NETWORK PRESERVATION THROUGH A TOPOLOGY CONTROL ALGORITHM FOR WIRELESS MESH NETWORKS

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ABSTRACT
Wireless mesh networks (WMNs) is becoming a promising new technology for extending coverage to far-flung rural areas. This it achieves by linking the various wireless LANS (WLANs) in distant locations thus providing a vital mode complimentary to the wireless infrastructure-based networks. The benefits of WMN deployments, however, come with certain challenges e.g., power management. While focussing on WMN applications in rural areas, this paper explains the need for transmit power consumption control in WMNs and proposes an Enhanced Local Minimum Shortest-path Tree (ELMST) algorithm for topology control for the WMNs. The algorithm is distributed with each node using only the information gathered locally to determine its own transmission power. In the first phase of its construction, a minimum local shortest-path tree is obtained. The last phase then involves the removal of all unidirectional links. The performance of the algorithm is demonstrated via several simulation tests. The resultant network topology preserves network connectivity in addition to possessing other desirable features such as: (1) reduction in the average node degree, (2) evenly distributed power consumption among the nodes as well as (3) a reduced total power consumption leading to longer connectivity periods.

KEY WORDS
Topology Control, Wireless, Backbone, Mesh Network, Energy Efficiency, Localized Algorithm.

1. INTRODUCTION

The efficient management of radio resources (e.g., energy) in multihop wireless networks (MWNs) greatly impacts on the performance of such networks [1]. Through transmission power control for instance, a network topology is affected, interference levels are adjusted and spatial channel re-use is enhanced. One way for efficient management is to have the network nodes select their appropriate logical neighbours (from a given physical topology network) according to some specified rules. For instance, there can be a coordinated decision making regarding each node's transmission power ranges with a goal of generating a network with some desired properties e.g., connectivity, reducing energy consumption and/or increasing network capacity [2]. This is referred to as topology control.

Although several topology control techniques e.g., [3], [4], [5] with the aim of conserving power consumption have been proposed for other MWNs like MANETs and wireless Sensor Networks (WSNs), little attention has been drawn to such needs in wireless mesh networks (WMNs). This is mainly because the backbone wireless mesh routers are static and have usually been assumed [6] to have electrical mains power supply and hence are purported not to have power constraints. However, with specific considerations to rural area applications of WMNs, we argue that the mesh routers would be stationary but with power constraints. In rural areas, electrical mains power sources are limited and/or often not available and the mesh nodes have to rely on exhaustible and renewable means of energy supply such as solar, battery or generator. Furthermore, the mesh clients are definitely power constrained [6].

With the aim of addressing these constraints, this paper proposes an energy-efficient topology control algorithm for WMNs which computes the best path based on the link weight functions. One advantage with this approach is that the channel conditions e.g., weather conditions are catered for since the link weights, as is shown later in this work (definition 2 and section 4B), is a function of the transmission power and the distances between nodes. The remainder of this paper is organized as follows. In section 2, the details of the network model is given. In section 3, previous related work is reviewed. The proposed algorithm is presented in section 4. Section 5 gives the simulation results and analysis. Finally, in section 6 the work is concluded and a suggestion for future work is given.

2. RELATED WORK

Rodoplu and Meng [7] describe the first algorithm which is based on the concept of relay region. A node decides to relay through other nodes if less power will be consumed. The algorithm guarantees the preservation of minimum energy paths between every pair of nodes connected in the original graph. Based on the results of [7], Li and Halpern [8] proposed an improved protocol which is computationally simpler and better in performance with the resulting topology being a sub-network of the one generated by [7]. Li and Halpern [9] further propose the small minimum energy communication network (SMECN). In this algorithm, each node u initially broadcasts "hello" message with some initial power and after reception of *ACKs* from the receiving nodes, checks if the current range covers the region of maximal transmission range less the union of the compliment of the relay regions of all the nodes reachable by node u. The process terminates if node u reaches its maximal transmission power. The work in [7], [8] and [9], however, implicitly assume that a long link consumes more power than a shorter link, an assumption that is not practical for instance in heterogeneous networks according to [3].

In [10], [11], the concept of local neighbourhood is first introduced. This concept proposes that a logical topological view of a node in a network be constructed based only on its local information. This forms the basis of the family of the distributed and localized topology control algorithms. In the work of Li et al [10], a node builds its local minimum spanning tree (LMST) based only on its one hop neighbourhood information. It keeps only the one hop nodes as neighbours in the final topology. The resulting topology has been shown to be connected and with node degree bounded by six. In addition they provide an optional phase where the topology is transformed to one with bidirectional links only. However, LMST does not preserve the minimum energy paths. Another angle of approach is given by Li et al [12] for heterogeneous networks, in which the resulting network contains unidirectional links.

Other old variants of topology control algorithms such as in [13] also discuss a distributed and localized algorithm to obtain a reliable high throughput topology by adjusting a per node transmission power. However, their focus is not on minimizing the energy consumed in the network.

All of the algorithms shown in [10], [11], [12], [13] have not been applied to WMNs. It can not be generally assumed that the algorithms will automatically function in WMNs as the requirements on network preservation, power efficiency and mobility are very different between WMNs and other Multihop Networks [6]. The algorithm proposed in this work consists of two phases with the resulting topology ensuring connectivity and reduced node logical out degrees and is shown to apply for WMNs.

3. NETWORK ARCHITECTURE AND SYSTEM MODEL

In this section, the WMN architecture considered in this paper is presented. Additionally a discussion is given on how the network is modelled.

3.1 Architecture

A sample hybrid WMN architecture modelled is as shown in figure 1. The network is composed of three groups of wireless network elements [6],[14]: (1) ***mesh gateways***, mesh router with gateway functionalities, are used for relaying traffic between the WMN and the internet, (2) ***Access Points***, mesh routers, are the stationary nodes that act as wireless access points for the mesh clients and also form the multi-hop wireless network infrastructure and (3) ***Mesh clients*** are the end-user 802.11 mesh nodes. They are either mobile or stationary.

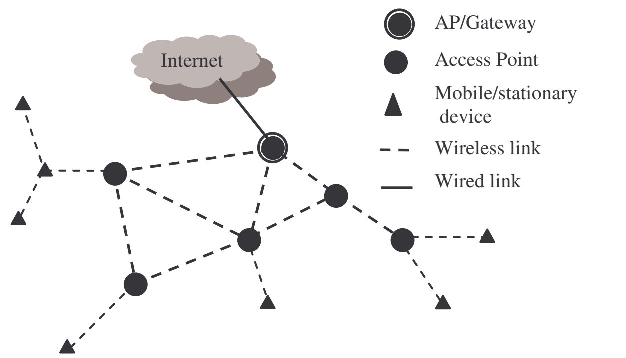

Figure 1: An example of a mesh network architecture for a community mesh networking for resource sharing with six MAPs where one acts as a Gateway to the internet.

It is important to note that the mesh gateways can also function as mesh routers [15], [16]. Hence, the mesh gateway nodes and the access points form the backbone wireless mesh network and are sufficiently referred to as mesh access points (MAPs). Examples of WMN applications [6] include community surveillance, community resource sharing, broadband home networking, enterprise networking. These applications generate a large amount of client to client traffic as well as client to gateway traffic [15], [17]. Hence, it is sufficient to assume that most traffic appear at the backbone network. The focus of this work is therefore, to maximize certain properties such as network lifetime based on the backbone wireless mesh network thus allowing us to ignore the mesh clients.

3.2 System Model

Consider a set $V = \{v_1, v_2, ..., v_n\}$ of randomly distributed static MNs located on a 2D plane, each node $u \in V$ has a unique $id(u_i) = i$, where $1 \le i \le N$ (N = |V|, number of nodes) and is specified by its coordinates

$(x(u), y(u))$ at any instance. Each node $u \in V$ is assigned a power function p_{tx} where $p_{tx}(d_u)$ is the minimum transmission power needed to establish a communication link to another node $v \in V$ located d_u distance away from u.

Two assumptions are made: (1) that the maximum transmission power, $p_{tx}^{\max}$, $\forall\, u \in V$ is the same and (2) that the maximum distance, D, needed for any two nodes $u, v \in V$ to communicate directly is also the same. Therefore, $p_{tx}(D) = p_{tx}^{\max}$, $\forall u \in V$. At the beginning of simulation, every node transmits with full power $p_{tx}^{\max}$ and an induced graph modelled as a quasi Unit Disk Graph (qUDG), $G = (V, E)$ is created. Here, V is the set of all nodes in the network and E is the set of all links/edges i.e., $E = \{(u,v) \mid d(u,v) \le D\}$.

The WMN topology is modelled as a weight directed graph in which for each edge $(u,v) \in E$, node v has to be within the transmission range of u. The notation $d(u,v)$ denotes the Euclidean distance between the nodes u and v.

The following gives a list of definitions to the terms used in the paper.

Definition 1 (Accessible Neighbourhood Set): The Accessible Neighbourhood Set, A_u^N, is defined as the set of all nodes that have a direct link with node u, when u transmits at maximum transmission power. The set is given by $A_u^N = \{v \in V \mid d(u,v) \le D\}$.

Definition 2 (Weight Function): An edge (u,v) has a weight given by the following expression:

$$w(u,v) = t.d(u,v)^{\alpha} + rx(u,v)\,, \tag{1}$$

where t is a threshold related to signal to noise ratio at node u and $\alpha \in [2,5]$ is a constant real number depending on the wireless transmission environment. Both parts of (1) are summed up to give the transmission power. The first part is the transmitter power consumed by transmitting a packet from node u to v and $rx(u,v)$ is the receiver power. Assuming all receivers have the same threshold power for signal detection hence the value of t becomes some appropriate constant.

Definition 3 (Logical Neighbour Set): A logical neighbour set of node u is given by NS_u^L. Node $v \in NS_u^L$ if and only if there exists an edge (u,v) in the topology generated by the algorithm and $NS_u^L = \{v \in V \mid u \to v\}$.

Definition 4 (Fully Connected): A network is fully connected if and only if $\forall\, u \in V$, there exist either a direct path or a multihop path from u to every other node $v \in V$ in the network.

Definition 5 (Relay Region): Given a node v, let the physical location of v be denoted by $Loc(v)$. The relay region of the transmit-relay node pair (u,v) is the physical region $RL_{u \to v}$ such that relaying through v to any other point in $RL_{u \to v}$ consumes a lesser power than direct transmission to that point.

Definition 6 (Network Lifetime): Given a set of nodes V and for all $v \in V$ an energy value $E(v)$, the lifetime of node v is $Lt_v = \{t \mid f_v(t) \le E(v)\}$ until when $E(v) = 0$, where $f_v(t)$ is the energy consumed by v. The network lifetime $Lt_V = Min_{v \in V}(Lt_v)$ i.e., the time taken till the first node goes off.

Definition 7 (Bi-directionality): A topology $G'' = (V'', E'')$ generated by the algorithm is bi-directional if, $E'' = \{(u,v) \mid (u,v) \in E(G')$ and $(v,u) \in E(G')\}$ and $V'' = V$.

4. PROPOSED ALGORITHM

In this section, we present the algorithm design assumptions. Additionally, a two phased design algorithm i.e., construction of a *Local Minimum Shortest-path Tree* and *unidirectional links removal* is proposed.

4.1 Algorithm Design Assumptions

The design of the algorithm assumes that: (1) each node use either a GPS receiver or other localization techniques [20] to gather its location information, (2) each node uses an omni-directional antenna for both transmission and reception, (3) each node is able to adjust its own transmission power and (4) the initial topology graph $G = (V, E)$ is fully connected. The objective of the topology control algorithm is to find a subgraph of the qUDG, $G = (V, E)$, such that the resultant topology preserves certain network requirements namely, decrease in average node degree, an averagely low power consumption thus longer network lifetime and a maintenance of connectivity in the resultant network topology. Each node must adjust its transmission radius to reduce its power consumption while still maintaining the connectivity. Since the architecture is more of infrastructure-less, the topology has to be constructed in a distributed and localized manner to avoid flooding of the network. This implies that, each node must establish its transmission power based only on the information of the nodes reachable by a small constant number of hops.

4.2 The ELMST Algorithm Design Phases

Phase 1: Construction of Local Minimum Shortest–path Tree (LM-SPT).

In this phase, each node gathers neighbour information and constructs an LM-SPT (as depicted in Figure 2). The phase involves three stages:

i. **Information collection and exchange: -** Each node in this step periodically broadcasts a beacon '*Hello'* messages using maximum power p_{tx}^{max}. The information exchanged here includes the node ID and the position in the 2D plane. This information is used to calculate the node to node distance, the link weights and the path weights. The link weight represents the power required for transmission along a link, and the path weight represents the sum of all minimum link weights of a path from source to destination. The result of this stage is the '*Accessible Neighbourhood Set'* A_u^N for each node $u \in V$. The '*Hello'* message is also sent by each node asynchronously and periodically giving each node's information about its neighbours.

ii. **Construction of a Logical Visible Neighbourhood Topology: -** Each node applies the concept of the relay region in order to gather the nodes in the set of '*Logical Visible Neighbourhood'*. The set $LVN(u,k) \subseteq A_u^N$ at $k=1$. If a node $v \in A_u^N$ is in the relay region of another node $w \in A_u^N$ then node v is moved to a new set of non neighbours called $NotNbr$. This is repeated for all the nodes $i \in A_u^N$. All nodes reachable via other nodes are moved out of the set A_u^N and the remaining set is called $LVN(u)$. Each node then applies the Dijkstra's algorithm independently from a source node to all the other nodes in V in order to build its LM-SPT.

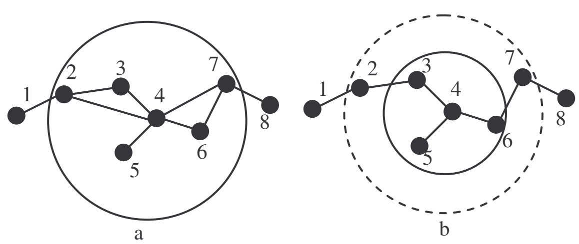

Figure 2: (a) the topology from the point of view of node 4 before topology control. (b) the view after topology control.

iii. **Computing the transmission power: -** Each node computes its minimal transmission power to cover only all of the nodes contained in the set $LVN(u,k)$, in which case, it determines which node among the nodes is furthest. The node then adjusts its transmission power to reach this node and thus all other nodes in the set $LVN(u,k)$ are covered. The set is given by $G' = (V', E')$. From the information on the location of the nodes, the inter node distance is calculated. The distance is applied in the propagation model formulas to obtain the minimum transmission power. The free space model is used for short distances and the two ray ground reflection model is used for longer distances depending on the value of the Euclidean distance in relation to the cross over distance.

The cross over distance is calculated using the following expression:

$$Cross\_over\_dist = \frac{4\pi h_t h_r}{\lambda}, \qquad (2)$$

where $h_t = h_r = 1.5$, are the antenna heights of the transmitter and receiver respectively. Lambda λ, denotes the wavelength.

For $d(u,v) < Cross\_over\_dist$, the Free Space model is used whereas if $d(u,v) \geq Cross\_over\_dist$, the Two-ray-ground model is used. The free-space propagation model is given by the following expression:

$$Pmin = \frac{RxThresh((4\pi d)^2 L)}{G_t G_r \lambda^2}. \qquad (3)$$

The two ray ground reflection model is given by the following expression:

$$Pmin = \frac{RxThresh(d^4 L)}{G_t G_r h_t^2 h_r^2}, \qquad (4)$$

where $G_t = G_r = 1$ is the transmitter and receiver Antenna gain respectively, $L=1$ is path loss exponent and again the values of $h_t = h_r = 1.5$.

Figure 2 shows an illustration of the operations of phase 1. Node 4 broadcasts *"hello"* messages with full transmission power and obtains responses from the nodes in the A_4^N such as nodes 2,3,5,6 and 7. After stage 2, node 4 establishes that node 7 is in the relay region of node 6 and node 2 is in the relay region of node 3 hence, $LVN(4) = \{3,5,6\}$ and $NotNbr(4) = \{2,7\}$. In stage 2, node 4 calculates its final transmission power as that used to reach node 6 which is the furthest node in the $LVN(4)$ set. The LM-SPT is then built using the Dijkstra's algorithm.

Table 1 shows the algorithm that runs in each node $u \in V$ to compute the minimum transmission power. Let $p(u,v)$ be the minimum power required to transmit a data packet from node u to node v at any time instance. Also let initial power $p = p_{tx}^{max}$ and $F(u,p)$ be the region that node u can reach if it broadcasts with power p. It is assumed that every node u knows its terrain and antennae characteristics and is able to compute the region $F(u,p)$. The sets Accessible Neighbourhood (A_u^N), Not neighbour ($NotNbr$), and Logical Visible

Neighbourhood ($LVN(u)$) of node u are initialized to *empty set,* ϕ. Node u broadcasts the *'Hello'* messages at full transmission power $p_{tx}^{\max}$ stating its position. It collects all the *ACKs* recording each nodes ID, and Location ($Loc(v)$) in the Accessible Neighbourhood set $A_u^N = \{v \mid Loc(v) \in F(u, p_{tx}^{\max}), \quad v \neq u\}$ where $Loc(v)$ is the location of the node v and $F(u, p_{tx}^{\max})$ is the region covered by node u at full transmission power.

Table 1. The Topology Control Algorithm Listing

Phase 1:
Input: the set $G = (V, E)$
Output: Power assignment to node u

001 $p = p_{tx}^{\max} \longleftarrow$ initialize the maximum power
002 $A_u^N = \phi \longleftarrow$ accessible neighbors at $p = p_{tx}^{\max}$
003 $NotNbr = \phi \quad \longleftarrow$ non neighbor set
004 $LVN(u) = \phi \longleftarrow$ local Visible neighbors at $p(u)$
Begin
005 broadcast "Hello" message with $p = p_{tx}^{\max}$
006 receive Acks and record the neighbors' id and their locations in the set A_u^N
007 $A_u^N = \{v \mid Loc(v) \in F(u, p_{tx}^{\max}), \quad v \neq u\}$
008 **if** ($A_u^N == \phi$)
009 Return,
010 **else**
011 $\forall\, v \in A_u^N$, calculate distance $d(u,v)$
012 sort distance in ascending order.
013 calculate $p(u,v), \; \forall\, v \in A_u^N$ using $d(u,v)$, received power & propagation models.
014 sort A_u^N by $p(u,v)$, in increasing order, $\forall\, v \in A_u^N$
015 **for** each $v \in A_u^N$ do
016 **for** each $w \in A_u^N$ do
017 **if** $Loc(v) \in RL_{u \to w}$ **&&** $p(u,w) + p(w,v) \leq p(u,v)$
then $NotNbr = NotNbr \cup \{v\}$
018 **else if** $Loc(w) \in RL_{u \to v}$ **&&** $p(u,v) + p(v,w) \leq p(u,w)$
then $NotNbr = NotNbr \cup \{w\}$
019 $LVN(u) = A_u^N - NotNbr$
020 $p(u) = \max\{p(u,v) \mid v \in LVN(u), F(u,p) \leq F(u, p_{tx}^{\max})\}$

For every node $v \in A_u^N$, node u computes the distance $d(u,v)$ and the power $p(u,v)$ and arranges them in ascending order. For every two nodes $v, w \in A_u^N$, if node v is in the relay region of node w i.e., $Loc(v) \in RL_{u \to w}$ and $p(u,w) + p(w,v) \leq p(u,v)$ then node v is moved to the $NotNbr$ set, otherwise it remains. If $Loc(w) \in RL_{u \to v}$ and $p(u,v) + p(v,w) \leq p(u,w)$ then node w is moved to the $NotNbr$ set otherwise it remains. The Logical Visible Neighbourhood of node u i.e., $LVN(u)$ is therefore given by the set A_u^N less $NotNbr$ set of node u.

Phase 2: Removal of Unidirectional links.

Bi-directional links are quite important for link level acknowledgements and for packet transmissions and retransmissions over the unreliable wireless medium. In phase two of the algorithm, unidirectional links generated in phase 1 are removed so as to obtain bi-directional edges using edge addition. The resulting topology is given by $G'' = (V'', E'')$ where $V'' = V$, $E'' = \{(u,v) \mid (u,v) \in E(G') \text{ and } (v,u) \in E(G')\}$. Table 2 depicts the algorithm used. For every node $v \in LVN(u)$, if there is an edge $u \to v$, then there must be an edge $v \to u$ and node $u \in LVN(v)$.

Table 2. Algorithm Listing For Unidirectional Links Removal

Phase 2:
Input: $LVN(u) \leftarrow$ 1 hop uni/bi - directional link neighbours of u.
Output: $LVN(u) \leftarrow$ new $LVN(u)$ with bi-directional links
Convert to bidirectional
(*convert unidirectional links to bidirectional links*)

001 $LVN(u) \leftarrow$ 1 hop unidirectional neighbours of node u,
002 **if**
003 **for** each node k in $LVN(u)$
004 **if** edge $u \to k$ and $u \notin LVN(k)$
005 **then** add edge $k \to u$
006 **then** add node u in $LVN(k)$
007 repeat 2 – 6 for all $u \in V$
008 Return $LVN(u)$

5. SIMULATION AND RESULTS

In this section, some of the simulation results to verify the effectiveness of ELMST are presented. The performance of ELMST and IEEE 802.11b Maximum Power are compared. The topology control algorithm is implemented in NS-2. The nodes are randomly distributed in a rectangular region of 1200m x 1200m and are varied in number from 10 to 100 nodes. All the nodes have a maximum transmission range D of 250m. A carrier frequency of 2.4GHz and a transmission bandwidth of 2MHz is used. It is assumed that the omni-directional antennas used have a 0dB gain and are placed at a height of 1.5m above a node.

OLSR is used as the routing protocol in the simulations due to its distributive nature. UDP traffic is used as the application traffic source with the number of connections varying from 10, 20, 30 or 40.

The average connectivity is obtained by evaluating the average node degree (the *mean connectivity* per node) using the formula $C_u = y/(N)$, where y is the number of nodes reachable by node u and N is the total number of nodes in the network. The average *mean connectivity* denoted by ψ is given by:

$$\psi = \frac{1}{N}\sum_{u=0}^{N-1} C_u \ , \qquad (5)$$

which is equivalent to summing up all the *mean connectivity* of every node in the entire network. The value of C_u should not be too large as this would imply that a node communicates even with very distant nodes and this increases interference and collision and also wastes energy. On the other hand, it should not be made too small as this would imply that longer paths have to be taken to reach destinations and this also increases the overall energy consumption in the network. Figure 3 shows a comparison of the average node degree levels. The ELMST algorithm records a great reduction in the average node degree not exceeding 6.0 for the entire 10 to 100 nodes network, while maintaining node connectivity. This results from the fact that with reduced power, a node's neighbours becomes only those that are closest to the node unless there is no relay node to a far neighbour.

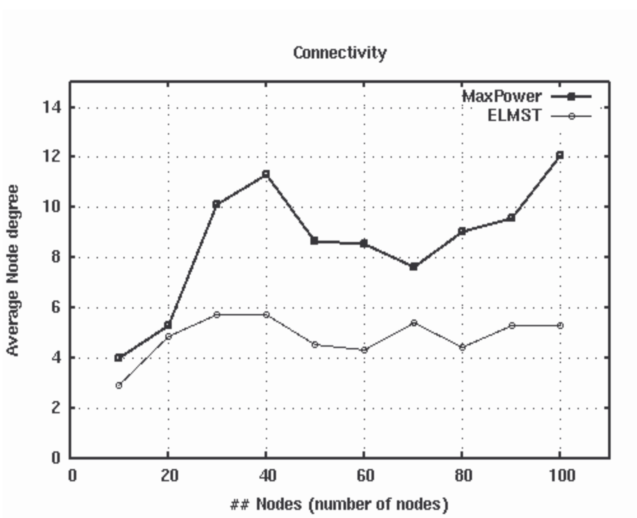

Figure 3: Performance comparisons between a conventional IEEE 802.11b at Max transmission power and ELMST in terms of Average Node Degree. Nodes range from 10 to 100.

The lifetime of each of the network instances is also considered. This is measured in terms of the number of nodes that remain alive over a period of time. The simulations are based on the assumption that nodes are static and are run for a period of 150 seconds. Figure 4 shows the lifetime of a network of 50 nodes with 20 traffic connections at random times. A total of 1024 packets were sent with 512bytes of data. It is noted that when using maximum power, the network gets disconnected after around 52s. At a controlled power, the lifetime is extended to the 73s.

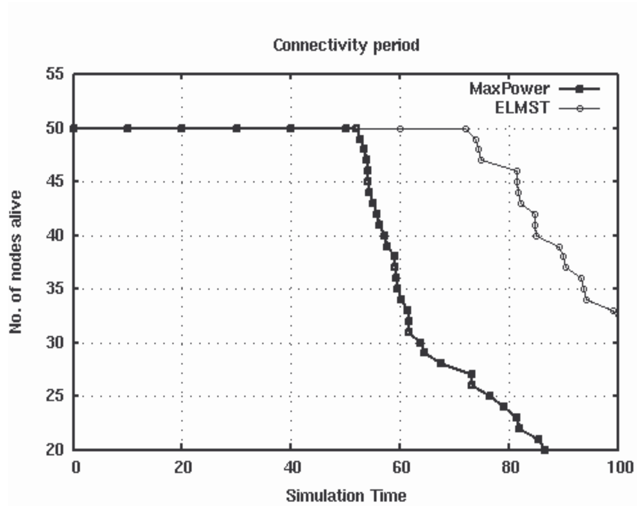

Figure 4: Performance comparisons between a conventional IEEE 802.11b at Max transmission power and ELMST in terms of network lifetime for a 50nodes network.

Similarly, in figure 5, a network of 100nodes is simulated with 40 traffic connections at random times. As expected with controlled power, ELMST ensures the network remains connected up to 85s. This is because, at reduced per node transmission energy, channel contention is reduced and a nodes total amount of processing power is reduced as it only reaches few neighbours and eventually the overall consumed power in the network is reduced.

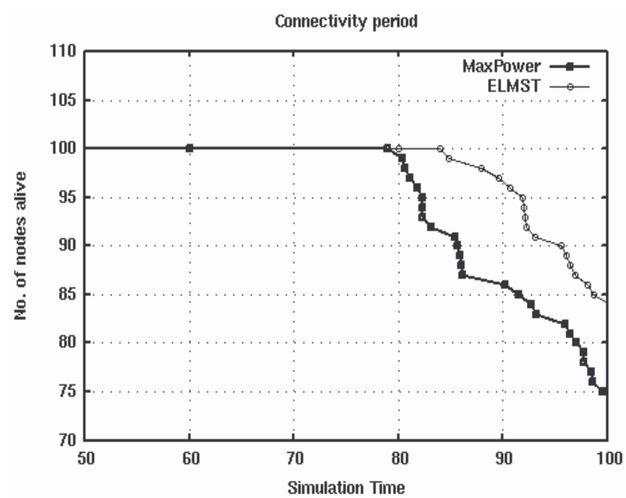

Figure 5: Performance comparisons between a conventional IEEE 802.11b at Max transmission power and ELMST in terms of network lifetime for a 100 nodes network.

6. CONCLUSION

In order to realize the effectiveness of WMNs, the lifetime of the network is very critical. In this work, an enhanced minimum shortest-path tree based energy efficient topology control algorithm (ELMST) for wireless mesh networks with limited mobility was presented. The algorithm uses only the locally available information to determine the nodes that should be its logical neighbours at any given time. The resulting topology ensures connectivity, lower average node degree as well as reduced power consumption in the network. The algorithm was validated via simulations on the ns-2 platform. The algorithm was however limited to the static backbone mesh nodes.

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