Topology Control Using Distributed Power Management Algorithm for Mobile Ad Hoc Networks

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Original scientific paper

Abstract: **In order to be strongly connected in the network, a node may increase its power indiscriminately causing interference. Since interference is one of the major problems in wireless network, the proposed algorithm will co-operatively reduce inter-node interference in the network. Further, uni-directional links are a major source of interference as most of the routing protocol only utilizes bi-directional links. The algorithm will attempt to prevent such links or if required convert them into bi-directional links.**

We will show that the proposed algorithm provides strongly connected and more reliable network over dynamic physical channel modeled by log-distance path loss model, log-normal shadowing model and rayleigh fading model. It stabilizes node connectivity over the dynamic network and environment and even, to a certain extent, prevent node from being completely disconnected from the network. For the selected simulation environment, we will show that the proposed algorithm provides a shorter packet delay, improves the network throughput by as much as 37%, decreases the routing overhead and reduces interference.

Index Terms– **Mobile ad hoc networks, distributed power management algorithm, routing protocol, interference, physical propagation model.**

I. Introduction

Reference [1] shows that the network topology and the performance of routing protocol in mobile ad hoc wireless network significantly depends on the network physical environment.

The propagation model determines 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 [2].

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The proposed algorithm is generic network layer power management algorithm and does not use special functionality of any routing protocol. Therefore, it can be applied to any routing protocol. Different routing protocols such as Dynamic Source Routing (DSR) in reference [3], Any Path Routing without Loops (APRL), Ad hoc On-Demand Distance Vector (AODV), On-demand Multicast Routing Protocol (ODMRP) and System- and Traffic- dependent Adaptive Routing Algorithm (STARA) in reference [4] have been used by the authors to prove their concept. To demonstrate the performance and the capability of the proposed algorithm, we have applied it to Optimized Link-State Routing (OLSR) protocol as an example of a typical routing protocol.

In this paper, we will show that the proposed distributed power management algorithm adapts well in dynamic network topology and physical environment and provides a more reliable and strongly connected network. The related works in power control are listed in Section II. Section III describes the proposed distributed power management algorithm. Propagation models are surveyed and the reasons for selecting log-distance path loss, log-normally distributed shadowing and rayleigh fading models are stated in Section IV. A brief description of OLSR protocol is presented in Section V. Section VI and VII presents the simulation parameters and results. Section VIII concludes the paper.

II. Related work

Power control algorithms have been studied primarily as a way to improve energy efficiency. It is an important consideration in mobile ad hoc wireless networks because it can improve network capacity and node's battery capacity.

Most of the approaches studied in literature attempt to find a complete set of transmission power for the nodes with the purpose to minimize the total power consumption [5], [6] and [7]. Such approaches are centralized and cannot be transformed to mobile ad hoc network because they do not have any central schedulers.

Another approach is to find optimal transmit power for nodes such that network connectivity is preserved. Two distributed algorithms LINT and LILT are proposed in reference [8] which adjust nodes' transmission powers to maintain the desired connectivity. However, the algorithms are reactive schemes and use Carrier Sense Multiple Access (CSMA), as a multiple access technique, to evaluate its performance. In COMPOW and CLUSTERPOW [5] [9], every node uses the smallest power required to maintain network connectivity.

Cone-Based Topology Control (CBTC) in reference [10] is a distributed topology control protocol based on directional information. The basic idea is that node i transmits with the minimum power such that there is at least one neighbor in every cone of the angle, $\boldsymbol{\theta}$, centered at the node. It is shown in reference [11] that $\boldsymbol{\theta} \le \boldsymbol{5\pi/6}$ *is* necessary and sufficient condition to guarantee network connectivity.

In Minimum Spanning Tree (MST) based algorithm [12], each node builds its local MST independently and only keeps on-tree one-hop nodes as its neighbors.

These power control algorithms, however, do not dynamically adjust to the changes in the topology and the environment the network is in.

III. Distributed power management algorithm

We propose a dynamic co-operative power management algorithm that optimizes node transmit power and minimizes inter-node interference in the network.

Consider a network of n nodes in an area A. If $P_i\ (t)$ and $\psi_i(t)$ represent the transmitting power and connectivity of node i in the network at time t, then select

$$P_i\ (t) \quad for\ node\ i\ \forall\ 1, 2, 3, \ldots\ldots, n$$

subject to the following 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.

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

2. For a packet from node j to node i to be correctly detected, SINR must be greater than a threshold, γ_{th}.

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

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

$$min\left[P_0 + \sum_{\substack{k\epsilon\mathcal{N} \\ k\neq j}} P_{ki}(t)\right] for\ node\ i\ \forall\ 1, 2, 3, .., n \tag{3}$$

If a node has high node connectivity, then it can probably afford to decrease its power level and still maintain acceptable connectivity. 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.

$$\psi_i(t) \le \psi_{i_{max}}(t) \quad for\ node\ i\ \forall\ 1, 2, 3, .., n \tag{4}$$

3. The transmit power for the nodes should be more than the minimum power level, $P_{i_{min}}$, but less than the maximum power level, $P_{i_{max}}$, defined by network and node power specifications.

$$P_{i_{min}} \le P_i(t) \le P_{i_{max}} \quad for\ node\ i\ \forall\ 1, 2, 3, \ldots, n \tag{5}$$

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

$$C_i(t) \ge C_{i_{critical}} \quad for\ node\ i\ \forall\ 1, 2, 3, \ldots, n \tag{6}$$

We assume that each node has no knowledge of other node's transmission power level. The algorithm is illustrated in a flowchart shown in figure 1.

In this algorithm, nodes continuously check their connectivity, interference level from other nodes and their battery capacity.

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

Now if the node moves into a dense area, it can probably afford to decrease its P_i 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 the upper connectivity threshold, $\psi_{i_{max}}$, it decreases its P_i and checks its ψ_i after τ_{short_delay}. It also decreases its P_i if its battery capacity, C_i, becomes less than the $C_{i_{critical}}$. It, thus, effectively selects the lowest P_i to keep the node well connected with at least $\psi_{i_{min}}$.

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

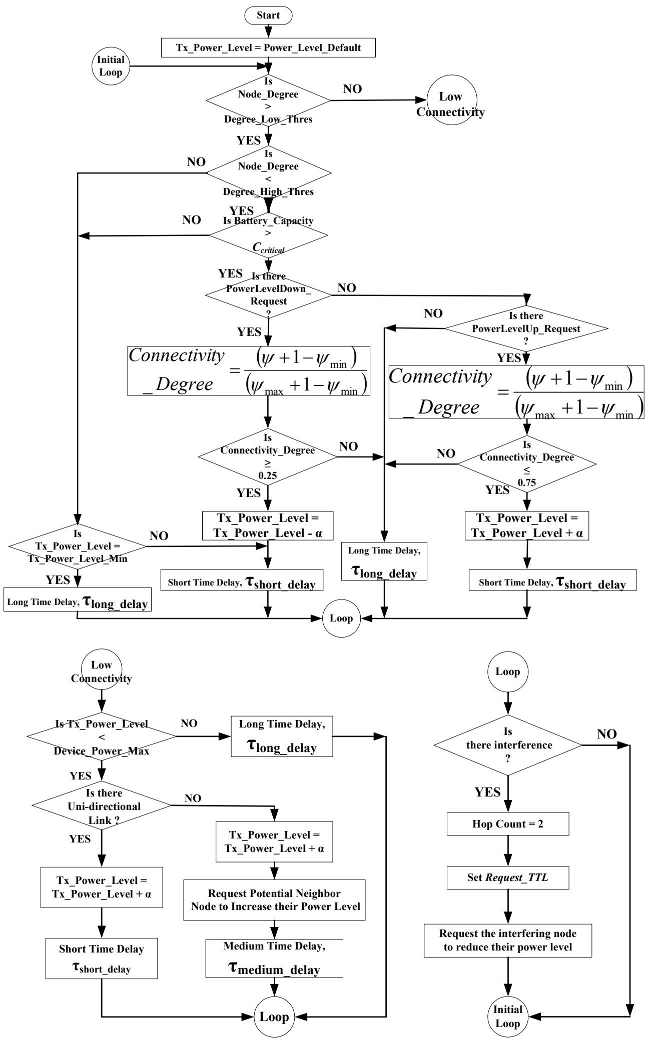

Fig. 1. Flowchart of the proposed distributed power management algorithm

If a node receives a *PowerLevelDown_Request*, it will decrease its P_i if its ψ_i is in a higher acceptable range. If it changes its P_i, it checks its ψ_i after $\tau_{\text{short\_delay}}$. Otherwise, it waits for a long time delay, τ_{long_delay}, to avoid excessive calculations and overhead from frequent changes in P_i. If a node i receives a *PowerLevelUp_Request*, it increases its P_i only if its ψ_i is in the lower acceptable range. It then waits for $\tau_{\text{short\_delay}}$ to check its ψ_i. A node will forward other node's requests if the hop count of the request is more than 1 and the *Request_TTL* is still valid.

If at any instance the node's C_i is not sufficient, i.e. less than $C_{i_{critical}}$, it will reduce its P_i to maintain minimum connectivity, $\psi_{i_{min}}$. The algorithm is in a sense greedy because achieving lowest connectivity is given the highest priority.

IV. WIRELESS PROPAGATION MODEL

Propagation model predicts average received signal strength at a given distance from transmitting node. Most of the simulations done in ad hoc network use either the trivial disk propagation model, the free space propagation model [13] or the two-ray propagation model [14].

The disk propagation model is the simplest propagation model where the signal propagates to a certain distance and no more. It does not take the physical channel into consideration. Free space propagation model is generally used to predict the signal strength at the receiving node when there is a clear Line of Sight (LOS) path. The two-ray propagation model considers both direct and ground reflected propagation path between the source and the destination. This model, though reasonably accurate for predicting 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.

Although several empirical or statistical propagation models for path loss such as Okumura model or Hata model are well documented in literature [15], they are generally limited to frequencies below 2 GHz and used in cellular network. Since ad hoc network operates in a higher frequency range, we will not utilize these models in simulations.

We will, therefore, use the log-distance path loss propagation model to model the ad hoc wireless channel. In this path loss model, the average path loss of the propagating signal is expressed as a function of the distance and the path loss exponent, η, and is given by equation 7 [14][16].

$$\begin{gathered} P_{PL}(dB) = P_{PL}(d_0) + 10\,\eta \log\left(\frac{d}{d_0}\right) \\ P_{PL}(d_0){:}\ Path\ loss\ at\ reference\ distance\ d_0 \\ d{:}\ distance\ between\ transmitting\ and \\ receiving\ node \end{gathered} \tag{7}$$

The reference path loss is determined from measurements close to the transmitter. The parameter η indicates the rate at which the path loss increases with distance. The value of η depends on the specific propagation environment.

Signal received at the same separation distance, d, can be very different in two different surrounding environments because of random shadowing effects. This fading loss at a particular location is random and log-normally distributed as shown in equation 8 [17].

$$\begin{gathered} P_L\,(dB) = P_{PL}(dB) + X_\sigma \\ X_\sigma{:}\ is\ a\ zero-mean\ random\ variable\ with \\ standard\ deviation\ \sigma \end{gathered} \tag{8}$$

Different versions of signal wave, because of reflecting objects and scatterers, travel through different paths to reach the receiver at different times. These multi-path waves then combine in receiving antenna to give a resultant signal which can vary widely in amplitude and phase. The relative movement between the nodes also introduces a frequency spreading phenomenon known as Doppler Effect. We will assume that the fading loss, P_F, used to model this small-scale fading and doppler effect has a Rayleigh distribution probability density function (pdf) given by equation 9 [16],

$$p(r) = \begin{cases} \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) & (0 \le r \le \infty) \\ 0 & (r < 0) \end{cases} \tag{9}$$
$$\sigma^2: time - average\ power\ of\ the\ received\ signal\ because\ of\ fading$$

The mobility of users not only changes the separation distance affecting the path loss but also fading experienced by the signal. The Random Waypoint Mobility Model (RWMM) [18] is used to model node's mobility. In this mobility model, a node randomly selects a destination within a roaming area and moves towards it at a speed uniformly distributed between predefined minimum and maximum set value. Once the node reaches destination it stops for a predefined pause time and then selects another destination randomly and moves towards it. This node mobility behavior is repeated for the duration of the simulation.

So, a propagation model is used to determine the Signal to Noise Ratio (SNR) at the receiving node. SNR is defined as the ratio of power of the receiving signal to the noise power at the receiver [3]. We will model the multi-user network as interference-limited rather than noise-limited and consider Signal to Interference and Noise Ratio (SINR) given by equation 2 to determine the BER of a communication link [2].

The SINR or the BER determines the quality of the link and whether it can be selected for routing packets.

V. Optimization Link-State Routing 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 [19]. 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 neighborhood which may retransmit its messages. MPRs are selected in such a manner that every node in the its two-hop neighborhood has a bidirectional link with it. Only MPRs are allowed to advertise the links by periodically broadcasting Topology Control (TC) messages. Neighbors, who are not selected as a MPR, receive and process the broadcast messages but do not retransmit broadcast messaged received.

Compared to classical flooding mechanisms where every node forwards each message received this technique of using MPR substantially reduces the message overhead as clearly evident in figure 2. The smaller the set of MPR the lesser the control traffic overhead resulting from the routing protocol.

Besides TC message, node also periodically sends HELLO message. The HELLO message maintains the local link and neighborhood information in the network and is used in selecting MPRs. The topology information from the HELLO and TC packets are used to construct routes in the network.

VI. Simulation Parameters

The performance of power management algorithm is analyzed here through simulations carried out in OPNET network simulator [20].

The network consists of 100 nodes distributed over a 1000 meter by 1000 meter area. All the nodes are configured with OLSR and IEEE 802.11 MAC protocol. Each node, transmitting at 15dBm, always has packet of average size of 1024 bits to send. The simulation is conducted over urban area such as a city characterized by no LOS path but multiple versions of the signal due to many obstacles such as buildings and trees in the propagation path. We will model this environment by typical value for η of 3.2 and standard deviation of 4.0 dB [1]. The node mobility is modeled with a minimum speed of 0 m/s and maximum speed of 3 m/s to simulate a pedestrian environment.

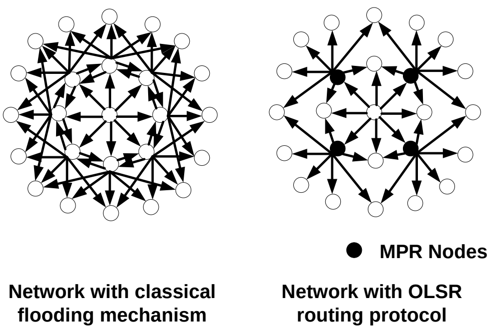

Fig. 2. Classical flooding mechanism and flooding in OLSR

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. All multi-user interference is treated as noise. 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 parameters of the power management algorithm: minimum and maximum connectivity, minimum and maximum power level and the time delays are all design considerations. We have conducted numerous simulations on this model over a wide range of these parameters. We have analyzed the impact of these parameters and its sensitivity on the network topology and performance.

However, to evaluate performance and capability of the algorithm in this paper, we have selected typical values for node connectivity of 6 and 8 for the lower threshold, $\psi_{i_{min}}$, and upper threshold, $\psi_{i_{max}}$. Similarly, the minimum and maximum transmission power levels, $P_{i_{min}}$ and $P_{i_{max}}$, are set at 5 mW and 100 mW. The node can select the power level between $P_{i_{min}}$ and $P_{i_{max}}$ at an increment, α, 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 delay 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 its mean value. This prevents simultaneous power level change of all the nodes in the network and also gives node opportunity to react to power level changes of its surrounding nodes. The initial transmission power level for all the nodes is set at 15dBm (approximately 30mW).

VII. Simulation Results

Node connectivity fluctuation of a typical node in the network over the period of simulation with and without power management algorithm is shown in figure 3. Without the power management algorithm, it is clearly seen that node connectivity initially increases to 20. It then steadily decreases as the node moves to a low node density area becoming totally disconnected from the network around 750 to 800 seconds. Throughout the simulation, node connectivity of a typical node in the network severely fluctuates even becoming disconnected from the network.

In case of power management algorithm, as node connectivity increases beyond the higher connectivity threshold, it decreases it's transmit power to approximately 5 mW clearly evident in figure 4. Similarly to earlier case, the node moves to an area with low node density and its connectivity starts decreasing. The power management algorithm, however, realizes that node connectivity has decreased below the lower connectivity threshold and starts increasing it power level to 100 mW. The node with the power management algorithm does not even get disconnected from the network at any point during the simulation. It is clear from figure 3 and 4 that node adjusts its power level between 5 mW to 100 mW to maintain acceptable network topology.

The distribution of node connectivity of all the nodes in the network with and without power management algorithm is shown in figure 5. Connectivity of node without power management algorithm was found to be distributed from 0 to 25 with more than 2% of the node totally disconnected. However with power management algorithm, approximately 46% of the nodes have acceptable connectivity with less than 0.1% of the nodes totally disconnected from the network at any time during the simulation. Figure 6 shows the distribution of transmit power level of the nodes in the network. Approximately 57% of the nodes have their power level less than the initial power level of 15 dBm with 7% of the nodes at the highest power level of 100 mW.

Figures 3 and 4 highlight the variation in routing parameter because of changes in environment and network. The routing protocol with power management algorithm clearly reduces node connectivity and topology fluctuations. The algorithm adapts to the changes in the physical environment and the network to provide strongly connected and more reliable network thereby reducing routing overhead as seen in figure 7.

Improvement in average network throughput and average packet delay because of the power management algorithm is shown in figure 8 and 9. Network throughput, defined as the total number of data delivered, is almost 37% higher with power management algorithm. Also a shorter packet delay is observed with power management algorithm.

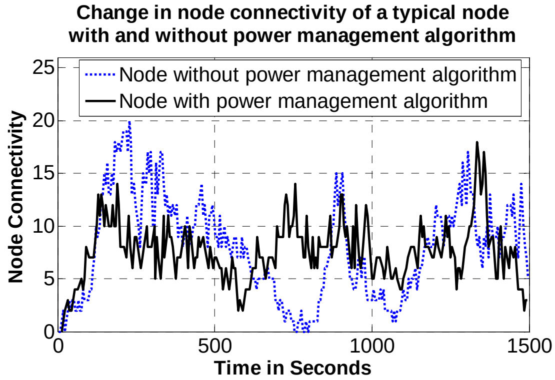

Fig. 3. Change in node connectivity of a typical node in the network with and without power management algorithm

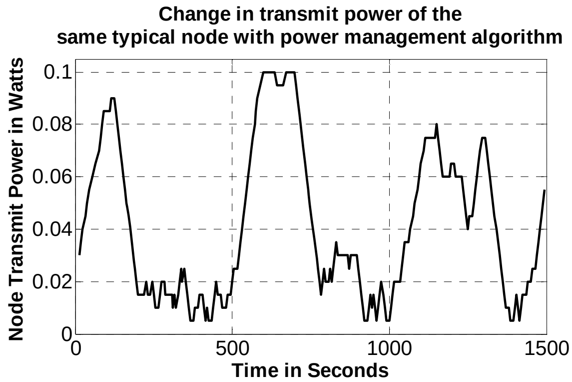

Fig. 4. Change in transmit power of the same typical node with power management algorithm

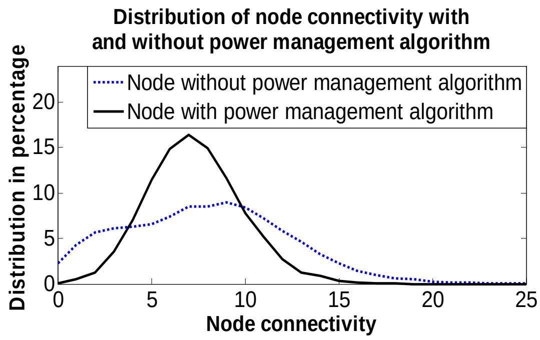

Fig. 5. Distribution of node connectivity of all the nodes in the network with and without power management algorithm

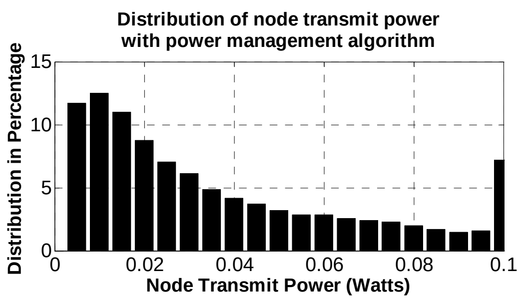

Fig. 6. Distribution of node transmit power of all the nodes in the network with power management algorithm

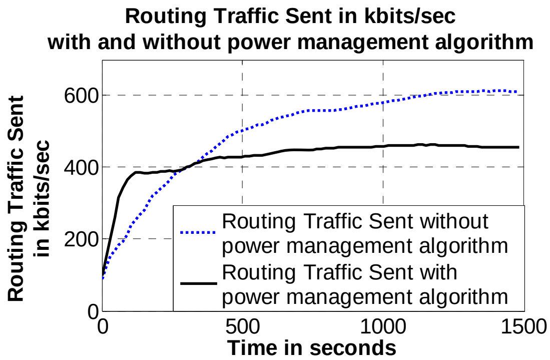

Fig. 7. Average total routing traffic sent with and without the power management algorithm

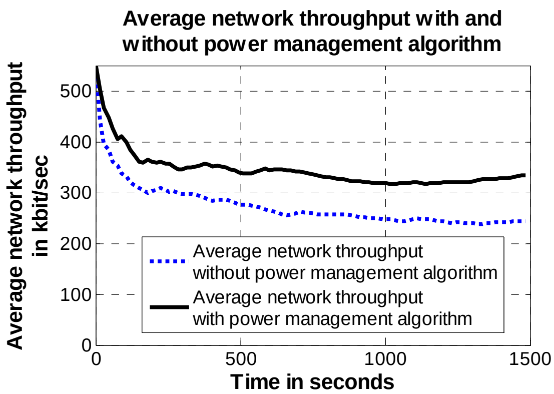

Fig. 8. Average network throughput and average packet delay with and without power management algorithm

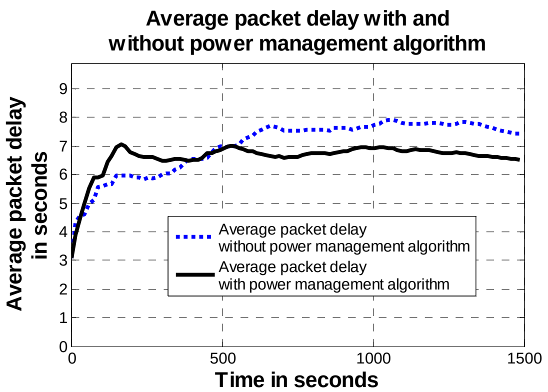

Fig. 9. Average packet delay with and without power management algorithm

Figure 10 shows the average node transmission power and average total noise power with and without the power management algorithm. The average node transmission power obviously depends on several factors such as network density and physical propagation channel. For the simulation environment selected, the average node power with power management algorithm is found to increase to 19.37 dBm from the initially set 15 dBm. This increase in average node power implies an increase in inter-node interference. However, the total noise interference actually decreased by 2 dB because the algorithm tries to prevent nodes from interfering each other.

VIII. Conclusion

The proposed distributed power management algorithm adaptively preserves network connectivity, reduces interference with the dynamic environment and network topology thereby optimizing the network performance. It is generic network layer power management algorithm and can be applied to any routing algorithm. To demonstrate its performance and capabilities, we have applied it to OLSR as an example of a typical routing protocol. It does not utilize any functionality specific to a particular protocol such as OLSR in this case.

Figure 3 shows that the node connectivity of a typical node in the network severely fluctuates from 0 to 20 even becoming disconnected from the network for a significant period of time during the simulation. Figures 3 and 4 show that the network adapts better to the changes in the physical environment and network topology with the power management algorithm. It reduces node connectivity fluctuations even preventing node, to a certain extent, from being totally disconnected from the network.

The average power of the nodes in the network depends on physical environment and network topology. It increases with more attenuating environment and low node density. By increasing node power, we inevitably increase interference. Figure 6 shows that even though the average node power increased to 19.37 dBm from 15 dBm for this simulation scenario, the algorithm actually decreased the noise interference by 2 dB.

Thus the proposed algorithm provides strongly connected and more reliable network. It lowers interference and routing overhead consequently reducing packet delay and improving network throughput by as much as 37%.

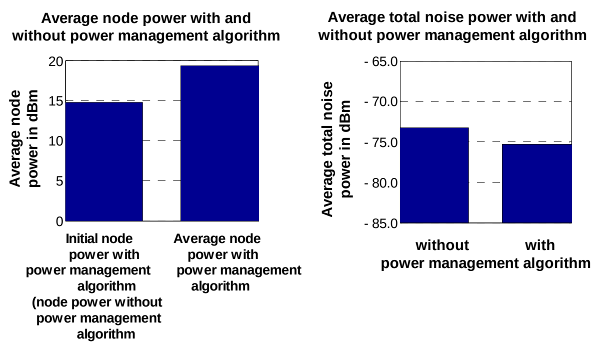

Fig. 10. Average node transmission power and average total noise power without and with power management algorithm

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