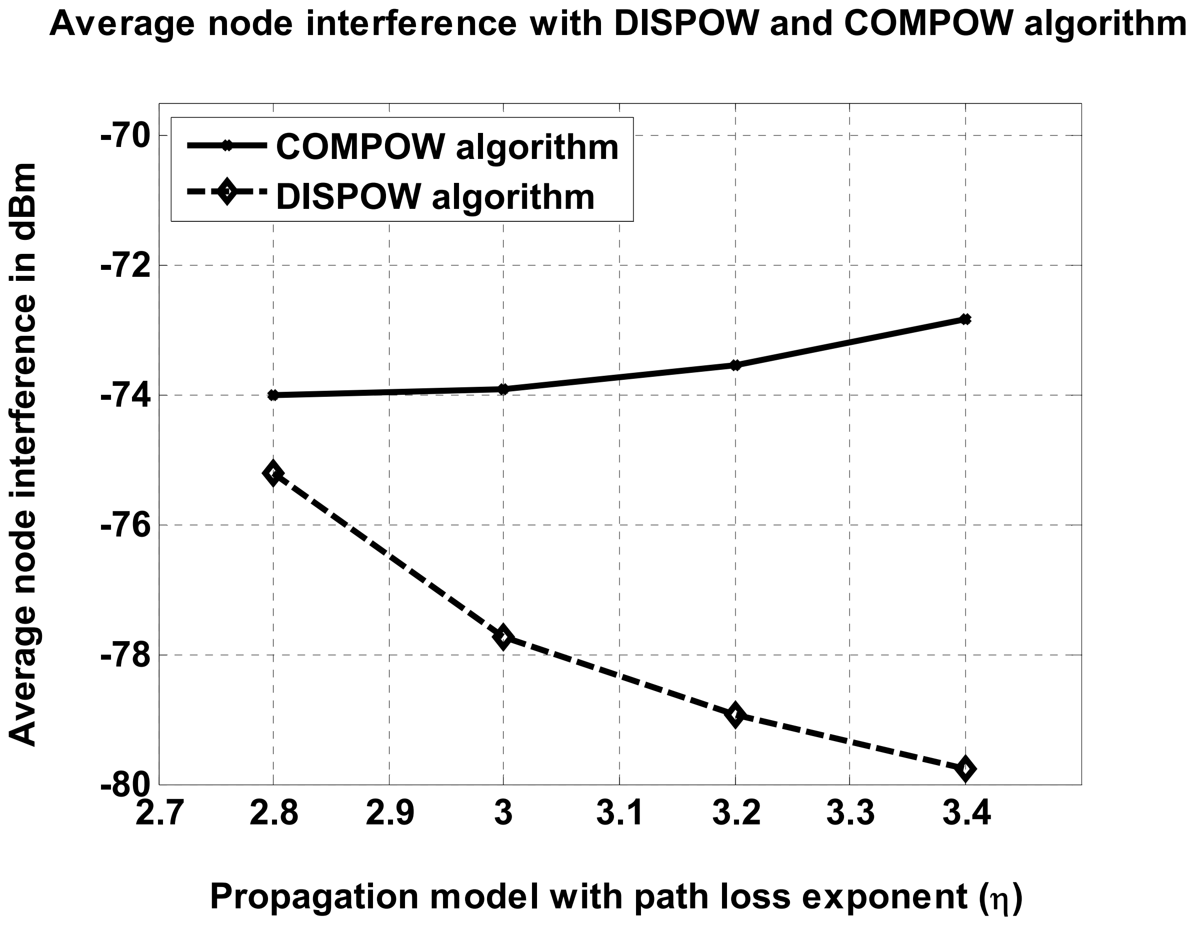


Figure 3-15 Average node interference with COMPOW and DISPOW algorithms.

Additionally, connectivity of a typical node is found to severely fluctuate due to the dynamic nature of wireless propagation channel and node mobility. Nodes are even disconnected from the network for significant period of time. It is clear from the results that the network adapts better to these changes with DISPOW. The proposed algorithm reduces node fluctuation even preventing node, to a certain extent, from becoming totally disconnected from the network. Thus, it reduces the changes in the node's neighbor and network topology providing stable strongly connected network. Simulation results show that DISPOW lowers routing overhead, interference and packet delay by approximately 25%, 33% and 12% respectively and improves throughput by as much as 37% in equal energy consuming networks.

It is also clearly evident that DISPOW, unlike common power schemes, is not heavily dependent on very small percentage of nodes in the network that are isolated by physical location and propagation environment. It adapts and provides a stable strongly connected interference-aware topology in a realistic network with non-uniform node distribution and dynamic propagation environment.

Chapter 4

Distributed Power Management Algorithm with Directional Antenna (DDISPOW)

Distributed Power Management Algorithm with Directional Antenna (DDISPOW) is presented here through theoretical and simulation analyses. DDISPOW couples power control algorithm with directional antenna to significantly reduce interference and increase network performance. It will be shown that DDISPOW can lower interference by an average of 73%. It highlights the benefits of using directional antenna leading to improved throughput and energy efficiency.

A comparative study of the algorithms, DDISPOW and DISPOW, with common power strategy COMPOW is presented over various network and physical propagation environments.

4.1. Motivation

Directional antenna offers a variety of potential benefits to power control algorithms. It can concentrate transmission energy in a specific direction and is an effective technique to reduce inter-node interference in a network. It increases channel utilization thus enhancing spatial reuse of the dynamic wireless channel. These benefits resulting from the use of directional antenna coupled with power control can significantly increase connectivity, reduce interference leading to a considerable increase in network performance.

Unlike the algorithm presented in section 1.2 the proposed localized algorithm DDISPOW develops a strongly connected network topology in a completely distributed manner tailored to its surrounding node density and propagation environment. It takes advantage of cross-layer design to provide an energy efficient strongly connected network in a dynamic topology and varying physical environment. In effect DDISPOW has a cross-layer design approach since the physical parameters and the environment effect feed into the routing protocol and the route establishment.

Additionally, DDISPOW also focuses in developing low energy consumption and low interference topologies. It limits node's transmit power and functionality if its battery capacity deteriorates to critical level to extend its lifetime. DDISPOW has a receiver-based interference model which attempts to lower inter-node interference and also has the capability of converting asymmetric link, which is a major source of concern, to symmetric link if required. DDISPOW operates in a completely distributed manner and thus is scalable and readily applicable to large heterogeneous networks.

To demonstrate the performance and capability of DDISPOW, it will be evaluated through analysis and simulation over a dynamic interference-limited wireless network. We will consider Signal to Interference and Noise Ratio (SINR) to determine the BER of a communication link. SINR and BER, in turn, determine the available bandwidth, stability of the link, error probabilities, and thus number of retransmissions and signal coverage area. Implementation of DDISPOW requires a suitable Medium Access Control (MAC) protocol. MAC protocol such as 802.11 assumes omni-directional antenna at its physical layer. And most of the work on wireless networks with directional antenna has been aimed at the design of MAC protocols. We will however select functional MAC layer and focus on network layer energy efficient topology control.

4.2. Distributed Power Management Algorithm with Directional Antenna (DDISPOW)

We propose an adaptive distributed power management algorithm with directional antenna (DDISPOW) that selects node transmit power for each sector of directional antenna to provide strongly connected network and minimize inter-node interference in the network.

4.2.1. System Model

Consider a network of N nodes in an area A. Let us consider that each node is equipped with switched-beam antenna that consists of M sectors. There are three types of directional systems: the switched beam antenna system, the steered beam antenna system, and the adaptive antenna system. The switched beam antenna system consists of several highly directive fixed, pre-defined beams of width θ of 2π/M and coverage area, A_s, of radius d_s defined by (4.9). A node uses only one of the beams for each transmission. In this paper, every node has M beams collectively covering all directions.

4.2.2. Problem Definition

If $P_{T_{is}}(t)$ and $\psi_{is}(t)$ represent the transmitting power and connectivity of node *i* sector *s* in the network at time *t* respectively, then we need to select

$$P_{T_{is}}(t) \qquad \begin{array}{l} \forall \;\; node \;\; i \; in \,\{1, 2, \dots, N\} \\ \forall \; sector \; s \; in \,\{1, 2, \dots, M\} \end{array}$$

subject to the following four constraints:

1. The node should have at least minimum connectivity, $\psi_{is_{min}}$, in each sector s i.e. minimum acceptable number of neighbors with which the node has a bi-directional link at any time t.

$$\psi_{is}(t) \geq \psi_{is_{min}}(t) \qquad \begin{array}{c} \forall \ \ node \ \ i \ in \ \{1,2,\dots,N\} \\ \forall \ sector \ s \ in \ \{1,2,\dots,M\} \end{array} \tag{4.1}$$

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}*, calculated in (4.2) must be greater than a threshold, γ_{th}.

$$SINR_{ji}(t) = \frac{P_{ji}(t)}{P_0 + \sum_{\substack{k \epsilon \mathrm{T} \\ k \neq j}} P_{ki}(t)} \geq \gamma_{th} \quad \forall \ node \ i \ in \ \{1,2,\dots,N\} \tag{4.2}$$

where,
T: $set \ of \ transmitting \ nodes \ causing \ interference$
P_{ki}: $Received \ power \ level \ from \ node \ k \ to \ node \ i$
P_0: $thermal \ noise$

A 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 total noise power P_{N_i} in node *i*, i.e.

$$\begin{array}{l} min \ P_{N_i} \qquad \forall \ node \ i \ in \ \{1,2,\dots,N\} \\ where \ P_{N_i} = P_0 + \sum_{\substack{k \epsilon \mathcal{N} \\ k \neq j}} P_{ki}(t) \\ k \ is \ nodes \ in \ node \ set \ \mathcal{N} \ expect \\ \quad trasmitting \ node \ j \ and \ receiving \ node \ i \end{array} . \tag{4.3}$$

If a node has high connectivity in a sector *s*, then it can probably afford to decrease its transmitting power P_{Ts} and still maintain acceptable ψ_s. Let $\psi_{is_{max}}(t)$ be the maximum number of neighbors allowed in a sector, i.e. the upper acceptable connectivity threshold. This has an advantage of decreasing interference in nodes closer to the transmitting node.

$$\psi_{is}(t) \leq \psi_{is_{max}}(t) \quad \begin{matrix} \forall\ node\ \ i\ in\ \{1, 2, \ldots, N\} \\ \forall\ sector\ s\ in\ \{1, 2, \ldots, M\} \end{matrix} \tag{4.4}$$

3. The $P_{T_{is}}$ for node i sector s should be equal to or more than the minimum power level, $P_{T_{ismin}}$, but less than or equal to the maximum power level, $P_{T_{ismax}}$, as defined by network and node power specifications.

$$P_{T_{ismin}} \leq P_{T_{is}}(t) \leq P_{T_{ismax}} \quad \begin{matrix} \forall\ node\ \ i\ in\ \{1, 2, \ldots, N\} \\ \forall\ sector\ s\ in\ \{1, 2, \ldots, M\} \end{matrix} \tag{4.5}$$

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 node i to increase its $P_{T_{is}}$ if its C_i is higher than the critical battery power level, $C_{i_{critical}}$.

$$C_i(t) \geq C_{i_{critical}} \qquad \forall\ node\ i\ in\ \{1, 2, \ldots, N\} \tag{4.6}$$

4.2.3. Relationships of Node Connectivity with Node Density, Transmit Power and Physical Network Environment

We will highlight the dependency of sector connectivity ψ_s on node density ρ and physical network environment with path loss exponent η. It also shows how a node can achieve a certain ψ_s by changing its transmitting power P_{T_s}. This sensitivity analysis will provide a guide for suitable range of algorithm parameters.

We will model the wireless channel with the log-distance path loss and fading propagation model. The propagation loss at the node receiver d_{is} meter away from node i in sector s, assuming a unit reference distance d_0, is given by

$$P_L = P_L(d_0) + 10\,\eta\,\log(d_{is}) + L_{Fading} \tag{4.7}$$

where L_{Fading} is the fading loss due to shadowing and rayleigh fading effects and η is the propagation path loss exponent. $P_L(d_0)$ is the reference path loss at d_0.

For a correct reception of packet, $P_{T_{is}}$ should be enough to overcome the propagation loss and meet the receiver sensitivity, P_{rs}. Then from (4.7) we have

$$P_{T_{is}}dB \geq P_{rs}dB + P_L(d_0) + 10\eta \log(d_{is}) + L_{Fading}. \tag{4.8}$$

Simplifying (4.8) by ignoring fading loss we get

$$d_{is} \leq \sqrt[\eta]{\kappa\, P_{T_{is}}}\ , \quad \text{where } \kappa = \left(P_{rs} * P_L(d_0)\right)^{-1}. \tag{4.9}$$

Therefore for a randomly distributed node *l* to receive packets successfully from node *i*, transmitting with an directional antenna with *M* sectors, node *l* must be in the coverage area of node *i* defined by sector area, A_{is}, of radius d_{is} as given by (4.9).

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 each equal sector area A_{is} is given by

$$\psi_{is} = \frac{\pi\rho}{M}\left(\kappa\, P_{T_{is}}\right)^{\frac{2}{\eta}} - 1. \tag{4.10}$$

Clearly, sector connectivity, ψ_s, directly depends on number of sectors *M*, ρ and the physical environment through the propagation parameter η as seen in Figures 4-1 and 4-2. It increases steadily with more nodes in the network as evident in Figure 4-1. Also, ψ_s depends on the node's physical network environment through the propagation parameter η. This dependency of number of neighbors a node has on the propagation environment is shown in Figure 4-2.

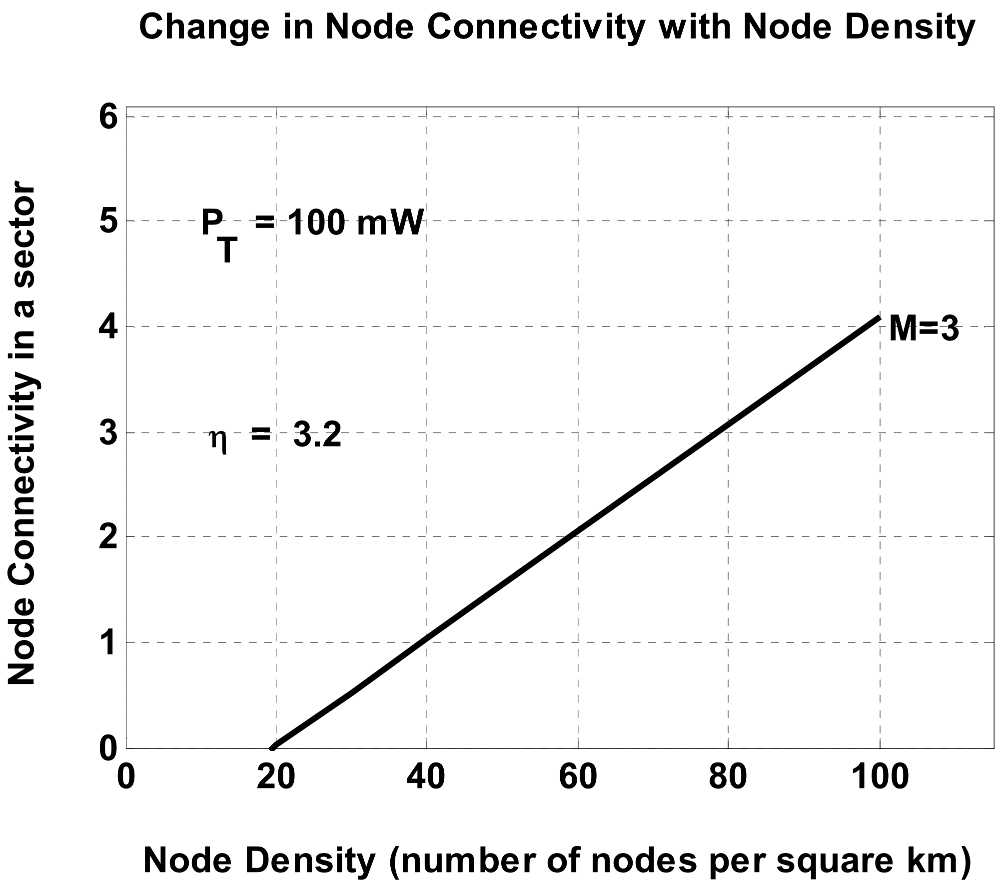


Figure 4-1 Change in node connectivity with node density for different directional antenna with M sectors.

Therefore by adjusting sector power level, P_{T_s}, node with DDISPOW can maintain at least $\psi_{s_{min}}$. Thus the mathematical lower bound, $P_{T_{is}}$, of node *i* to guarantee $\psi_{is_{min}}$ is given in (4.11).

Lower bound: $$P_{T_{is}} \geq \frac{1}{\kappa}\left(\frac{M\,(\psi_{is_{min}}+1)}{\pi\,\rho}\right)^{\frac{\eta}{2}} \tag{4.11}$$

Figure 4-3 shows how a node can preserve its ψ_s by tailoring its $P_{T_s}$to ρ and propagation environment.

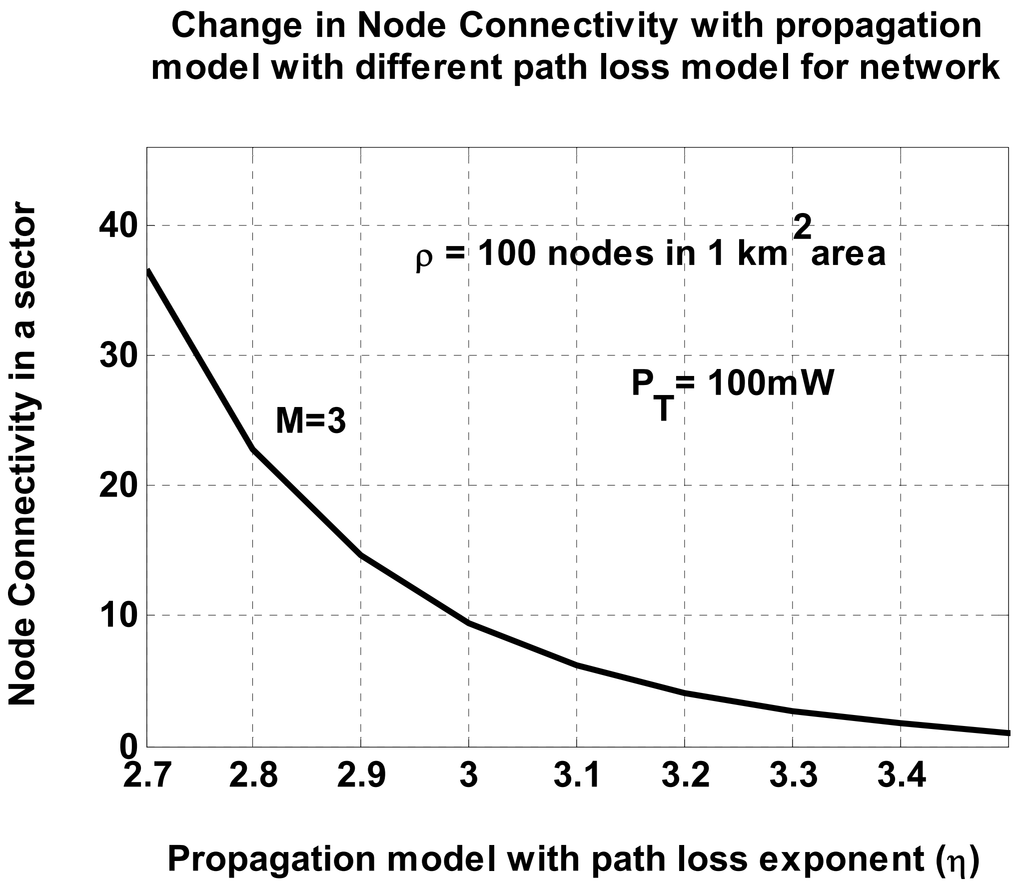


Figure 4-2 Dependence of node connectivity on propagation model for different directional antenna with M sectors.

Assuming node *i* increases its $P_{T_{is}}$ in sector *s* by an increment, ΔP, in an attempt to build links with other nodes that are already not its neighbor in the network. Similarly, a node, in an attempt to reduce interference, can also decrease its $P_{T_{is}}$ by ΔP possibly losing links with some of its neighbors and still maintain at least $\psi_{is_{min}}$. The consequent change in connectivity, $\Delta\psi_{is}$, because of these power level updates can be evaluated as

$$\Delta\psi_{is} = \frac{\pi\,\rho}{M}\,\kappa^{\frac{2}{\eta}}\left[\left(P_{T_{is}} \pm \Delta P\right)^{\frac{2}{\eta}} - \left(P_{T_{is}}\right)^{\frac{2}{\eta}}\right]. \tag{4.12}$$

Therefore, $\Delta\psi$ significantly depends on ρ and physical network environment with path loss exponent η as seen in Figure 4-4. It is clearly evident that a node can effectively select its ψ_{is} by adjusting its $P_{T_{is}}$ with respect to its surrounding ρ and attenuating propagation environment. An adaptive power increment or decrement scheme with a certain probability of connectivity change will be more suitable.

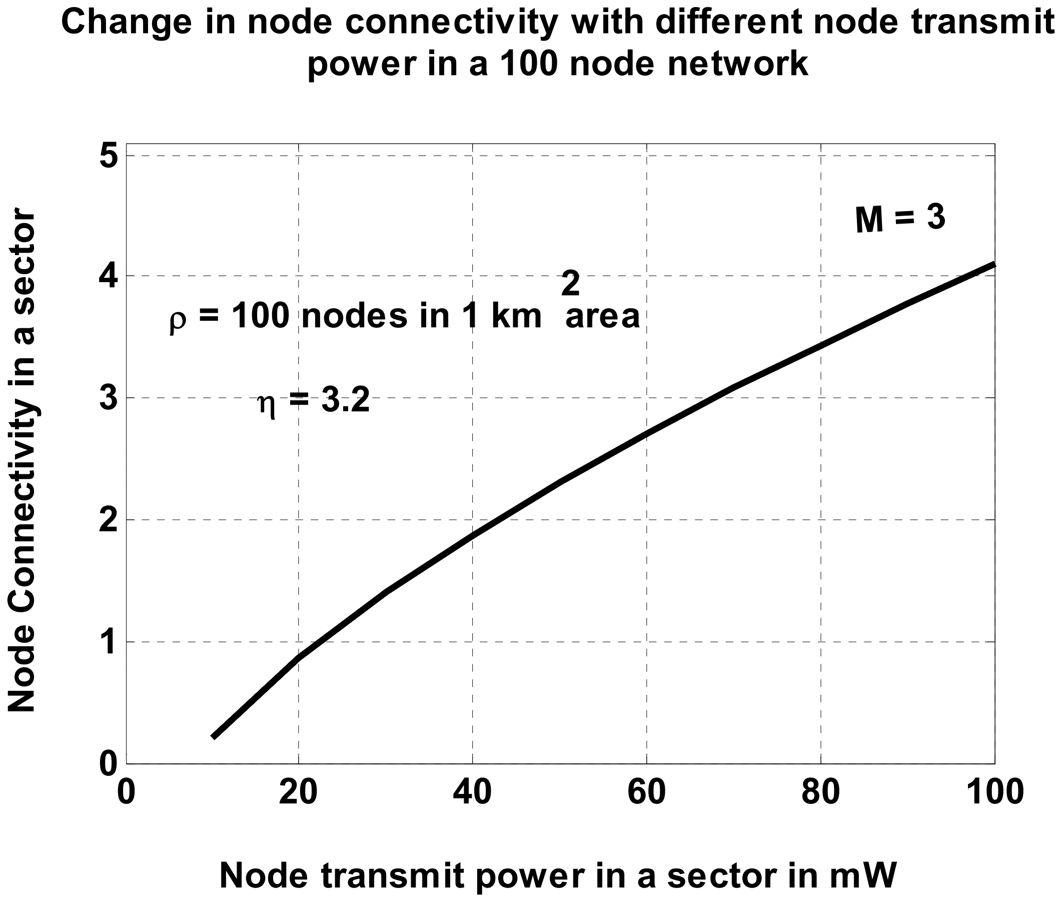


Figure 4-3 Effect in node connectivity by changing its transmit power for different directional antenna with M sectors.

However nodes can increase P_{Ts} indiscriminately and might end up interfering each other, thus severely reducing network performance. DDISPOW will keep the total noise floor below a threshold, Γ_{inf}, so that a transmitting node i does not overwhelm nearby nodes. Given a specific ρ, the required SINR or BER, and wireless propagation environment, we can approximately estimate the interference threshold level.

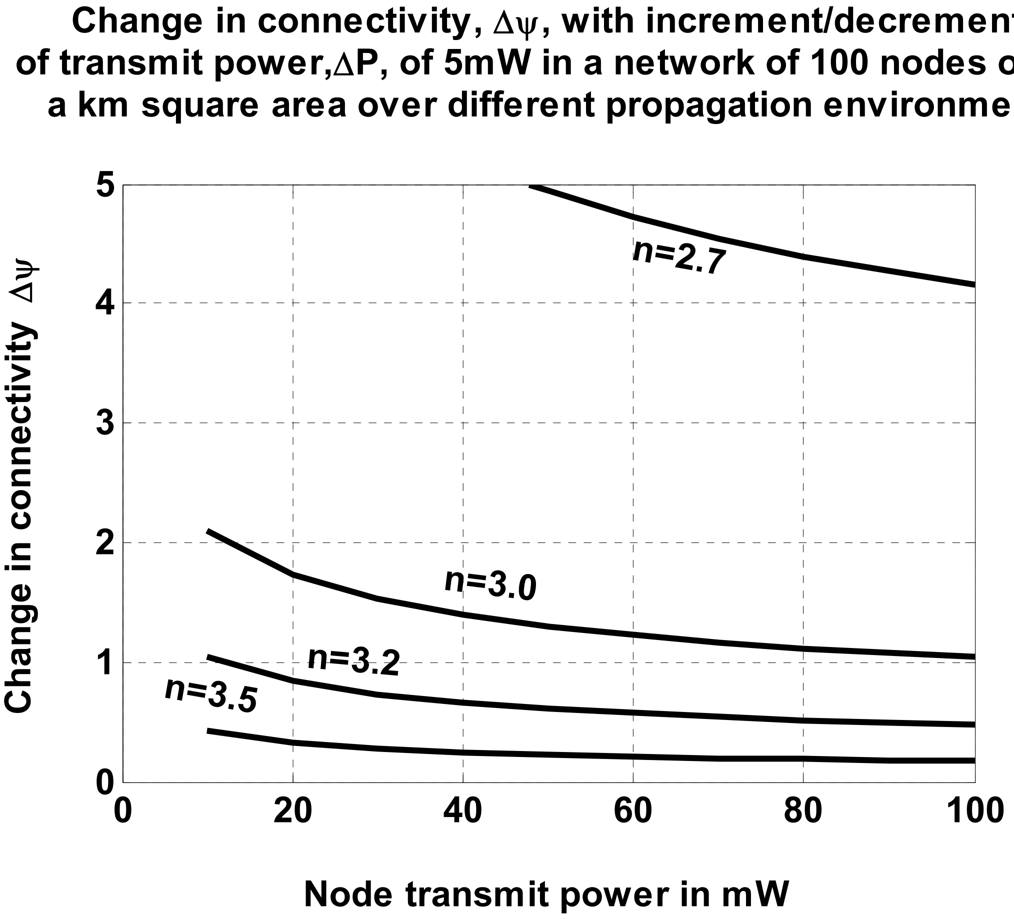


Figure 4-4 Change in node connectivity with power increment or decrement over different propagation environment with directional antenna with M sectors.

4.2.4. The Proposed Algorithm, DDISPOW

In the proposed algorithm, shown in Table 4-1, nodes periodically check their connectivity in every sector ψ_s, interference level and their battery power C. We assume that each node is equipped with switched-beam antenna of M sector and is fully capable of transmitting directionally. We also assume that nodes do not have any knowledge of other nodes' transmit power level.

If, at any time, the connectivity of node *i* in sector s, ψ_{is}, is less than $\psi_{i_{min}}$, it will increase its $P_{T_{is}}$ to improve its ψ_{is}. It checks if there are any uni-directional links with potential neighbor nodes. If there are, it will try to build bi-directional links with those potential neighbor nodes. It increases its $P_{T_{is}}$ by an increment ΔP and checks after a short time delay, τ_{sd}. If there are no uni-directional links to the node, it can only create uni-directional link by increasing its $P_{T_{is}}$. Thus it's equally important for the potential neighbor to try to establish a link with it too. Hence the node increases its $P_{T_{is}}$ and broadcasts power up request, *PowerUp_Req*. It then waits for medium time delay, τ_{md}, to check if it was able to successfully construct links. The node will therefore eventually select the lowest $P_{T_{is}}$ that will create bi-directional link.

Now if the node moves into a dense network area, it can afford to decrease its power, conserve its energy and still maintain acceptable connectivity.

Further, a node *i* will broadcast a power down request, *PowerDown_Req*, if it's suffering from interference. It sets the maximum hop count and *Req_TTL* (Time to Live) to prevent forwarding overheads.

If a node receives a *PowerDown_Req*, it will decrease its $P_{T_{is}}$ if it has a higher connectivity degree, $\psi_{DEG_{is}}$, defined as $\frac{\psi_{is} - \psi_{is_{min}}}{\psi_{is_{max}} - \psi_{is_{min}}}$. The node, after changing its power, will check its ψ_{is} after τ_{sd}. Otherwise, it sets its timer to long time delay τ_{ld} to avoid excessive calculation and overheads. Also, if a node receives a *PowerUp_Req*, it will increase its $P_{T_{is}}$ only if it has a low $\psi_{DEG_{is}}$. A node will forward other node's requests if they have a valid *Req_TTL* and hop count.

The list of main notations used is summarized in Table 4-2.

Table 4-1. Distributed Power Management Algorithm with Directional Antenna (DDISPOW)

```
DDISPOW.Node
Set $P_{T_{is}} = P_{Ts_{initial}}$ , compute $\psi_{is}$ and set timer=$\tau_{ld}$
If $\psi_{is} \leq \psi_{is_{min}}$ , then DDISPOW.LowConnectivity
Else if $C_i < C_{i_{critical}}$ , then DDISPOW.CriticalBatteryLevel
Else if $\psi_{is} \geq \psi_{is_{max}}$ , then DDISPOW.HighConnectivity
Compute Connectivity Degree, $\psi_{DEG_{is}} = \frac{\psi_{is} - \psi_{is_{min}}}{\psi_{is_{max}} - \psi_{is_{min}}}$
If PowerDown_Req received, then
        DDISPOW.PowerDown_Request
If PowerUp_Req received, then
        DDISPOW.PowerUp_Request
If suffering from interference, then DDISPOW.Interference
Sleep until timer expires

DDISPOW.LowConnectivity
If $P_{T_{is}} < P_{T_{ismax}}$, then calculate $P_{T_{is}} = P_{T_{is}} + \Delta P$ and
    set timer=$\tau_{sd}$
Else set timer=$\tau_{ld}$
If No Asymmetric link to itself, then
    broadcast PowerUp_Req and set timer=$\tau_{md}$

DDISPOW.HighConnectivity
If $P_{T_i} > P_{T_{imin}}$ , then calculate $P_{T_i} = P_{T_i} - \Delta P$ and set
    timer=$\tau_{short\_delay}$
```

```
    Else set timer=$\tau_{long\_delay}$
DDISPOW.Interference
    Broadcast PowerDown_Request
    Set TTL and hop count
DDISPOW.PowerUp_Request
    If $\psi_{DEG_i}$ in lowrange, then calculate $P_{T_i} = P_{T_i} + \Delta P$ and
        timer=$\tau_{short\_delay}$
    Else set timer=$\tau_{long\_delay}$
DDISPOW.PowerDown_Request
    If $\psi_{DEG_i}$ in highrange, then calculate$P_{T_i} = P_{T_i} - \Delta P$ and
        timer=$\tau_{short\_delay}$
    Else set timer=$\tau_{long\_delay}$
DDISPOW.CriticalBatteryLevel
    If $\psi_{DEG_i}$ in highrange, then calculate$P_{T_i} = P_{T_i} - \Delta P$and
        timer=$\tau_{short\_delay}$
    Else set timer=$\tau_{long\_delay}$
```

4.3. Simulation Parameters and Results

The performance of DDISPOW with 3 sectored directional antennas (M=3) with unit gain over a dynamic network of 100 nodes randomly distributed over a 1000 meter by 1000 meter urban area is evaluated through simulations carried out in MATLAB and OPNET network simulator [52].

Table 4-2. Main Notations

N	Number of nodes in the network
A	Area of the network
M	Number of sectors of the switched-beam antenna
θ	Beam width of the directional antenna
$P_{T_{is}}(t)$	Transmitting power of node *i* in sector *s* at time *t*
ΔP	Transmit power increment/decrement
$\psi_{is}(t)$	Connectivity of node *i* in sector *s* at time *t*
$\psi_{DEG_{is}}$	Connectivity degree of node *i* in sector *s* specifying level of
$SINR_{ji}(t)$	Signal to Interference and Noise Ratio for a packet from node *j* to
P_{ki}	Received power level from node *k* to node *i*
$C_i(t)$	Battery capacity of node *i* at time *t*
ρ	Node density
η	Log-distance path loss model path loss exponent
d	Propagation distance between transmitting node and receiving
L_{Fading}	Fading loss due to shadowing and rayleigh fading effects

4.3.1. Simulation Parameters

We have selected typical values for upper and lower bound of the DDISPOW algorithm parameters from numerous simulations and sensitivity analysis presented. In this paper, we have selected typical values for $P_{T_{ismin}}$ and $P_{T_{ismax}}$ at 5 mW and 100 mW. Node i can select $P_{T_{is}}$

between $P_{T_{ismin}}$ and $P_{T_{ismax}}$at an increment ΔP of 5 mW and 10 mW. Also time delays τ_{sd}, τ_{md}, and τ_{ld} are set to typical values of 5, 10 and 15 seconds. This selection of delays gives nodes enough time to adjust to their new topology and does not overload the network with overhead. It should be noted that delays are statically distributed around its mean value and therefore prevents simultaneous P_{T_S} change of nodes in the network. It should also be noted that request packets sent between the nodes are not independent control packets but are attached to the periodic routing control packets.

All the nodes are configured with OLSR routing protocol [46] and a modified MAC protocol for directional antenna. OLSR is a proactive table driven protocol which optimizes the classic link state protocol by using only selected nodes called Multipoint Relay (MPR) to advertise link in the network. Each node always has packet of average size of 1024 bits to send.

We will select log-distance path loss model with path loss exponent, η, typically between 2.7 and 3.5 to model an urban environment such as a city characterized by no LOS path and multipath effects. Random log-normally distributed fading due to surrounding environment clutter is modeled by log-normal shadowing model. We will simulate a dynamic pedestrian environment with nodes randomly moving with speed up to 3 m/s with Random Waypoint Mobility Model (RWMM) [44].

Propagation model determines the SINR and BER at the receiving node in a multi-user interference-limited network. The SINR or BER determines the quality of the link and whether it can be selected for routing packets.

4.3.2. Building Network Topology

Topology of a random network without topology control with a common P_T of 5 mW is shown in Figure 4-5. The network topology clearly has very few connected clusters with approximately 7 percent of the nodes totally disconnected. Since most of the routing protocols require bidirectional links, we will in this paper only consider bidirectional links as valid links between the nodes. Figure 4-6a illustrates how DDISPOW builds a topology on the initial network of Figure 4-5. Every node with DDISPOW individually selects P_{TS} between the minimum and maximum power rating to build a strongly connected network with none of the nodes disconnected from the network. There are no segments or disconnected clusters of nodes with DDISPOW as each node attempts to secure at least ψ_{min} in each sector. The distribution of transmit power level of nodes in the network with an average P_T of 26mW is shown in Figure 4-7. It is interesting to note that almost three-fifth of the nodes have their P_T less than the average P_T and only one percent of the nodes have P_T at $P_{T_{max}}$.

Further, Figure 4-6b shows network topology of a common node power scheme with node power of 26mW (equal to DDISPOW average power) i.e. an equivalent total energy consuming network. Comparing Figures 4-6a and 4-6b, it is clear that common node power scheme leads to denser clusters. But more importantly, it leaves out isolated nodes in the network (2 percent of nodes in this case). Additionally, without well distributed power control, nodes nearby interfere each other as seen in Table 4-3. Clearly, DDISPOW algorithm with receiver-based interference model yields a 73% reduction in average interference level compared to an equal energy consuming network.

4.3.3. Adapting to the Changing Network Topology

Figure 4-8 shows that ψ of a typical node in a changing network, characterized by random distribution over the network area and mobility model, fluctuating over the period of simulation with and without DDISPOW. The node initially has a good connectivity. Without DDISPOW, the ψ then steadily decreases as it moves to a low ρ area even becoming totally disconnected around 240 seconds. However in the same scenario, DDISPOW realizes that ψ has decreased below the threshold and starts increasing its P_T. The node does not even get disconnected from the network at any point during the simulation. Then, the node moves to a denser area of the network toward the end of the simulation. DDISPOW then decreases its P_T still maintaining acceptable ψ and reducing interference on its neighbors.

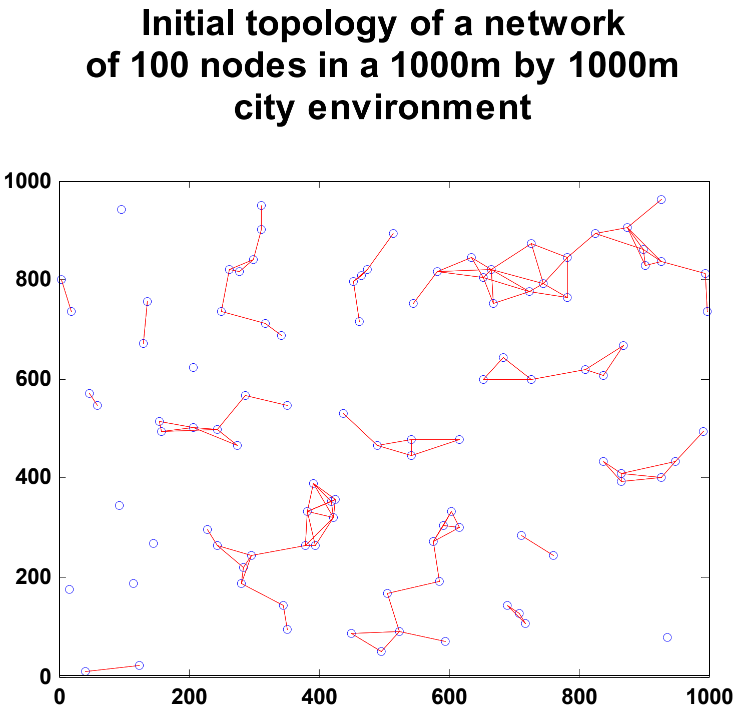
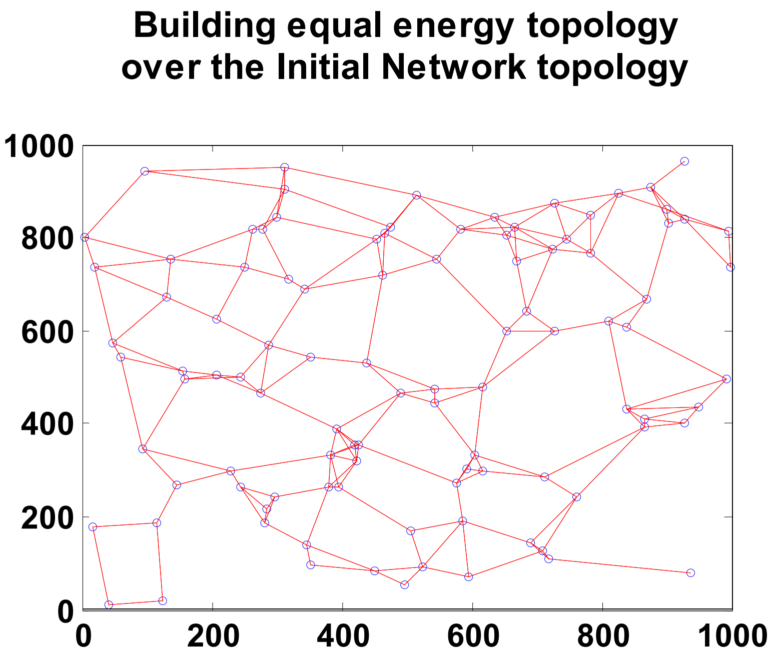
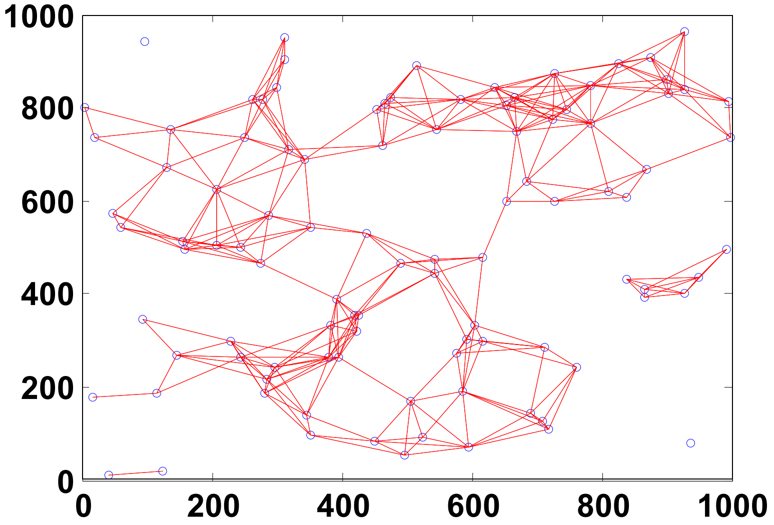


Figure 4-5 Initial topology of a network with 100 nodes randomly distributed over 1000m by 1000m city environment.


Building equal energy topology over the Initial Network topology

a) with DDISPOW Algorithm



b) with common power level

Figure 4-6 Building equal energy network topology over the initial network topology with DDISPOW and with common node power.

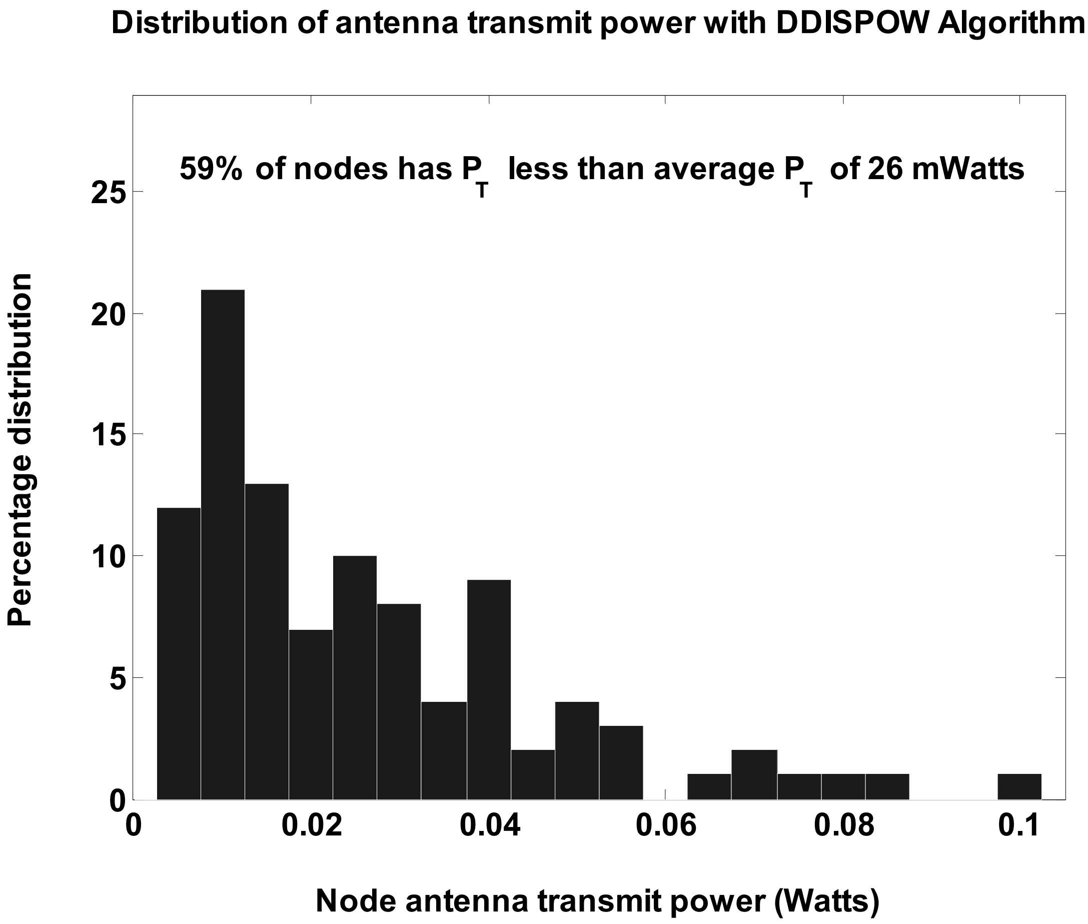


Figure 4-7 Distribution of transmit power of node's directional antenna with DDISPOW algorithm.

Throughout the simulation, the node connectivity was found to severely fluctuate in a dynamic network, even becoming totally disconnected from the network. DDISPOW clearly maintains network topology even preventing node, to a certain extent, from becoming disconnected from the network.

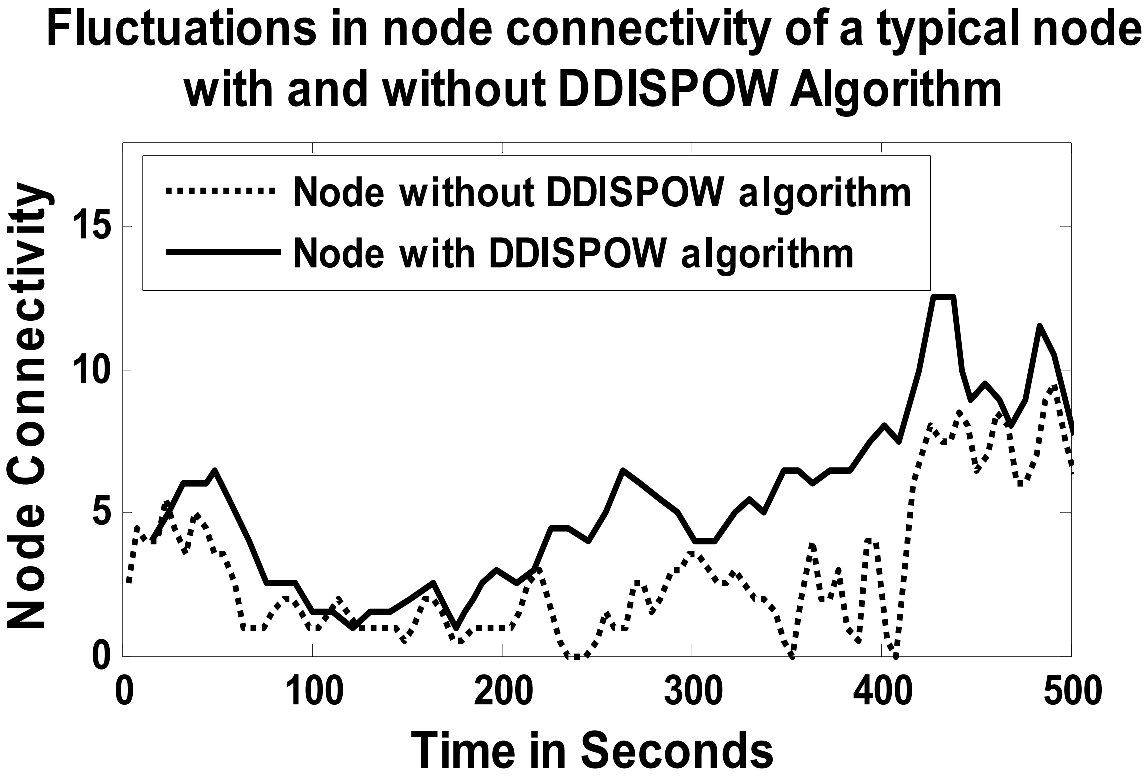
4.3.4. Node Transmission Power

Here we evaluate the performance of DDISPOW algorithm over 100 random network topology. Figure 4-9 shows how DDISPOW assigns transmit power to individual node depending on its surrounding node density and environment. Additionally, about 58% of nodes have their power level less than the average power level and only isolated nodes have higher power levels.

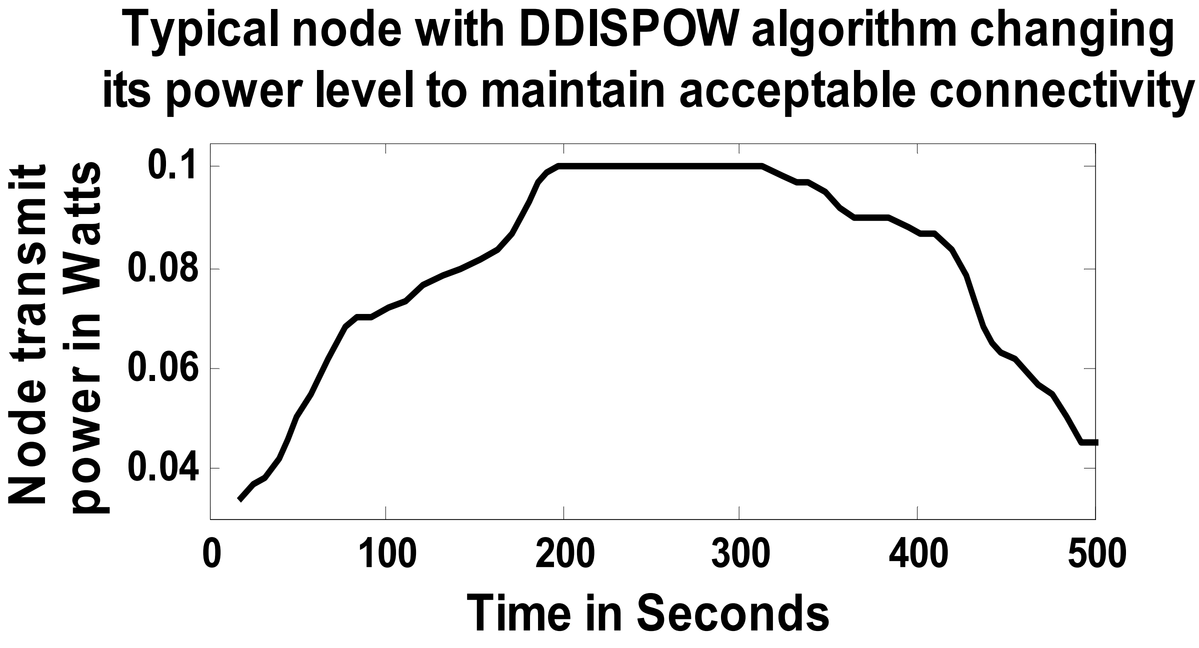
It is also clear from Figure 4-10 that the average P_T per antenna increases with attenuating environment and as node density decreases. Propagation loss increases as the node moves to a higher attenuating environment. Therefore nodes have to increase their power level to maintain the same network connectivity. Also in lower ρ network, nodes are spread apart and therefore the nodes have to increase their transmit power to build links with their neighbors. Detailed analysis of antenna power distribution shows that as much as three-fifth of the nodes have lower P_T than the average P_T. So we can conclude that the few nodes that are isolated in the network are mainly responsible for raising the total network energy consumption.

4.3.5. Node Connectivity

DDISPOW keeps the nodes connected in the network by assigning node transmit in a distributed manner. Figure 4-11 shows the distribution of node connectivity with DDISPOW and without DDISPOW in 100 random equal energy consuming networks. It is clear that without DDISPOW the node connectivity is distributed between 0 and 16. Connectivity of a node entirely depends on its surrounding node density and environment. Nodes in a highly dense area of the network have a high connectivity. More importantly, approximately 1% of nodes isolated by physical location are left completely disconnected from the network. In contrast, DDISPOW maintains node connectivity independent of its surrounding node density. Additionally, it doesn’t leave any isolated node totally disconnected from the network.



Fluctuations in node connectivity of a typical node with and without DDISPOW Algorithm



Typical node with DDISPOW algorithm changing its power level to maintain acceptable connectivity

Figure 4-8 Fluctuation of connectivity of a typical node and how DDISPOW algorithm selects its power level to maintain acceptable connectivity.

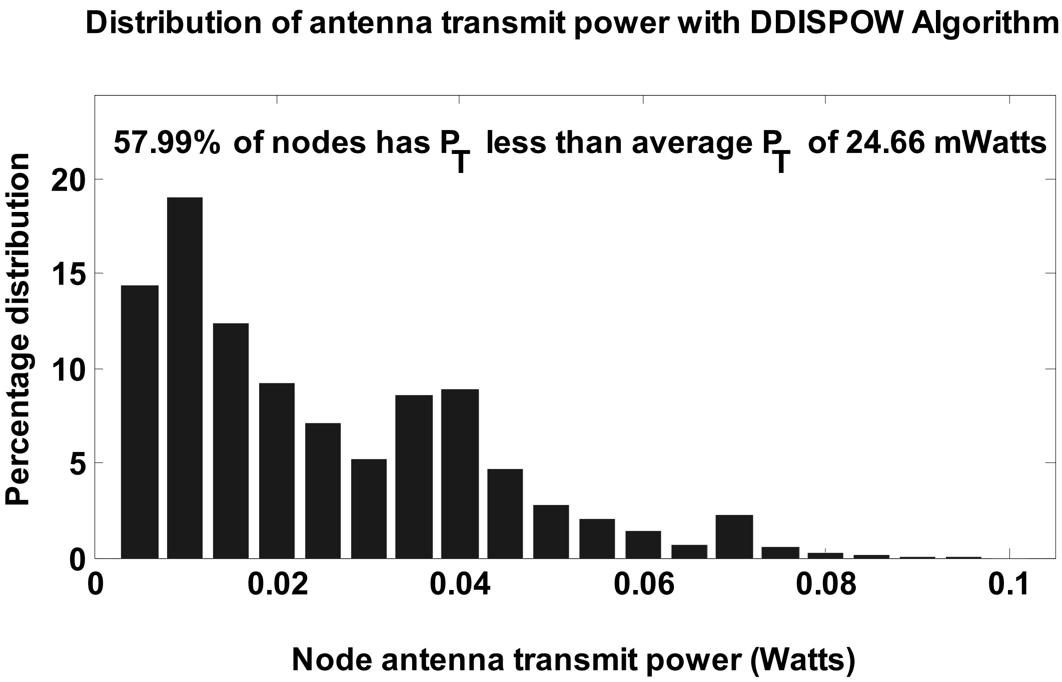


Figure 4-9 Distribution of node transmit power per antenna with DDISPOW in 100 random network topologies.

Further with the same connectivity thresholds, the average node connectivity changes with *ρ* and the propagation environment as clearly seen in Figure 4-12. Node connectivity in a denser network is higher since a relatively small node power can build links with more neighbors. Additionally signal travels a longer distance in lower attenuating environment and therefore the node can set up links with neighbors farther apart. Thus, the average connectivity also increases as the node moves to a lower attenuating environment.

Table 4-3. Average Interference in Equal Energy Consuming Network

Without DDISPOW Algorithm	-73.65 dBm	
With DDISPOW Algorithm	-79.40 dBm	73% less

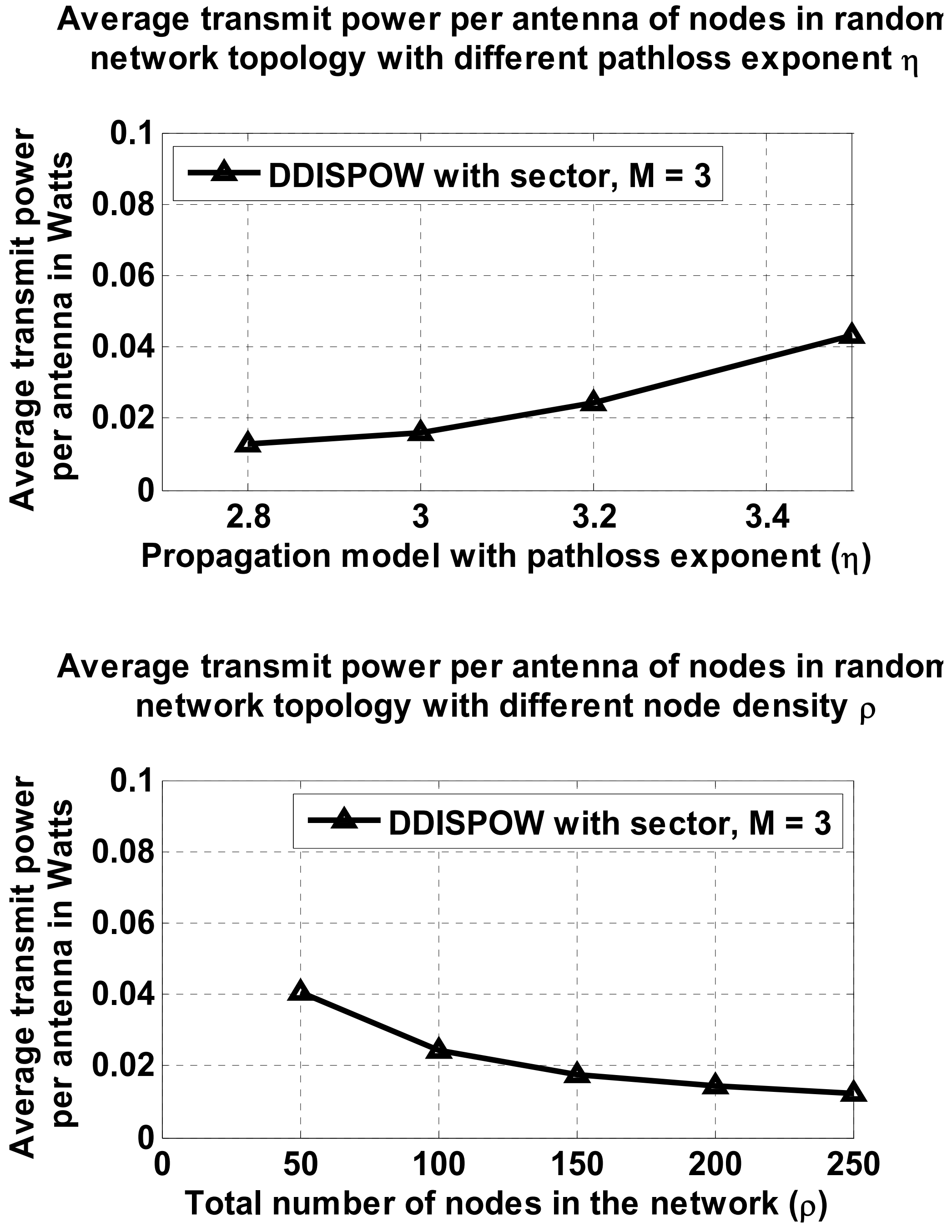
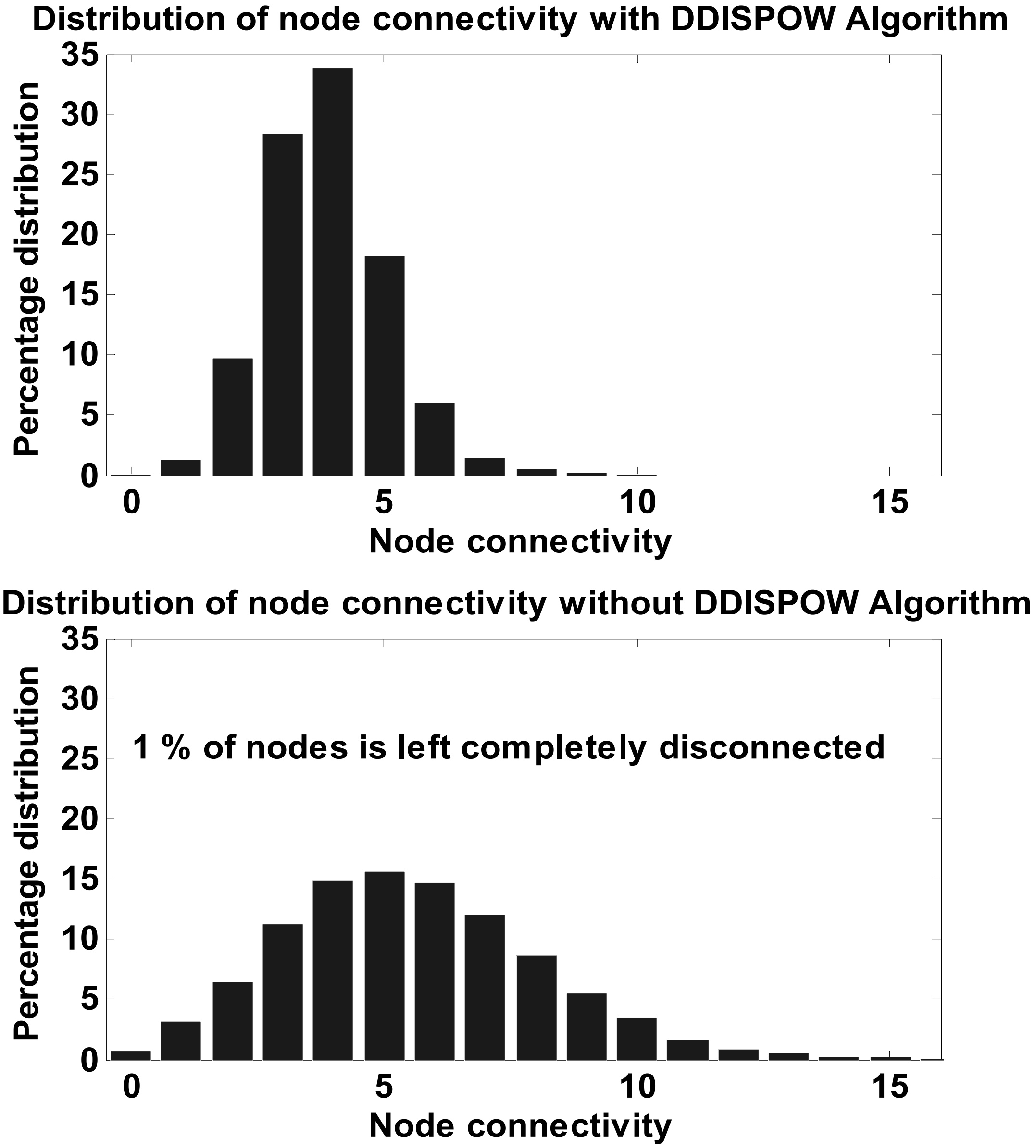


Figure 4-10 Change in average transmit power per antenna with different attenuating environment and with node density for DDISPOW algorithm with *M* sector.

Thus, by adapting to its surrounding ρ and propagation environment, DDISPOW provides a stable strongly connected network. Common node power schemes generally leave out nodes in the network isolated by physical location and the environment.


Distribution of node connectivity with DDISPOW Algorithm

Distribution of node connectivity without DDISPOW Algorithm

1 % of nodes is left completely disconnected

Figure 4-11 Distribution of node connectivity with and without DDISPOW in 100 random equal energy consuming networks.

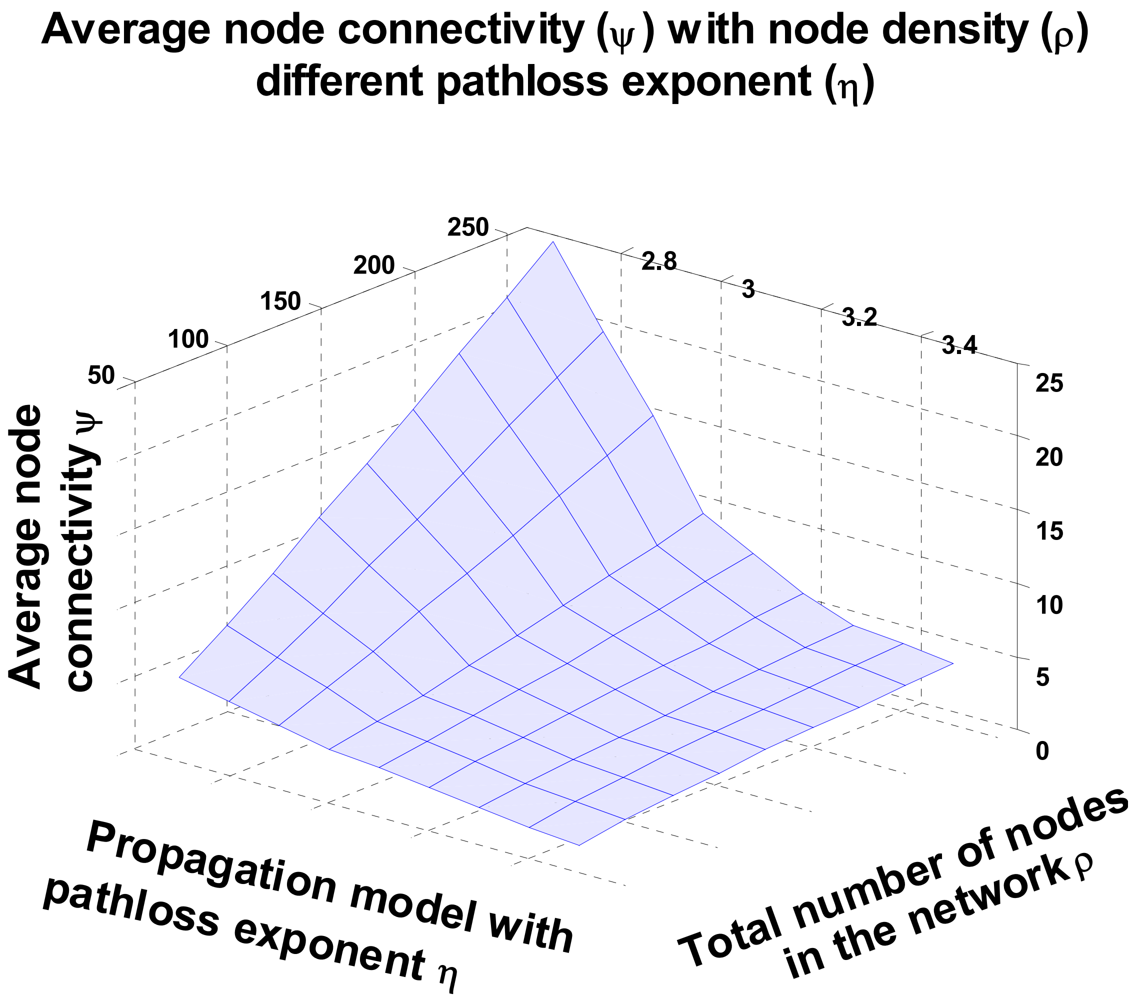


Figure 4-12 Connectivity of nodes with DDISPOW in the network depends on their surrounding node density and propagation environment.

4.3.6. Network Throughput

Figure 4-12 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. This leads to better quality and stable routes, improving network throughput by as much as 31%, see Table 4-4.

Table 4-4. Network Throughput

	DDISPOW Management Algorithm		
	Without	With	
Network throughput	314.14 kbits/sec	413.40 kbits/sec	*31.60% increase*

4.3.7. Convergence and Stability of DDISPOW

DDISPOW, given sufficient time, guarantees a stable solution for a network topology. Since P_{T_s} is incremented by $\pm\Delta P$ and is confined between $P_{T_{min}}$ and $P_{T_{max}}$, the number of P_{T_s} steps $n_{St}(\Delta P)$ is $\left(P_{T_{max}} - P_{T_{min}}\right)/\Delta P$. Now, let us define Normalized Convergence Rate (NCR) as

$$NCR = \frac{n(\mathrm{T})}{n_{St}(\Delta P)}$$
$$\begin{aligned} &where, \\ &n(\mathrm{T}): number\ of\ P_T\ steps\ needed\ to\ reach \\ &\qquad steady\ state\ power\ levels\ for\ all\ the\ nodes \\ &\qquad in\ all\ sectors\ M\ in\ topology\ \mathrm{T}. \end{aligned} \tag{4.13}$$

Basically $n(\mathrm{T})$ represents number of P_T changes in all sectors across all nodes in the network until there are no further changes in any nodes within the network. Average NCR with ΔP of 10 mW in a city environment with over 100 random network topology is almost consistent at approximately 1.17 as seen in Figure 4-13. Thus, it is clear that DDISPOW converges, with almost a constant NCR, to a steady network topology with approximately same number of steps.

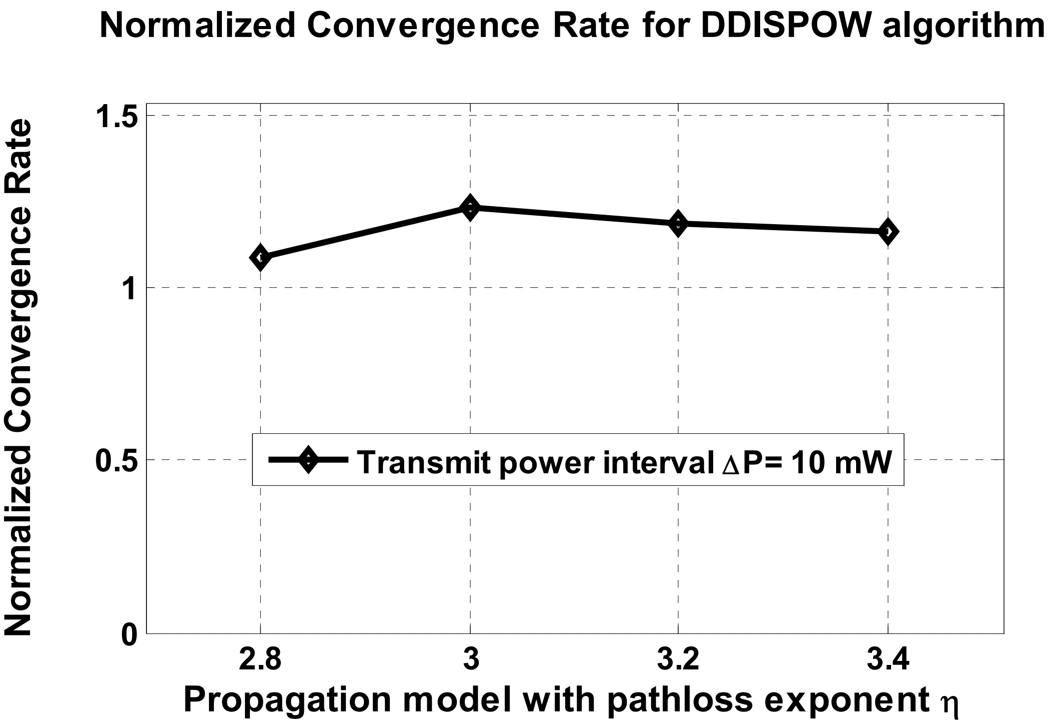


Figure 4-13 Normalized Convergence Rate (NCR) of DDISPOW algorithm with power intervals, ΔP, of 5 mW and 10 mW.

4.3.8. Comparing with Common Power Strategy and Distributed Power Control Algorithm

We will compare the performance of DDISPOW with our implementation of COMPOW (COMmon POWer) protocol [9] with similar network conditions and OLSR routing protocol and a distributed power control algorithm DISPOW [53] over 100 random network topologies. COMPOW protocol operates all nodes at the smallest power level at which the network is connected. DISPOW builds a strongly connected in a distributed manner.

It is shown in Figure 4-14 that COMPOW leads to unnecessarily high common node power due to the few isolated nodes in the network. Thus, average node power with COMPOW is much higher than DDISPOW. DDISPOW also has a lower average node power than DISPOW. It is clear from Figure 4-2 that network connectivity decreases with higher attenuating environment i.e. higher η. The nodes then have to increase their power levels to maintain their connectivity as seen in Figure 4-10. Therefore, average power level of all three algorithms increases with increased propagation loss in higher attenuating environment as seen in Figure 4-14.

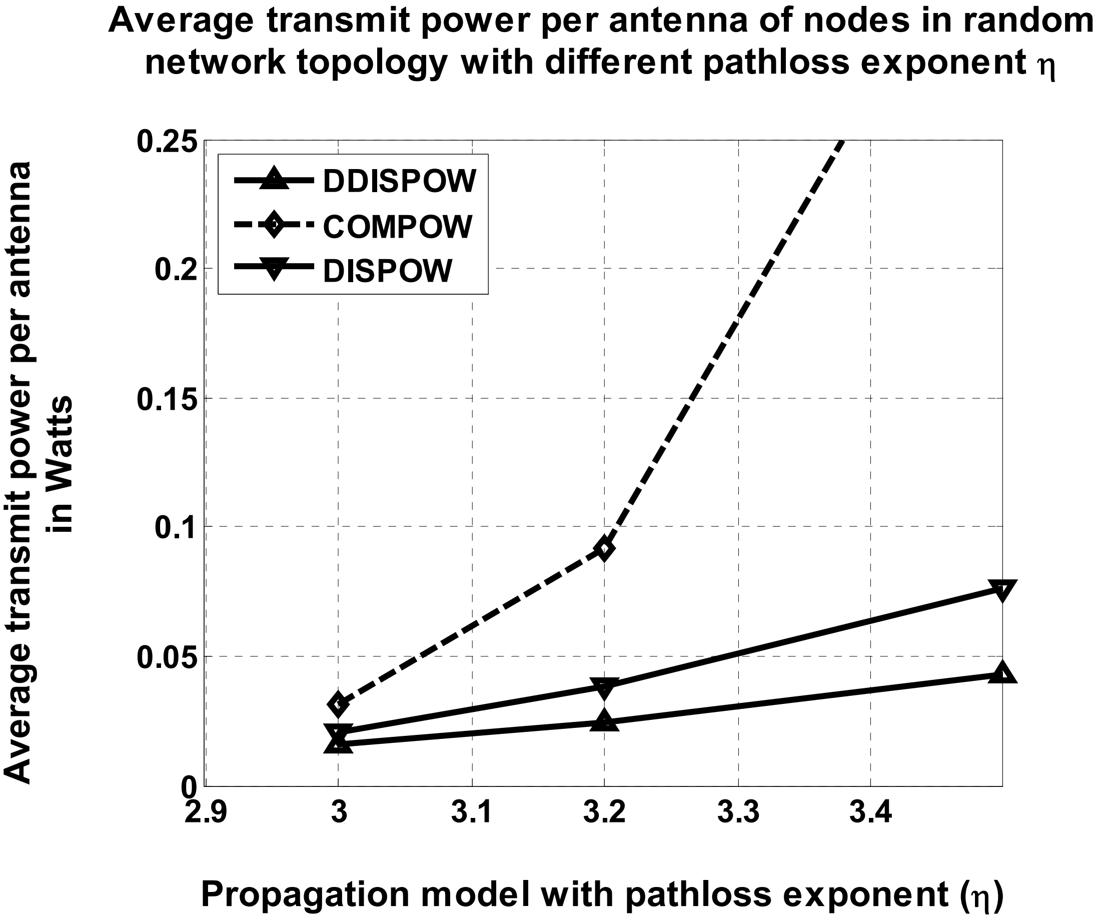


Figure 4-14 Comparing average node transmit power with DDISPOW, COMPOW and DISPOW algorithms over different propagation environment.

Further, Figure 4-15 compares the average node interference for the same network with DDISPOW, DISPOW and COMPOW. It can be seen that COMPOW, in an effort to connect isolated nodes, can cause high interference in a denser part of the network. Compared to

COMPOW and DISPOW, directional antenna undoubtedly is an effective technique to reduce interference level in a network.

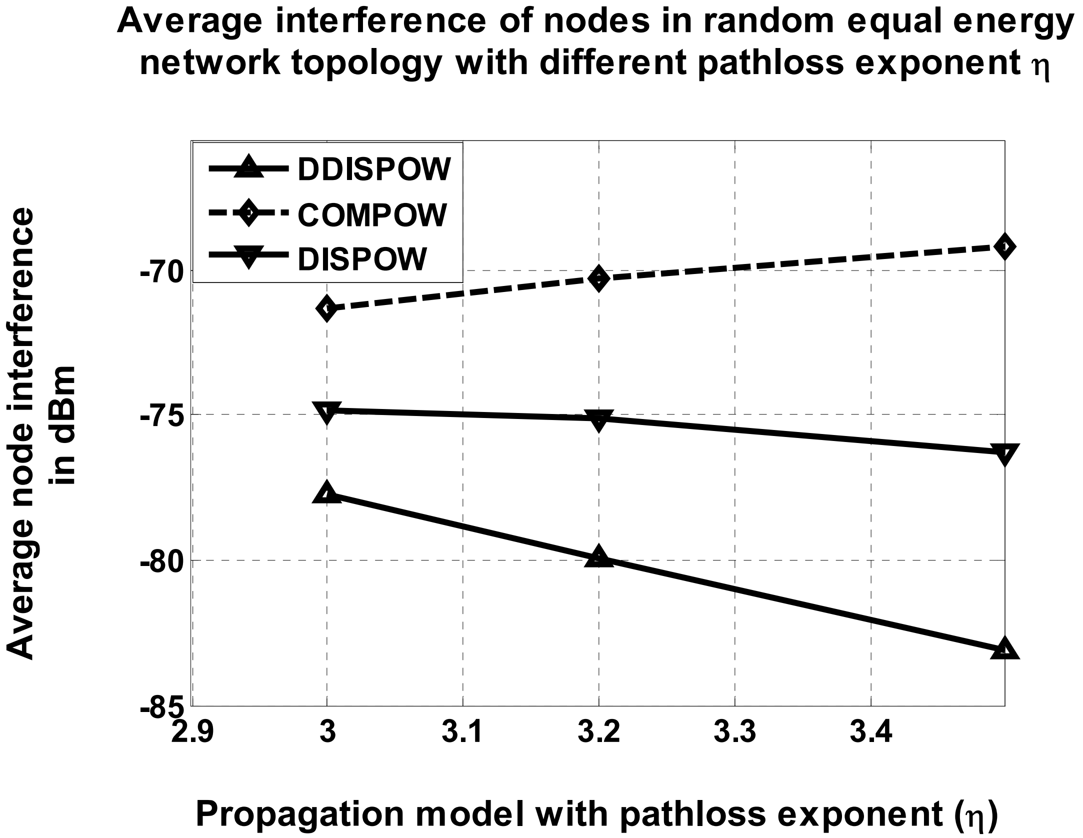


Figure 4-15 Comparing average node interference with DDISPOW, COMPOW and DDISPOW algorithms over different propagation environment.

Thus, for similar network conditions (in a city environment with η = 3.2), DDISPOW provides as much as 73.64% and 36.65% lower energy consumption than COMPOW and DISPOW algorithms respectively. Further, DDISPOW has 89.14% and 67.41% lower interference levels than COMPOW and DISPOW algorithms respectively.

This reinforces the earlier arguments that few nodes isolated by physical location and the environment significantly dominate common power strategies and that directional antenna can effectively reduce interference and improve network performance.

4.4. Conclusion

DDISPOW is a localized asynchronous algorithm that utilizes cross-layer optimization to adaptively build a stable strongly connected network tailored to its surrounding node density and propagation. Topology of an equal energy consuming network without DDISPOW is seen to have denser but disconnected segments that can lead to an increase in the interference among the nodes. Also, nodes isolated by physical location and propagation environment are crucially left totally disconnected from the network. Further, network topology was found to severely fluctuate due to dynamic nature of the wireless channel and node mobility even leaving some nodes totally disconnected. DDISPOW adapts to the dynamic network and maintains network topology even preventing nodes from becoming disconnected from the network.

Detail analysis shows that DDISPOW is energy efficient with significantly less energy consumption than COMPOW and DISPOW algorithms for similar network conditions. Detail analysis of nodes' transmits power shows that almost three-fifth of the nodes with DDISPOW have lower power level per antenna than the average power level in the network. There are those few isolated nodes, less than 10%, which require higher power level to stay connected. These nodes are mainly responsible for raising the energy consumption of the network.

Increase in node power inevitably suggests increase in network interference. However in the topology shown in Figure 4- 5, DDISPOW actually has as much as 73% lower node interference level compared to common node power in an equal energy consuming network. Simulation results show that DDISPOW provides strongly connected network with significantly lower interference thereby improving throughput by as much as 31%.

It is clearly evident that nodes with DDISPOW can adjust and adapt their power level to maintain connectivity in a realistic network with non-uniform node density and dynamic physical propagation environment. Compared to other schemes such as COMPOW and DISPOW, DDISPOW not only provides strongly connected network in various network conditions, reduces interference and improves network performance but also provides significantly better energy efficiency.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this thesis, we analyzed the impact of physical propagation model on the performance of a wireless network. Propagation model which represents the propagation and fading losses that a signal experiences over a wireless channel is an integral part of a realistic network environment simulation. It affects the metrics the routing protocol uses to route the data packets. Simulation result on the performance of OLSR over *open_environment* and *city_environment* lead to two distinctly different outputs. Higher attenuation of signal in *city_environment* limits the communication range of the nodes and degrades the quality of the wireless links. As a result, a higher packet delay and a lower throughput are observed in *city_environment*. Further in both the environments, node mobility introduces additional fading of the signal and frequent changes in topology. This change of topology has to be reported throughout the network via control packets. Thus, the routing overheads increase at high mobility and throughput of the network degrades.

Therefore, there is an inherent need for the ad hoc network to adapt to the surrounding node density, mobility and the physical environment. Power control algorithms are responsible for building network topology using deterministic or probabilistic techniques that satisfies certain cost metrics such as connectivity, minimizing interference or achieving QoS requirements. However, without a central node to administrate power management, building network topology is more challenging in wireless ad hoc networks. Further, if the ad hoc network is large consisting of thousands of nodes, then collecting information from all the nodes and passing it to the concerned nodes lead to high overheads. Therefore, power control algorithm for MANET must be adaptive, scalable and distributed.

The proposed distributed algorithm, DISPOW, uses a dynamic multi-parameter optimization approach that develops a strongly connected network topology in a completely distributed manner tailored to its surrounding node density and propagation environment. It adapts to the changing network topology because of node mobility and dynamic physical environment. Simulation results show that DISPOW provides a strongly connected reliable network over different physical environments and network conditions. It is shown that connectivity of a typical node severely fluctuates due to dynamic nature of wireless propagation channel and node mobility. Nodes are even disconnected from the network or significant period of time during the simulation. DISPOW reduces node fluctuation even preventing node, to a certain extent, from becoming totally disconnected from the network. It also has a receiver-based interference model which attempts to reduce inter-node interference. Asymmetric links, which are the major source on interference in wireless network, are the main drawback of distributed approaches. DISPOW has a receiver-based interference model which attempts to reduce inter-node interference and converts asymmetric link to symmetric links if required. It lowers routing overhead and packet delay and improves throughput by as much as 37% in similar networks.

DDISPOW takes advantage of directional antenna to provide a strongly connected stable network with much lower interference. Directional antenna can concentrate transmission energy in a specific direction and enhance spatial reuse of the wireless channel. Thus, directional antenna coupled with power control algorithm can lead to significant increase in connectivity and network performance. Simulation results show that DDISPOW has as much as 73% lower interference level than common power scheme in equal energy networks. Additionally, it is also energy efficient with significantly less energy consumption than COMPOW and DISPOW algorithms for similar network conditions.

Compared to common power strategies, DISPOW and DDISPOW are shown to be energy efficient over various physical environments increasing lifetime of the network. Both the algorithms are not heavily dependent on very small percentage of nodes in the network that are isolated by physical location and propagation environment.

5.2 Future Work

Adaptive antenna techniques such as MIMO, MISO and SIMO increase the capacity of a wireless network. Adaptive Antenna System (AAS) increases the efficiency of the frequency spectrum leading to a higher frequency reuse and extended coverage area. Adopting smart antenna technique in the physical layer can improve the network capacity and load balancing capability of Mobile Ad Hoc Networks.

The proposed algorithms, DISPOW and DDISPOW, assume full cooperation from each node in the network. All the nodes are entrusted to fully follow the power management algorithm. Ad hoc network depends on the cooperative and trusting nature of its nodes to route and forward packets to its neighbors. However in reality, malicious nodes can that take advantage of these algorithms to increase its payoff could exist. Malicious nodes can choose not to forward other nodes' traffic to conserve its battery life. However, this can have a disastrous effect on the overall throughput of the network. Therefore, future works would address security issues and presence of selfish nodes in the network.

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