

# A Distributed Topology Control Algorithm to Conserve Energy in Heterogeneous Wireless Mesh Networks

F. O. Aron, T. O. Olwal, A. Kurien, and M. O. Odhiambo

**Abstract**—A considerable amount of energy is consumed during transmission and reception of messages in a wireless mesh network (WMN). Reducing per-node transmission power would greatly increase the network lifetime via power conservation in addition to increasing the network capacity via better spatial bandwidth reuse. In this work, the problem of topology control in a hybrid WMN of heterogeneous wireless devices with varying maximum transmission ranges is considered. A localized distributed topology control algorithm is presented which calculates the optimal transmission power so that (1) network connectivity is maintained (2) node transmission power is reduced to cover only the nearest neighbours (3) networks lifetime is extended. Simulations and analysis of results are carried out in the NS-2 environment to demonstrate the correctness and effectiveness of the proposed algorithm.

**Keywords**—Topology Control, Wireless Mesh Networks, Backbone, Energy Efficiency, Localized Algorithm.

## I. INTRODUCTION

IN a hybrid Wireless Mesh Networks (WMNs) [1], each node operates both as a host and as a router. The nodes in the network automatically establish an Ad Hoc network and maintain mesh connectivity. They dynamically self organize and self configure and hence, can be viewed as special cases of Ad Hoc networks. The general architecture of WMNs [2],[3] is composed of three distinct wireless network elements: a *Network Gateway* (a mesh router with gateway/bridge functionalities), *Access Points* (mesh routers) and *mobile or stationary nodes* (mesh clients). For the purpose of this work, the elements are referred to as mesh nodes (MNs). When the radius of coverage of two different MNs covers each other then a wireless link is established. In

the event that the radio transmission range between two MNs is insufficient then multiple hops are used to forward packets to the intended destination. Real-world WMNs applications [1] have been witnessed in metropolitan area networking, broadband home networking, community and neighbourhood networks, enterprise networking and building automation. Energy efficiency [4] has been a major topic of discussion in the history of Multihop Wireless Networks (MWNs), such as MANETs for quite a long time. Issues of concern include the possibility of efficiently using per node energy with a view to lengthening the lifetime of the said network.

Other benefits of controlling the energy usage include, the increase in capacity due to the spatial reuse thus enhancing throughput [5] and reduction of node to node interferences during communication. On the other hand reducing a nodes transmission range can also quite negatively affect the network connectivity especially if the network is heterogenous where the MNs have varying maximum transmission ranges and the occurrence of uni-directional links is not unusual in the topology e.g., in a hybrid WMN.

Although several contributions have been tailored towards studying power control problems in energy-constrained conventional IEEE 802.11 wireless network standards, little attention has been drawn to the power control problems in WMNs. This is mainly because the backbone wireless mesh routers are static and have usually been assumed [1] to have electrical mains power supply and hence are purported not to have power constraints. However, with specific considerations to rural areas 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. Mesh nodes have thus to rely on exhaustible and renewable means of energy supply such as solar, battery or generator. Furthermore, the mesh clients are definitely power constrained [1]. In order to address these constraints, a localized distributed energy efficient topology control algorithm for application of WMNs in rural areas is presented.

Topology control algorithms [6],[7],[8],[9],[10], have largely been proven to be one way of achieving energy efficiency in MWNs. The main goal of a topology control algorithm is to select appropriate logical neighbours of a node (from a given physical topology network) according to some specified rules. Each node should be able to apply the rules to adjust its transmission power accordingly so that only the

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necessary logical neighbours are covered.

Considerable previous work exist that address the problem of topology control, for example, Rodoplu and Meng [11] 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 [11], Li and Halpern [12] 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 [11]. Li and Halpern [13] further propose the small minimum energy communication network (SMECN). In this algorithm, each node  $u$  initially broadcasts a "hello" message with some initial power and after reception of acknowledgements (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 [11][12][13], 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 [6].

In [8][9][10], the concept of local neighbourhood is 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 distributed and localized topology control algorithms. In the work of Li et al [8], a node builds its local minimum spanning tree (LMST) based only on its one hop neighbourhood information. It keeps only one hop nodes as neighbours in the final topology. The resulting topology has been shown to be connected and with node degree bounded by 6. In addition they provide an optional phase where the topology is transformed to one with bidirectional links only. But the authors of [8] also assume a homogenous network which is not practical according to [7][14]. Li et al [7] presents DRNG and DLMST for heterogeneous networks. Their focus is mainly on connectivity maintenance and bi-directionality in the network although the algorithms are also shown to be power efficient. The authors in [14] present localized strategies for heterogeneous wireless devices to self-form a globally sparse power efficient network topology.

However, all of the algorithms shown in [7][8][9][10][14] have not been applied to WMNs. It can not be generally assumed that the algorithms will automatically function in WMNs as the requirements on power efficiency and mobility are very different between WMNs and other Wireless Multihop Networks [1].

Therefore, in this work, an energy-efficient distributed topology control algorithm for heterogeneous WMNs is proposed with the following characteristics: in a stationary WMN, the minimum energy topology is constructed in one pass; the algorithm guarantees maintenance in network connectivity and with reduced average node degrees. Since algorithm decisions are based on the locally gathered information, the algorithm scales well for large WMNs. The

execution consists of three phases.

The remainder of this paper is organized as follows. In section 2, the details of the network model is given. In section 3, a discussion on the phases of the proposed algorithm is presented followed by a mathematical analysis in section 4. Simulation results are presented in section 5 to validate the performance of the algorithm. Finally, the paper is concluded in section 6 and a suggestion for future work given.

## II. NETWORK MODEL

Consider a set  $V = \{v_1, v_2, \dots, v_n\}$  of randomly distributed static heterogeneous wireless mesh nodes (MNs), each node  $u \in V$  has a unique  $id(u) = i$  where  $1 \leq i \leq N$  ( $N = |V|$ , number of nodes) and is specified by its location coordinates  $(x(u), y(u))$  on a 2D plane. Each node is equipped with an Omni-directional antenna with an adjustable transmission power. Due to the heterogeneity of the nodes, they have varying maximum transmission powers and radio ranges. For all  $u \in V$ , let  $P_u$  denote  $u$ 's transmission power and  $P_u^{\max}$  denote the maximum transmission power (also called full power) for node  $u$ . Let  $P_{uv}$  be the transmission power required by node  $u$  to reach  $v$ .

Assuming the medium is symmetric and that asymmetric links are only caused due to a difference in transmission ranges then  $P_{uv} = P_{vu}$  otherwise in the event that  $P_u^{\max} \neq P_v^{\max}$  for  $u \neq v$  then asymmetric link would occur if  $P_u^{\max} \geq P_{uv} > P_v^{\max}$  in which case  $P_{vu} > P_v^{\max}$  hence node  $v$  can not reach node  $u$  at full power.

The topology where each node transmits at full power is modelled as a directed graph  $\vec{G} = (V, \vec{E})$ . Here,  $V$  is the set of all the nodes in the WMN and  $\vec{E}$  is the set of all the directed links in the network. An edge/link  $\vec{E}_{uv} \in \vec{E}$  if node  $v$  is within the transmission range of node  $u$ . The notation  $d(u, v)$  denotes the Euclidean distance between the nodes  $u$  and  $v$ . The distance  $D_u$  is the range that is covered when node  $u$  transmits at full power. The topology  $\vec{G}$  can be *fully connected*, *partially connected* or *disconnected*. A *fully connected*  $\vec{G}$  implies that there is a directed (either multihop or direct) path from any source to destination in the network. *Partially connected*  $\vec{G}$  implies that there exists pairs of nodes for which only one can reach the other either directly or via multihop. Finally, *disconnected*  $\vec{G}$  implies that there exists pairs of nodes for which no path (direct or multihop) is available from one node to the other.

In order to communicate with another, a node broadcasts a message at a specific energy level in the range of  $(0, P_u^{\max}]$ . The algorithm assumes a path loss model previously adopted by the works of [11][15]. In this model, the power of a received signal is found to be  $1/d^\alpha$  where  $d$  represents the propagation distance and  $\alpha$  ranges from 2 to 5 depending on the environment. In spite of this, the algorithm still performs

well as long as a node knows the path loss models of its neighbours which can be obtained via the exchange of local neighbour information.

The following list gives the definitions of 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 has a direct link with node  $u$ , when  $u$  transmits at maximum transmission power. The  $A_u^N = \{v \in V \mid d(u, v) \leq D_u\}$ .

**Definition 2 (Weight Function):** An edge  $\overrightarrow{E_{uv}}$  has a weight cost given by the following expression:

$$w(u, v) = t_1 + t_2 \cdot d(u, v)^\alpha, \quad (1)$$

where  $t_1$ , and  $t_2$  are some constants depending on the electronic characteristics and the antenna characteristics of node  $u$  and  $\alpha \in [2, 5]$  is a constant real number depending on the wireless transmission environment.

**Definition 3 (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 4 (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  $RL_{u \rightarrow v}$  such that relaying through  $v$  to any other point in  $RL_{u \rightarrow v}$  consumes a lesser power than direct transmission to that point.

**Definition 5 (Network Lifetime):** Given a set of nodes  $V$  and an initial energy value  $E(v)$  for all  $v \in V$ , the lifetime of node  $v$  is  $Lt_v = \{t \mid f_v(t) \leq E(v)\}$  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 6 (Bi-directionality):** A topology  $\overrightarrow{G'} = (V', \overrightarrow{E'})$  generated by the algorithm is bi-directional if  $V' = V$ ,  $\overrightarrow{E'} = \{\overrightarrow{E'_{uv}} \mid \overrightarrow{E'_{uv}} \in \overrightarrow{E'}(\overrightarrow{G'}) \text{ and } \overrightarrow{E'_{vu}} \in \overrightarrow{E'}(\overrightarrow{G'})\}$ .

The objective of the proposed algorithm is to derive a minimum-energy topology  $\overrightarrow{G'}$  that is *fully connected*, such that the resultant topology satisfies certain requirements namely: decrease in average node degree, maintenance of the same number of bi-directional links available in  $\overrightarrow{G}$ , maintenance in connectivity (multihop or direct reachability) between every node pair, an averagely low power consumption thus longer network lifetime in the resultant network topology. Each node must adjust its transmission radius to reduce its power consumption while still maintaining the connectivity. It is assumed that the algorithm begins with a *fully connected* topology. It is further assumed that each node  $u \in V$  knows its location information  $(x(u), y(u))$  but is not aware of the positions of the others.

The algorithm assumes a hybrid WMN [1] which is infrastructure-less and hence has to be distributed and constructed in a localized manner to avoid flooding of the network, i.e., a node must decide its transmission power based only on the information of the nodes reachable by a small constant average number of hops. It will further be assumed that the MNs (the backbone mesh routers, the backbone mesh gateways, and the wireless mesh clients) are static.

### III. PROPOSED ALGORITHM

The main objective is to generate a minimum-energy topology  $\overrightarrow{G'}$  graph. Ideally the resultant topology should conserve energy consumption in the network. The algorithm has to be localized and distributed implying decisions are based solely on the locally collected information. Taking an arbitrary node  $u \in V$  in the network  $\overrightarrow{G}$ , a three phased topology control algorithm that runs in each node is presented as follows:-

#### Phase1: Establishing the accessible neighbourhood topology.

In this stage, node  $u$  broadcasts a “hello” message using its full power,  $P_u^{\max}$ . The nodes that receive the “hello” message form the set of accessible neighbourhood of node  $u$  denoted by  $A_u^N$ . The “hello” message contains the id of  $u$ , the location information of  $u$ ,  $(x(u), y(u))$  and the value of the  $P_u^{\max}$ . Every node  $v \in V$  that receives the “hello” message replies with an acknowledgement (ACK) also with its id,  $x(v), y(v)$  and  $P_v^{\max}$ .

In order to decide on the transmission power to use for sending an ACK two cases can arise:

**Case 1:-** for all  $v \in A_u^N$ , if  $P_v^{\max} \geq P_{uv}$ ,  $v$  is able reach node  $u$  via one hop link  $\overrightarrow{E_{vu}}$ .

**Case 2:-** if  $P_v^{\max} < P_{uv}$ , then  $v$  has to find a relay node within its relay region to reach node  $u$ .

Two solutions exist for case 2 of relaying:

- The node  $v$  uses its full power  $P_v^{\max}$  to broadcast the ACK with a special *on/off* bit to signal that the ACK message may have to be relayed. Any node  $w \in A_u^N$  that receives this ACK not addressed to them, assist by re-broadcasting the ACK with their full power  $P_w^{\max}$ .
- The node  $v$  can send the ACK using the network layer routing protocol to  $u$ . Considering the initial assumption of a *fully connected* topology  $\overrightarrow{G}$ , there exists a directed path from  $v$  to  $u$ .

Using this knowledge of the location information and the maximum transmission power of itself and its accessible neighbours, and assuming the path loss models of the neighbours are known, node  $u$  hence, derives the existence of accessible links. For every node pair  $v, w \in A_u^N$ , link  $\overrightarrow{E_{vw}}$  becomes one of the accessible edges of node  $u$  if

$P_v^{\max} \geq P_{vw}$ . Subsequently, node  $u$  constructs its local accessible neighbourhood topology that includes all the accessible nodes, itself and the accessible edges. A weight directed accessible topology graph  $\overline{G}_u = (V_u, \overline{E}_u)$  of node  $u$  is obtained, where  $\overline{E}_u$  defines the collection of all the accessible edges and  $V_u$  is the collection of all the local accessible nodes.

Fig. 1 depicts an example of what goes on during the operation of phase 1. Node  $b$  can only reach  $a$  via  $c$ . The accessible neighbours of  $a$  are  $A_a^N = \{b, c\}$  while that of  $b$  are  $A_b^N = \{c, d\}$ .

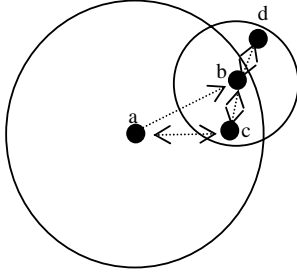


Fig. 1 Phase 1 operation, broadcasting “hello” with full power, node  $b$  respond via  $c$  obtaining the accessible neighbours of  $a$

The weight of each of the directed edges in  $\overline{E}_u$  is denoted by  $w(u_i, u_k)$  and is the power required by  $u_i$  to reach  $u_k$ . Every node  $v$  in the accessible neighbourhood of  $u$  eventually gets to start and construct its own Local accessible neighbourhood set  $\overline{G}_v$  after it is triggered by another node.

### Phase 2: Constructing the minimum-energy Local topology view.

At this stage, there exist a weighted directed graph topology  $\overline{G}_u, \forall u \in V$ . Node  $u$  has knowledge of the edge weights,  $w_e$  and path weights  $w_T$ , where path weight of a directed path  $w_T(u_i, u_k) = u_0 \rightarrow u_1 \rightarrow u_2 \rightarrow \dots \rightarrow u_k$  is the sum of the edge weights in the path from  $u_0$  to  $u_k$  and is given by the following expression:

$$w_T(u_0, u_k) = \sum_{n=1}^k w_e(u_{n-1}, u_n) \quad (2)$$

In this phase, node  $u$  applies shortest path algorithms either Dijkstra’s or Bellman-ford algorithm to all the other nodes in the local accessible neighbourhood. The shortest path from  $u$  to  $v$  is  $\min(w_T(u, v))$  for all the paths available for the node pair. The result is the minimum-energy local topology view,  $\overline{G}'$ , denoted by  $\overline{G}_{uM} = (V_{uM}, \overline{E}_{uM})$  with the following properties:

**Property 1:-**  $\forall v \in A_u^N$ ,  $\overline{G}_{uM}$  is a typical shortest path tree view from  $u$  to  $v$ , where  $V_{uM} = V_u$  and  $\overline{E}_{uM} \subseteq \overline{E}_u$  i.e., if node  $u$  receives ACK from  $v$  via some relay nodes and this path is the shortest then node  $u$  drops its direct edge to node  $v$  as

depicted in Fig. 2 where directed edge  $a \rightarrow b$  is dropped.

**Property 2:-**  $\overline{G}_{uM}$  is obtained based on the edge weights of node  $u$  to the other nodes whose calculation assumes no specific propagation model. But since different path loss models may exist,  $\overline{G}_{uM}$  may vary.

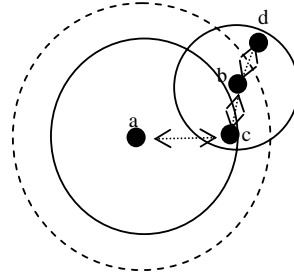


Fig. 2 Phase 2 operation, construction of the minimum-energy topology view with only the minimum energy paths

### Phase 3: Determining the Transmission power.

Finally in this phase, node  $u$  determines its own transmission power and the powers on the accessible edges of all the nodes in the accessible neighbourhood  $A_u^N$ . Node  $u$  takes as its power, the largest one-hop edge weight among the edges obtained in the minimum-energy local topology view  $\overline{G}_{uM}$ . After node  $u$  adopts its minimum-energy level, it propagates this minimum power value to the other neighbours in the accessible neighbourhood with the current Transmission Power Indicator (TPI) number. Every node  $v \in A_u^N$  on receiving the TPI message compares the value with its current setting and if increment is required and current  $P_v < P_v^{\max}$  then it increases its value accordingly. Otherwise, it drops the TPI message. It implies that the power setting can be assigned by node  $u$  itself or any other node in the accessible neighbourhood that executed the algorithm prior and successfully propagated its power value. The setting disregards a value that is below its current setting. For instance, in Fig. 3 below, node  $c$  is in the accessible neighbourhood of both nodes  $a$  and  $e$ .

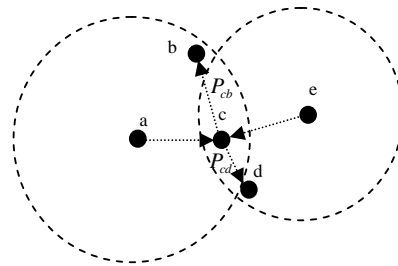


Fig. 3 Determining a node's transmission range

If the algorithm is first run in  $a$  and node  $a$  propagates its minimum power value (TPI) and given that  $P_{cb} > P_{cd}$ , the minimum power value of  $c$  given by  $P_c$  is set as value of

edge  $P_{cb}$  by node  $a$ . When later node  $e$  runs the algorithm and since it does not have node  $b$  in its accessible neighbourhood, it tries to fix the value of  $P_c$  as  $P_{cd}$  which fails because  $P_c$  is already set by node  $a$  as  $P_{cb}$  and  $P_{cb} > P_{cd}$  and besides this would violate the accessibility rule already defined in node  $a$ 's minimum-energy local topology view.

#### IV. ANALYSIS

The hybrid WMN presents challenges on full connectivity and scalability [1]. In this section, mathematical analyses of the proposed topology control algorithm satisfying these properties are presented. It is shown that the resultant minimum-energy topology guarantees maintenance of the network connectivity in addition to being scalable to large scale wireless mesh networks. The execution of the algorithm is done once at the topology construction time of network and hence, control overheads are not considered an issue in the analysis.

#### Guaranteeing Full Connectivity maintenance in the network

**Theorem 1:** the resultant network topology  $\bar{G}'$  ensures that if the maximum transmission power topology  $\bar{G}$  is fully connected, then  $\bar{G}'$  is also fully connected.

**Proof:** Taking any two nodes  $m, n \in V$ , and based on the previous assumption that the algorithm begins with a fully connected network topology, there exists a directed path (either direct or multihop) from node  $m$  to  $n$ . We prove that there is a path from node  $m$  to  $n$  in  $\bar{G}'$ .

In phase one of the algorithm, the local node  $m$  collects all the direct links to nodes in the accessible neighbourhood. In phase 2, node  $m$  constructs the minimum-energy local topology view using the shortest path algorithm and based on the edge weights. The shortest path algorithms such as Dijkstra's or Bellman-Ford algorithm includes all the nodes in the accessible neighbourhood and even though the edge  $\bar{E}_{mn}$  may not exist after the second phase (because of the availability of a more power efficient path e.g.,  $\bar{E}_{mk}$  and  $\bar{E}_{kn}$ ), there will be a path from node  $m$  to  $n$ . Phase 3 determines the required transmission power per node that also guarantees the validity of the minimum-energy local topology view. Therefore, after phase 3, a path from  $m$  to  $n$  exists and is guaranteed to be valid.

#### Scalability

The proposed algorithm is distributed and localized. Each node in the network runs the algorithm independently based on the information that is gathered from the locally accessible nodes. The initialization "hello" and the TPI message exchanges are restricted to only nodes in the accessible neighbourhood. This implies that no matter how large the wireless mesh network extends, the execution of the algorithm is not affected hence is scalable.

Additionally, since the execution of the algorithm is performed once during the network topology setup, the

control overheads are not considered an issue in this work. Furthermore, the execution is asynchronous from node to the next till convergence in the transmission power per node is achieved.

#### V. SIMULATION AND RESULTS

In this section, some of the simulation results to verify the effectiveness of the proposed topology control algorithm are presented. The algorithm is implemented in NS-2. A directed network of randomly distributed static nodes in a rectangular region of 1200m x 1200m is considered. The number of nodes  $n$  range from 10 to 100. Each of the nodes has a maximum transmission value in the range of up to 250m. A path loss model of  $1/(d^2)$  is assumed for distances below 100m and  $1/(d^4)$  for those above 100m. A carrier frequency of 2.4 GHz 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 number of connections varying from 10, 20, 30 or 40. Next is a discussion of the performance metrics considered and their analysis.

##### A. Energy Efficiency

Energy efficiency, denoted as  $\zeta$ , is defined as the average ratio of the total transmission power saved to the total maximum transmission power per node over the range of nodes in the network. It is given by:

$$\zeta = \sum_{n=1}^N \left\{ \left[ \frac{P_n^{\max} - TPI(P_n^{\max})}{P_n^{\max}} \right] / N \right\}, \quad (3)$$

where  $P_n^{\max}$  is the initial value of maximum power, and  $TPI(P_n^{\max})$  is the value after the execution of the algorithm.  $N$  is the total number of nodes in the network. In the worst case scenario where each node transmits with full power after the execution of the algorithm,  $\zeta = 0$ . The higher the energy efficiency value, the more the amount of power saved in the resultant topology network. Ideally the value of  $\zeta \leq 1$  though in practice  $\zeta$  can not be equal to 1 because the transmission

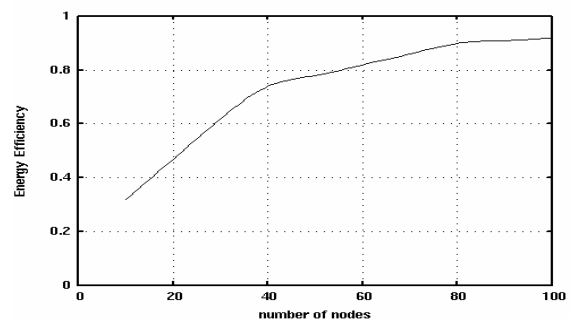


Fig. 4 Energy efficiency in a directed network topology with the proposed topology control algorithm executed

power can never be reduced to a 0 value considering that connectivity has to be maintained. Fig. 4 depicts the energy efficiency graph.

With fewer nodes e.g, 10, 20, the average energy efficiency is below 0.5 implying less than 50% of the energy is saved. This is to ensure connectivity in the sparsely populated networks. However, with an increase in the number of nodes, energy efficiency is way above 50% as shown by the networks of 30 nodes and above. This is because nodes are more close to each other in a dense network hence nodes reduce their transmission powers by a larger margin to ensure connectivity to the most nearest neighbours

### B. Scalability

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  $\psi$  is given by the following expression:

$$\psi = \frac{1}{N} \sum_{u=0}^{N-1} C_u, \quad (4)$$

Equation 4 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 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.

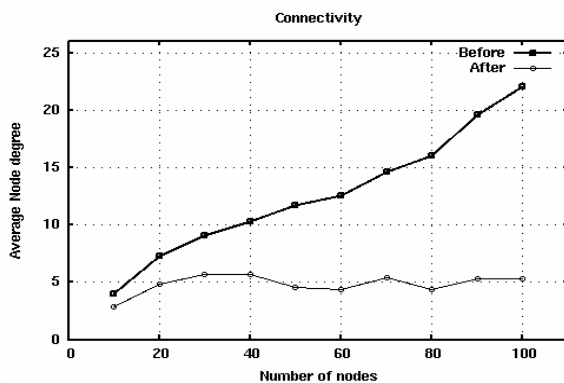


Fig. 5 Performance comparisons on the implementation of the algorithm before and after in terms of Average Node Degree. Nodes range from 10 to 100

Fig. 5 shows a comparison of the average node degree levels. With an increase in the number of nodes, the nodes in the maximum transmission power topology get to have more and more neighbours thus increasing the average node degree. With the distributed topology control algorithm, in spite of an increment in the number of nodes, the average node degree is shown to be bounded by a value below 6.0 for the entire 10 to 100 nodes network, while maintaining node connectivity. With this number of neighbours and considering that the

message exchanges is implicitly dependent on the number of neighbours as decisions are based on the locally collected information, the algorithm is shown to be very scalable even in large WMNs.

### C. Network Lifetime

The network lifetime, as per *definition 6* of section 2, is the time taken while the network is active until when the first node goes off in the network. The lifetime of each of the network instances is 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. Each simulation runs for a period of 150 seconds. Fig. 6 shows the lifetime of a network of 50 nodes with 20 traffic connections at random times.

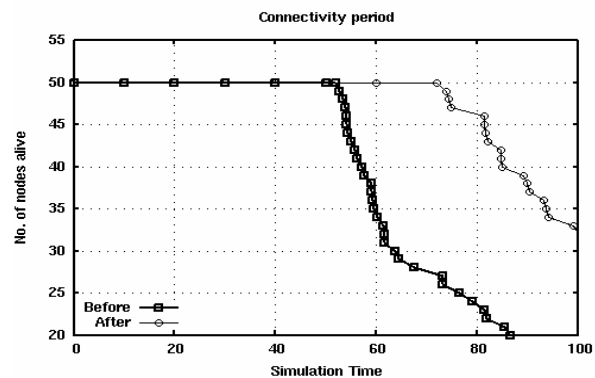


Fig. 6 Performance comparisons of the proposed algorithm before and after in terms of network lifetime for a 50nodes network

A total of 1024 packets are sent with 512 bytes of data. It is noted that, using Maximum power the network gets disconnected after around 52s and at controlled power the lifetime is extended up to 73s. Similarly, in Fig. 7, a network of 100nodes is simulated with 40 traffic connections at random times. At Maximum transmission power, the network lifetime ends after 79s and as expected with controlled power, the distributed algorithm ensures the network remains connected up to the 85<sup>th</sup> second. This is because at reduced per node transmission energy, channel contention is reduced. A node's total amount of processing power is reduced as it only reaches few neighbours and eventually the overall consumed power in the network is reduced.

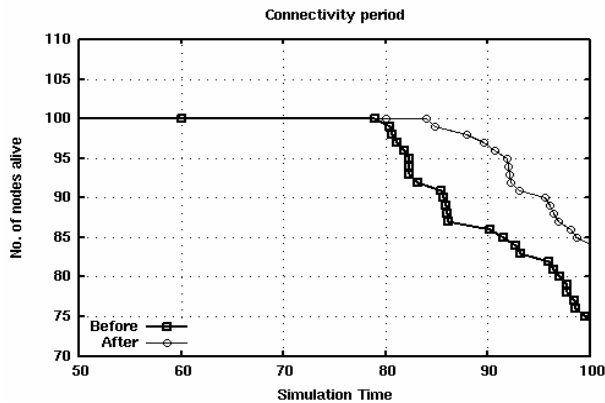


Fig. 7 Performance comparisons of the proposed algorithm before and after in terms of network lifetime for a 100 nodes network

## VI. CONCLUSION

In this paper, the notion of energy management in the context of heterogeneous wireless mesh networks was introduced. The objective was to develop a minimum-energy distributed topology control that ensures a reduction in the amount of energy consumed per node during transmissions and without loss of connectivity. A three phased topology control algorithm is proposed that executes distributively per node. A node uses only the locally available information to determine the nodes that should be its logical neighbours at any given time. The execution of the algorithm is asynchronous from node to the next till convergence in the transmission power per node is achieved thus runs in one pass thereby reducing concerns on control overheads.

Finally, a mathematical analysis for the proposed algorithm was presented to prove its ability to support energy efficiency and scalability in the WMNs. Simulation results also showed a reduction in the nodal transmission ranges leading to reduced number of neighbours and an extension in the networks lifetime. The work was based on the assumption of stationary nodes and it is in our interest to extend the work to develop a locally distributed algorithm in a more mobile environment at the mesh clients' side where node mobility is highly considered.

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