Evaluating Transceiver Power Savings Produced by Connectivity Strategies for Infrastructure Wireless Mesh Networks

Pragasen Mudali, Murimo B. Mutanga and Matthew O. Adigun
Department of Computer Science
University of Zululand
South Africa
Email: pmudali, madigun@pan.uzulu.ac.za

Ntsibane Ntlatlapa
Meraka Institute
Council for Scientific and Industrial Research
South Africa
Email: nntlatlapa@csir.co.za

***Abstract*—Infrastructure Wireless Mesh Networks (I-WMNs) are increasingly used to bridge the digital divide in rural areas around the world. Rural African areas in particular require energy efficient I-WMNs as the nodes comprising the I-WMN backbone network may be battery-powered in the absence of reliable power supplies. A key requirement for the proper functioning of the I-WMN backbone is that network connectivity be maintained. Two main types of connectivity strategies exist in the literature and the more practical Critical Number of Neighbors (CNN) method is focused upon. Three CNN-based connectivity strategies are evaluated via simulation to determine their effect on transceiver power savings when applied to the I-WMN backbone. The evaluation shows that these strategies are capable of cumulative transceiver power savings (in excess of 10%) and that the capacity for transceiver power savings largely corresponds to the position of a node relative to the (imaginary) network center. However, the evaluated connectivity strategies were found not to increase the network lifetime due to the nature of the network topologies created by these strategies. This particular result is however dependent upon the node energy model employed and further experiments with differing energy models are required to confirm this finding.**

***Index Terms*—wireless mesh networks; connectivity; power savings; network lifetime; topology control**

I. Introduction

Wireless Mesh Networks (WMNs) are increasingly used as both an inexpensive alternative to broadband provisioning in urban areas and as a primary method for broadband provisioning in rural areas. The most common form of WMN deployment consists of a two-tier architecture comprising an access and a backbone network. This type of WMN is commonly referred to as an Infrastructure WMN (I-WMN). Client devices connect to the I-WMN backbone which is typically self-organizing and self-configuring. These backbone nodes, comprising Mesh Points (MPs), Mesh Access Points (MAPs) and Mesh Portals (MPPs), collaborate to maintain network connectivity and deliver traffic to the intended destinations. (see Figure 1).

Despite the stationary nature of the I-WMN backbone, maintaining network connectivity is made difficult by the transient nature of wireless links, making them unreliable when deployed [1], [2], [3]. Network connectivity is traditionally assured by ensuring that each device in the I-WMN backbone utilizes its maximum transceiver power. The use of maximum transceiver power is disadvantageous, resulting in high levels of interference, increased contention for the shared transmission medium, a reduction in network capacity and unnecessary transceiver power consumption.

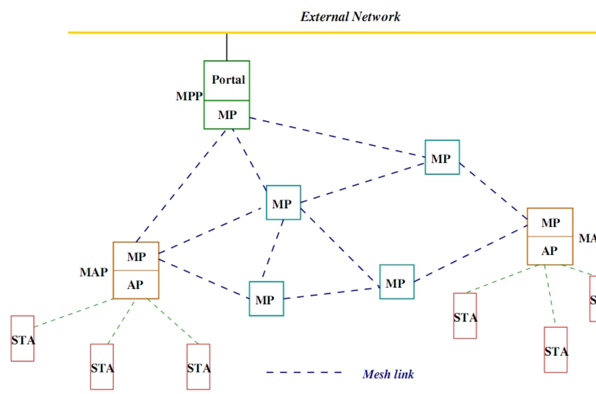

Fig. 1. Infrastructure WMN Architecture [12]

Conventional wisdom holds that WMNs do not suffer from power constraints [4], but in the rural African context where electrical mains power is often unreliable or more often non-existent, such an assumption is easily disproved. The I-WMN backbone is often battery- or solar-powered [5] and thus, in the rural African context, any power savings are welcomed such that the operational lifetime of the network may be maximized. Operating a network at maximum transceiver power output in this scenario is thus an ill-afforded luxury. The rural African context also constrains I-WMN deployments (and their associated QoS mechanisms) to those that are as autonomous as possible due to the lack of technical expertise in these areas.

As a result of the inefficiencies associated with the use of maximum transceiver power outputs, several studies have been undertaken to devise strategies for optimal network

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connectivity (where network connectivity is maintained with minimal transceiver power outputs). These connectivity strategies have demonstrated that they possess the ability to create interference-efficient network topologies [6], [7] as well as to provide route redundancy in some cases [8], [9], [10]. These connectivity strategies have been shown to produce cumulative transceiver power savings but, to the best of our knowledge, the effect of these transceiver power savings on the network lifetime has not been evaluated.

In this paper, various connectivity strategies based on the Critical Number of Neighbors approach are evaluated via simulation to determine the relationship between transceiver power savings and the network lifetime. The selected connectivity strategies have been subjected to an indoor I-WMN testbed evaluation [11] and the study presented in this paper attempts to validate the transceiver power output pattern reported in [11].

The evaluation reported in this paper indicates that the selected connectivity strategies are able to produce cumulative transceiver power savings. The extent of the power savings produced by individual backbone nodes is largely dependent upon the location of the node relative to the (imaginary) center of the backbone network. The evaluation also suggests that cumulative transceiver power savings do not automatically translate into corresponding extensions of network lifetime.

The remainder of this paper is organized as follows. Section 2 provides a review of the connectivity present in the literature. Section 3 details the simulation setup and measurement methodologies employed in this study whilst Section 4 contains the performance evaluation of the selected connectivity strategies. Section 5 concludes the paper.

II. Connectivity Strategies Applicable to Wireless Mesh Networks

Connectivity in the backbone of infrastructure WMNs can be achieved by using one of three possible approaches. The first approach specifies that each node utilizes its maximum transceiver power. The second approach determines the minimum transmission range, also dubbed the Critical Transmitting Range (CTR), required to maintain a connected network and the transceiver power output for all nodes is adjusted to sustain this transmission range. The third approach determines the optimal number of neighbors to be maintained in order to ensure network connectivity.

The CTR approach results in the homogeneous assignment of transceiver powers and may not minimize total transceiver power output. This approach is highly susceptible to the effect of outlying nodes that force a high common power level (or equivalently, transmission range) [13]. Using the CTR to achieve network connectivity may be done in one of three ways, each with its own disadvantages. The first technique requires that a central node determine the appropriate CTR and this value is subsequently broadcast throughout the network. Each node then automatically adjusts its own transceiver power output. The second technique also requires that the CTR is determined at a central location but the network nodes are manually adjusted to maintain this transmission range, as described in [14]. The third technique requires that all nodes broadcast their positions and the CTR is subsequently determined locally at each node, generating high messaging overheads. Thus, the practicality of the use of the CTR approach becomes limited when mobile nodes or dynamic network sizes are taken into account.

An alternative approach is for each backbone node to maintain an optimal number of one-hop neighbors, also referred to as the Critical Number of Neighbors (CNN). This approach may result in heterogeneous transceiver power outputs, potentially maximizing transceiver power savings. In addition, the CNN is less affected by the distribution and position of network nodes so there is no need to assume a uniform or homogeneous backbone node distribution or a GPS-enabled device. Lastly, maintaining connectivity via a CNN potentially eliminates human intervention (especially when a proactive routing protocol is employed) which is of fundamental importance if true autonomous configuration is to be realized in WMNs.

The CNN approach possesses the advantage of being distributed in nature and relying on locally-available information. This approach is also the most likely to lead to autonomous power and topology control mechanisms that are able to produce cumulative transceiver power savings whilst maintaining network connectivity. Thus, the CNN approach forms the basis for the work reported in this paper.

Prior research has produced CNN values that are both independent and dependent of the network size (total number of nodes), which are discussed below.

A. Network-Size-independent CNN

The work in [15] proposed a CNN of 6 which was later adjusted to 8 in [16]. The work in [17] suggested that the transmission range be dynamic and adjusted at the beginning of every transmission and the modelling of the adaptive transmission strategy resulted in each node having an optimal CNN of 3. CNN values of 8 and 6 were also proposed in [18]. It must be noted that these constant CNN values were derived for the optimization of packet forwarding strategies and that network connectivity was not explicitly considered.

Works that have taken network connectivity into account have also produced size-independent CNN values. In particular the work in [19] shows that the CNN converges to 9 as the network size approaches ∞. This result is shown to hold when the connectivity requirement is relaxed such that at least 95% of the nodes find themselves in the giant component of the original network.

B. Network-Size-dependent CNN

Works taking network connectivity into account have also provided ranges within which the CNN can be found. The first such work was described in [20] which proposed that the CNN could be found within the range expressed in 1,

$$2.186 < CNN < 10.588 \tag{1}$$

Subsequent research has seen a continuous tightening of the upper- and lower-bounds, firstly in [21] and subsequently in [22]. The work done in [22] found that the network is asymptotically disconnected with probability 1 as n increases if each node is connected to less than $0.074\log(n)$ nearest neighbors and that the network is asymptotically connected with probability 1 as n increases if each node is connected to more than $5.1774\log(n)$ nearest neighbors, where n refers to the number of network nodes. This result was shown in [7] to be valid for square deployment regions containing both sparse and dense ad hoc networks. A further tightening of the upper-bound derived in [22] was obtained in [10] resulting in connectivity being assured with high probability if a maximum of $2.718\log(n)$ neighbors are maintained (shown in 2),

$$CNN < \alpha 2.718\log(n) \tag{2}$$

where any real number $\alpha > 1$ and n is the number of nodes in the backbone network and provided that $n < 10000$. Experiments conducted in [22] suggest that the critical value of α may be close to 1. The connectivity bounds were further improved in [23] for both directed and undirected graphs, but it has been shown in [24] that the only way to guarantee full network connectivity in an ad hoc network is to ensure worst-case connectivity where each node is connected to every other network node. These size-dependent CNN-based connectivity strategies, except for the worst-case strategy, have been shown to create connected networks with increasing probability as the network size increases to infinity but to the best of our knowledge, their effectiveness in extending the network lifetime has not been previously evaluated.

III. Simulation Setup and Measurement Methodology

Details of the simulation tools and measurement methodology employed are presented in this section.

A. Simulation Setup

The Atarraya simulation tool [25] was used to generate the network topologies used in the simulation. This tool was chosen for its emphasis on power control simulations and was modified to support I-WMNs. Various network sizes, randing from 20 to 120 nodes were simulated with uniform node distribution. The simulated network areas were scaled to ensure a constant node density. The Atarraya simulator was also modified to record node positions and the resultant transceiver power levels assigned by the selected connectivity strategies.

In order to determine the resultant network lifetimes when employing the various connectivity strategies, the network topologies and the resultant transceiver power levels assigned to individual nodes by the connectivity strategies, were imported into the ns-2 simulation tool [26]. ns-2 (version 2.34) was found to possess better support for node energy models[1] and Application Layer traffic thus allowing for the analysis of the QoS achieved by the various connectivity strategies. The QoS data is, however, not reported in this paper. Additional simulation details can be found in Table I.

[1]The default energy model employed in ns-2 is used in this study.

TABLE I
Simulation Details

Simulation Time	100 seconds
Network Size	20–120 nodes
Network Area	300m x 300m – 1000m x 1000m
Routing Protocol	OLSR
Traffic type	CBR with 90% of nodes as traffic sources
Traffic rate	4 pkts per second with a max. of 1000 pkts
Max. transceiver range	100m
Initial energy	1.0 Joule
Transmit Energy	0.6W
Receive Energy	0.3W

B. Measurement Methodology

Justifications for the reported experiments are provided in addition to highlighting how the various evaluation metrics were recorded.

1) Network Connectivity: This experiment aims to establish the effectiveness of the connectivity strategies in maintaining a connected backbone network. Network connectivity was determined by the number of entries in the routing tables of each backbone node. The OLSR routing protocol creates and maintains an entry for each possible destination node and the presence of an entry signifies that a route to the destination exists. Network connectivity is assured when all nodes can potentially communicate with all other network nodes, ensuring $n^2 - n$ possible routes where n refers to the number of backbone nodes.

2) Transceiver Power Savings: The aim of this experiment is to determine the magnitude of transceiver power savings produced. Cumulative transceiver power savings are determined by the difference between the summation of the maximum power level of each node and the summation of the assigned power levels of all backbone nodes.

3) Transceiver Power Assignment: This experiment aims to establish whether a relationship exists between the assigned power level and a node's position in the network. The position of the imaginary network center is determined. Subsequently, the distance between every backbone node and the network center is calculated and plotted against the assigned transceiver power level.

4) Network Lifetime: The aim of this experiment is to determine whether the transceiver power savings that have been achieved will result in an extension to the network lifetime. Network lifetime is defined as the elapsed duration until the first node exhausts its energy supply. The number of alive nodes is determined and plotted against the simulated time.

IV. Performance Evaluation

The connectivity strategies defined by (Xue, Kumar) [22], (Wan, Yi) [10] and Blough [19] have been chosen for evaluation. The Xue, Kumar and Wan, Yi strategies exemplify

TABLE II
NETWORK CONNECTIVITY

Network Size	Src-Dest Pairs (Max. Power)	Src-Dest Pairs (Xue, Kumar)	Src-Dest Pairs (Wan, Yi)	Src-Dest Pairs (Blough)
20	380	380	380	380
40	1560	1560	1543	1560
60	3540	3539	3501	3527
80	6320	6317	6273	6303
100	9900	9898	9847	9882
120	14280	14277	14196	14256

adaptive CNNs whilst the Blough strategy is representative of a fixed CNN strategy.

A. Network Connectivity

The network is fully connected at max. transceiver power, where the number of source-destination (src-dest) pairs is $n^2 - n$. Table II shows that the Xue, Kumar strategy was best able to maintain network connectivity as there was little observed difference in the number of available src-dest pairs for all network sizes. The Xue, Kumar strategy benefits from maintaining an adaptive CNN that is based on the size of the backbone network.

The Wan, Yi strategy also maintains an adaptive CNN but the CNN is approximately half that maintained by the Xue, Kumar strategy. Thus, the Wan, Yi strategy does not provide the same degree of connectivity.

The Blough strategy maintains a fixed CNN for a large range of network sizes. This strategy is able to maintain full network connectivity for the smaller network sizes, but does not perform as well as the Xue, Kumar strategy due to a lower CNN being maintained at the higher network sizes.

B. Transceiver Power Savings

As shown in Figure 2, all 3 connectivity strategies being evaluated were found to produce cumulative transceiver power savings. The extent of the transceiver power savings produced can be found in Table III. Table III shows that the power savings produced by the adaptive CNN strategies (Wan, Yi and Xue, Kumar) remained fairly constant as the network size increased whilst the fixed-CNN Blough strategy produced increases in power savings. The Wan, Yi strategy produced the greatest magnitude of transceiver power savings due to the lower CNN being maintained. The Xue, Kumar strategy outperformed the Blough strategy at the smaller network sizes but the reverse began to occur at the largest network size. This particular phenomenon is explained by the CNNs required to be maintained by the Xue, Kumar and Blough strategies respectively. At a network size in the range $[20 : 100]$ the CNN maintained by the Xue, Kumar strategy is less than that required by the Blough strategy. At greater network sizes, due to the fixed nature of the Blough strategy, the adaptive Xue, Kumar strategy maintains a greater CNN thus increasing the transmission range assigned to the nodes, thereby limiting the magnitude of transceiver power savings produced.

TABLE III
PERCENTAGE POWER SAVINGS ACHIEVED

Network Size	Xue, Kumar	Wan, Yi	Blough
20	33.5	48.4	11.7
40	34.3	46.6	17.3
60	35.4	45.7	21.2
80	33.3	46.5	26.1
100	34.3	44.4	33.5
120	34.1	47.9	38.7

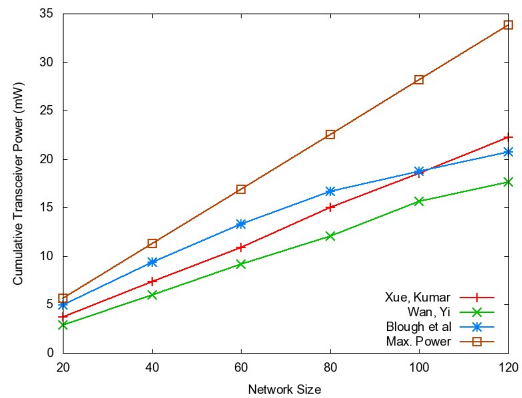


Fig. 2. Cumulative Transceiver Power Output

C. Transceiver Power Assignment

A closer look at the cumulative transceiver power savings produced by all three connectivity strategies reveals an interesting trend. Figure 3 depicts the relationship between the transceiver power levels assigned to individual nodes and the distance of these nodes from the (imaginary) network center.

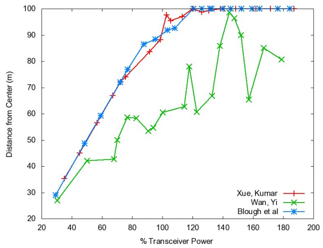
The evaluation has found that the nodes closes to the network center produced significantly greater transceiver power savings than nodes at the network edge. This phenomenon was observed for all the connectivity strategies and across all the network sizes under evaluation. Edge nodes suffer from situations where fewer candidate neighbors exist and these neighbors are not evenly distributed within the the node's transmission range but are rather loosely concentrated in a particular direction.

The correlation between the node position relative to the network center and the resultant transceiver power output is not exclusive to uniformly distributed nodes. This phenomenon has been previously observed in a clustered environment [27] as well as in a WMN testbed with arbitrary node distribution [11].

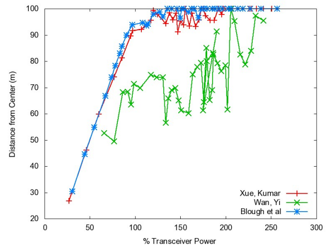
D. Network Lifetime

Figure 4 depicts the impact of the selected connectivity strategies on the network lifetime of a 120-node network and it can be seen that the application of the connectivity strategies does not result in extensions to the network lifetime. All three connectivity strategies result in the first node failing before the corresponding first node failure in the Max. Power scenario.

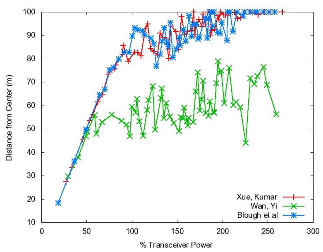
The reduction in network lifetime attributed to the three connectivity strategies can be explained by the effect that



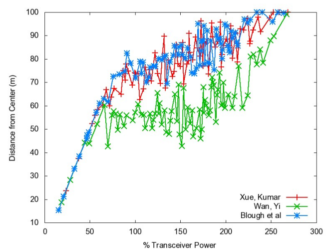
(a) 20 node network



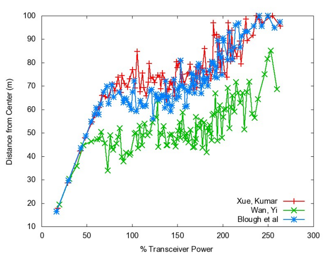
(b) 40 node network



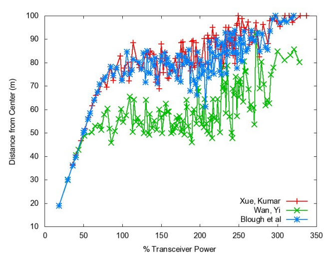
(c) 60 node network



(d) 80 node network



(e) 100 node network



(f) 120 node network

Fig. 3. Transceiver Power Output vs. Distance from Network Center

the reduction in node transceiver powers has on the resultant path lengths between source and destination nodes. Lower transceiver powers require data to traverse more hops to reach the intended destination. Energy is spent, at each intermediate node (hop), during packet reception and re-transmission thus negating the effect of transceiver power savings. In particular, nodes that still maintain maximum transceiver power outputs undertake greater packet forwarding responsibilities, thus depleting their energy sources at faster rates than before.

The three connectivity strategies do however lengthen the duration until the last node depletes its energy supply. This situation occurs since nodes with lower transceiver powers are overlooked as intermediaries for packet forwarding if nodes with higher transceiver powers are available and the nodes with lower transceiver powers conserve their energy sources for longer durations thus realizing lifetime extension gains. The Wan, Yi strategy produces the greatest number of alive nodes at the end of the simulated time due to the smallest CNN being maintained whilst the Xue, Kumar strategy produced the least number of alive nodes due to its maintenance of the highest CNN.

It must however be noted that the reduction in network lifetime caused by the evaluated connectivity strategies is not yet determined to be a universal consequence of the application

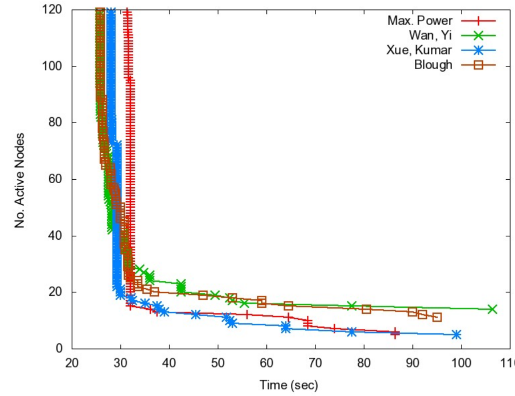


Fig. 4. Network Lifetime Achieved by the Connectivity Strategies

of these strategies as several factors prove influential. Network lifetime is highly dependent upon, amongst others:

- the resultant transceiver power assignment which is dictated by the network connectivity strategy being employed
- the energy consumption model being used
- the routing protocol and routing metric being utilized
- the prevalent traffic conditions

V. Conclusion

I-WMN deployments are being employed to bridge the digital divide in rural areas around the world. The rural African context requires energy-efficient I-WMNs since it is highly likely that the nodes comprising these networks will be battery-powered.

The key requirement for the I-WMN backbone is the maintenance of network connectivity and several connectivity strategies exist in the literature. In this paper, three CNN-based connectivity strategies have been evaluated via simulation to determine their ability to produce transceiver power savings.

The evaluation has indicated that cumulative transceiver power savings in excess of 10% can be attained and that the ability of a node to produce these transceiver power savings is dependent upon the position of the node relative to the (imaginary) center of the network. Despite the achievement of cumulative transceiver power savings, corresponding extensions of network lifetime were not achieved. On the contrary, decreases in network lifetime were recorded due to the overburdening of nodes that maintained the use of the maximum transceiver power and the longer path lengths that are a side-effect of transceiver power reductions.

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