Energy-Efficient Distributed Topology Control for Heterogeneous Wireless Mesh Networks

F. O. Aron, A. Kurien and Y. Hamam.

Abstract—The topology control problem is a well researched topic for energy saving in wireless ad hoc networks. However, little attention has been given to similar problems in the case of wireless mesh networks (WMNs) even though WMNs have very unique characteristics that are different from other wireless multihop networks e.g., MANETs. This is because many WMN surveys make the impractical assumption that since mesh routers are static, energy is not a problem. Consequently, with specific interests to WMN applications in rural areas, where power sources are limited, this work addresses the topology control problem for energy efficiency in a hybrid WMN of heterogeneous wireless devices with varying transmission ranges. A localized distributed algorithm is presented which computes an optimal per-node transmission power such that: (1) a node's average out degree is reduced considerably to cover only the nearest neighbours, (2) network connectivity is maintained and (3) the network lifetime is extended. The performance of the algorithm is evaluated via several mathematical analyses. Additionally, simulations are done in the NS-2 simulation environment to show correctness and effectives of the algorithm.

Index Terms— Topology Control, Wireless, Mesh Networks, Energy Efficiency, Localized Algorithm.

I. INTRODUCTION

In a hybrid Wireless Mesh Network (WMN), each node operates both as a host and as a router [1]. 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 nodes communicate in a multihop fashion. The general architecture of WMNs is composed of three distinct wireless network elements: a *Network Gateway* (a mesh router with gateway/bridge functionalities), *mesh access points* (mesh routers) and *mobile or stationary nodes* (mesh clients) [2][3] as shown in figure 1. Real-world WMNs applications [1] have been witnessed in metropolitan area networking, broadband home networking, community and neighbourhood networks, enterprise networking and building automation.

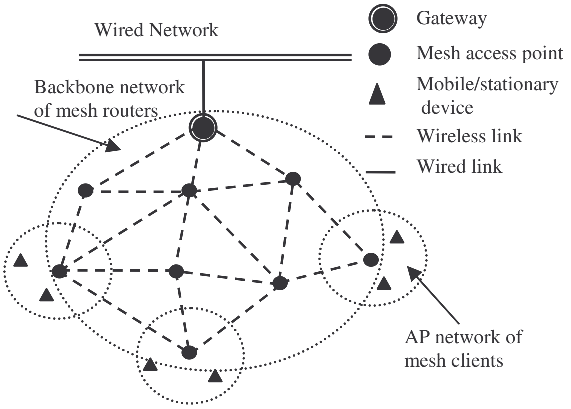

Fig 1: Wireless Mesh Network composed of nine Mesh routers (mesh access points), with one of the routers acting as gateway to the wired network.

Energy efficiency has been a major topic of discussion in the history of Multihop Wireless Networks (MWNs), such as MANETs for quite a long time [4][8]. Usually, the idea is to reduce each node's transmission range in order to address specific goals e.g., network lifetime and/or capacity. However, reducing a node's transmission range can also quite negatively affect network connectivity especially if the network is heterogeneous [6] in which the nodes have varying maximum transmission ranges and the occurrence of uni-directional links is not unusual in the topology.

The previous research on energy efficiency has not paid any attention to power control problems in WMNs. This is mainly because the backbone wireless mesh routers are static and have usually been assumed to have electrical mains power supply and hence are purported not to have power constraints [1]. 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. Mesh nodes (MNs) 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 [3]. In order to address these constraints, this work presents a localized distributed energy efficient topology control algorithm for application of WMNs in rural areas.

Figure 1 demonstrates the WMN under consideration. It is assumed that the hybrid WMN is used to provide internet connectivity to the mobile or stationary devices in the AP networks. Hence, most traffic appears between the mesh access points (MAPs) and the gateway and between the MAPs themselves. Consequently, the simulations are based on the backbone network. The communication between the

F. O. Aron and A. Kurien, are with the French South African Technical Institute in Electronics (F'SATIE), Tshwane University of Technology (TUT), P/Bag x680, Pretoria 0001. E-mail: jakajode@gmail.com, kurienam@tut.ac.za, respectively.

Y. Hamam, was formerly with the ESIEE-Paris, France. He is currently the Scientific Director at FSATIE, Tshwane University of Technology, E-mail: hamama@tut.ac.za.

MAPs and the mobile or stationary devices is ignored. It is further assumed that there is no interference between the AP network and the backbone network. In a practical WMN, this can be achieved by having the MAPs fitted with two radio models. This enables the AP networks to be assigned an independent channel different from that of the backbone mesh network. The WMN is therefore sufficiently described as a set of MNs trying to send packets between themselves and to the gateway.

The remainder of this paper is organized as follows. In section 2, related work is reviewed. In section 3, the problem is formulated by a presentation of the details of the network model. A discussion on the phases of the proposed algorithm is presented in section 4 followed by a mathematical analysis in section 5. Simulation results are presented in section 6 to validate the performance of the algorithm. Finally, the paper is concluded in section 7 and a suggestion for future work given.

II. RELATED WORK

Considerable work exists that addresses the problem of topology control in MWNs. For instance, Rodoplu and Meng [10] described 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 [10], Li and Halpern [11] 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 [10]. The work in [10][11], however, implicitly assume that a long link consumes more power than a shorter link. This assumption is not practical for instance in heterogeneous networks according to [5]. In [7][8][9], 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. In the work of Li *et al* [7], a node builds its local minimum spanning tree (LMST) based only on its one hop neighbourhood information. It only keeps 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. However, the authors of [7] also assume a homogenous network which is not practical according to [13]. The authors in [13] present localized strategies for heterogeneous wireless devices to self-form a globally sparse power efficient network topology. Generally, all of the algorithms shown in [6][7][8][9][13] have not been applied to WMNs. It can not be assumed that the algorithms will automatically function in WMNs as the requirements on power efficiency and mobility are very different between WMNs and other MWNs [1].

III. NETWORK MODEL

Consider a set $V = \{v_1, v_2, ..., v_n\}$ of randomly distributed static heterogeneous MNs, 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 location coordinates $(x(u), y(u))$ on a 2D plane. It is assumed that each node is equipped with an omni-directional antenna with an adjustable transmission power. Due to the heterogeneity of the nodes, they each 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 transmission 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 $P_u^{\max} \ne P_v^{\max}$ for $u \ne v$, then an asymmetric link would occur if $P_u^{\max} \ge P_{uv} > P_v^{\max}$ 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 $\overrightarrow{G} = (V, \overrightarrow{E})$. Here, V is the set of all the nodes in the network and $\overrightarrow{E}$ is the set of all the directed links in the network. An edge/link $\overrightarrow{E_{uv}} \in \overrightarrow{E}$ 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 $\overrightarrow{G}$ can be *fully connected, partially connected* or *disconnected.* A *fully connected* $\overrightarrow{G}$ implies that there is a directed (either multihop or direct) path from any source to destination in the network. *Partially connected* $\overrightarrow{G}$ implies that there exists pairs of nodes for which only one can reach the other either directly or via multihop. *Disconnected* $\overrightarrow{G}$ 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 in [10][14]. In this model, the power of a received signal is found to be $1/d^{\alpha}$, where d represents the propagation distance and α 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 set $A_u^N = \{v \in V \mid d(u,v) \le D_u\}$.

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

$$w(u,v) = t_1 + t_2.d(u,v)^{\alpha}, \qquad (1)$$

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 (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 less power than direct transmission to that point.

Definition 4 (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 $Lt_v = \{t \mid f_v(t) \le E(v)\}$ until $E(v) = 0$, where $f_v(t)$ is the energy consumed by v. The network lifetime $Lt_V = Min_{v \in V}(Lt_v)$ which is the time taken till the first node goes off.

Definition 5 (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, and an averagely low power consumption which results in longer network lifetime in the network. 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 but is not aware of the positions of the others.

IV. THE PROPOSED TOPOLOGY CONTROL ALGORITHM

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 phase, 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 $P_u^{\max}$. Every node $v \in V$ that receives the "*hello*" message replies with an acknowledgement *(ACK)* and also with the node's *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 $P_v^{\max} \ge P_{uv}$, v is able to 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 the knowledge of 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 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 $P_v^{\max} \ge P_{vw}$. 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 $\overrightarrow{G_u} = (V_u, \overrightarrow{E_u})$ of node u is obtained, where $\overrightarrow{E_u}$ defines the collection of all the accessible edges and V_u is the collection of all the local accessible nodes.

The weight of each of the directed edges in $\overrightarrow{E_u}$ 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 $\overrightarrow{G_v}$ after it is triggered by another node.

Phase 2: Constructing the minimum-energy local topology view.

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

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

In this phase, node u applies either Dijkstra's or Bellman-ford shortest path 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, $\overrightarrow{G'}$, denoted by $\overrightarrow{G_{uM}} = (V_{uM}, \overrightarrow{E_{uM}})$ with the following properties.

Property 1: $\forall\, v \in A_u^N$, $\overrightarrow{G_{uM}}$ is a typical shortest path tree view from u to v, where $V_{uM} = V_u$ and $\overrightarrow{E_{uM}} \subseteq \overrightarrow{E_u}$ 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.

Property 2: $\overrightarrow{G_{uM}}$ 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, $\overrightarrow{G_{uM}}$ may vary.

Phase 3: Determining the Transmission power.

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 $\overrightarrow{G_{uM}}$. 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 earlier and successfully propagated its power value. The setting disregards a value that is below its current setting.

For instance, in figure 2, node c is in the accessible neighbourhood of both nodes a and e. 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 the value of edge P_{cb} by node a. Later when 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 $P_{cb} > P_{cd}$. This would in any case violate the accessibility rule already defined in node a's minimum-energy local topology view.

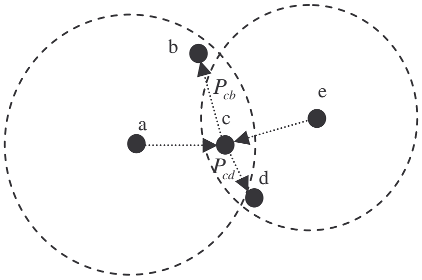

Fig 2: determining a node's transmission range

V. MATHEMATICAL ANALYSIS

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

1. Guaranteeing full connectivity maintenance in the network.

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

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 includes all the nodes in the accessible neighbourhood and even though the edge $\overrightarrow{E_{mn}}$ may not exist after the second phase (because of the availability of a more power efficient path e.g., $\overrightarrow{E_{mk}}$ and $\overrightarrow{E_{kn}}$), 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.

2. 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 WMN extends, the execution of the algorithm is not affected hence is scalable.

In addition, 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. When a node goes off, the network lifetime is considered ended and the setup procedure begins again. Furthermore, the execution is asynchronous from one node to the next till convergence in the transmission power per node is achieved.

VI. 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.

The OLSR is used as the routing protocol in the simulations due to its distributive nature. Constant Bit Rate (CBR) traffic is used as the application traffic source with number of connections varying from 10, 20, 30 or 40. The performance metrics considered and their analysis are as follows.

A. Energy efficiency

Energy efficiency, denoted as ζ, 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:

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

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 $\zeta \le 1$ though in practice ζ can not be equal to 1 because the transmission power can never be reduced to a 0 value considering that connectivity has to be maintained. Figure 3 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.

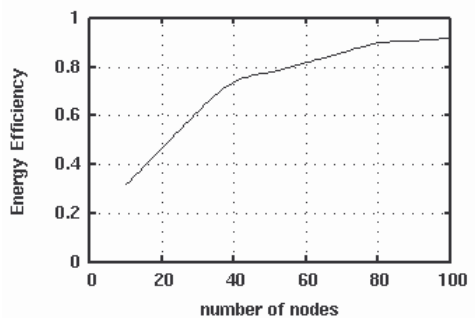

Fig 3: Energy efficiency in a directed network topology with the proposed topology control algorithm executed.

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 ψ is given by the following expression.

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

The above 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. Figure 4 shows a comparison of the average node degree levels.

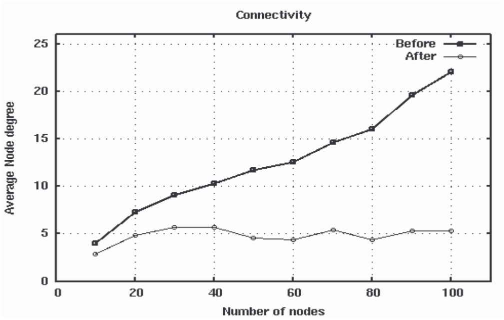

Fig 4: Performance comparisons on the implementation of the algorithm before and after in terms of Average Node Degree. Nodes range from 10 to 100.

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 lifetime of each of the network instances is considered. The network lifetime, as per *definition 4* of section 2, is the time taken while the network is active until when the first node switches off in the network. Figure 5 shows the lifetime of a network of 50 nodes with 20 traffic connections at random times. It is noted that at maximum transmission power, the lifetime ends after about 140s and at controlled transmission power, the lifetime is extended to about 160 seconds.

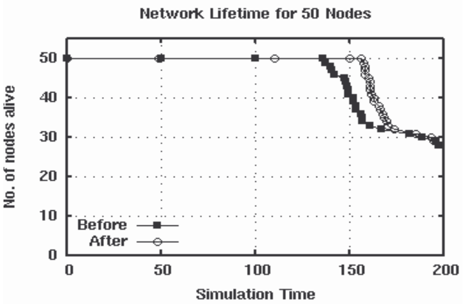

Fig 5: Performance comparisons of the proposed algorithm before and after in terms of network lifetime for a 50nodes network.

Similarly, in figure 6, a network of 100nodes is simulated with 40 traffic connections at random times. At Maximum transmission power, the network lifetime ends after 135s and as expected with controlled power, the distributed algorithm ensures the network remains connected up to about the 154th second. The life extensions results 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.

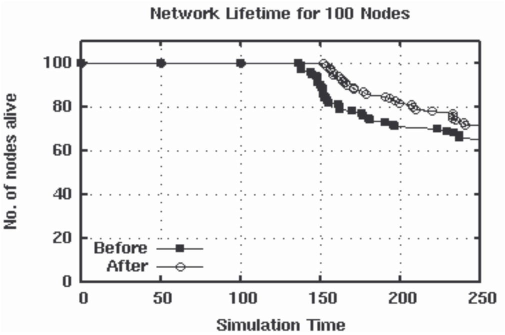

Fig 6: Performance comparisons of the proposed algorithm before and after in terms of network lifetime for a 100 nodes network.

D. Throughput

Finally, the performance is evaluated with respect to the network capacity by tracking the saturated throughput in the random networks. In each simulation, active data transmissions are set to take place for 200 seconds. A total of 1024 packets are sent with 512 bytes of data. Figure 7 shows results for the 50 nodes networks. An increase in the amount of throughput is noted. This increase is due to the fact that, with reduced average node degree, spatial reuse is enhanced leading to simultaneous data transmissions and thus increased throughput.

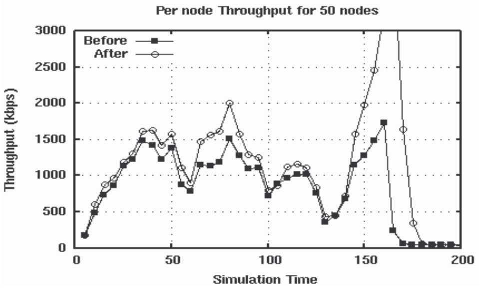

Fig 7: throughput on a per node basis calculated over time for the 50 nodes network.

In figure 8, the average throughput is shown for all the random networks. The proposed algorithm is shown to perform much better than the maximum transmission power scheme.

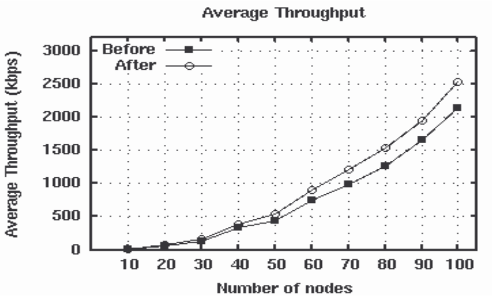

Fig 8: Average throughput for each of the networks.

We note that for networks with very little number of nodes e.g., below 30 nodes, the throughput performance, as shown in figure 8, is not quite significant. This is because in such networks, the nodes are quite sparsely spaced such that a reduction in the number of neighbours due to a reduction in transmit power is not quite significant if connectivity has to be maintained

VII. CONCLUSION

In this paper, the notion of energy management in the context of heterogeneous WMNs was introduced. A three phased topology control algorithm was 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. A mathematical analysis for the proposed algorithm proves 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, an extension in the networks lifetime and increased throughput. The work ignored the communication between the MAPs and the mesh clients and it is in our interest to extend the work to develop a locally distributed algorithm in a more fused environment where both front end and backend network is considered.

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F.O Aron received his BSc degree in Computer Science and Engineering from Maseno University, Kenya in 2002. He is currently pursuing an MTech degree in Telecommunication Engineering at the Tshwane University of Technology (TUT), and an MSc. degree in Electronic Engineering at the French South African Technical Institute in Electronics, (F’SATIE). His research interest is in energy efficiency and topology control in wireless mesh networks