Evaluating the Effect of a Topology Control Scheme on Application Layer Traffic Scenarios in Infrastructure Wireless Mesh Networks

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***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. These networks are deployed to support a variety of applications, the most common being a combination of Web browsing, local telephony and video-conferencing. In this paper the effect of the PlainTC Topology Control scheme on the performance of Web traffic and local intra-mesh traffic is investigated via simulations. The evaluation has indicated that the PlainTC scheme is able to maintain a high level of network connectivity whilst producing cumulative transceiver power savings. PlainTC was also shown to negatively affect the performance of the two traffic scenarios being considered. The results indicate that PlainTC may be more suited to smaller network sizes. This finding is largely a result of the higher data rates enabled by reduced transceiver power levels, where a higher data rate enables greater throughput but has the unfortunate side-effect of saturating node buffers leading to higher packet losses in some scenarios.**

***Keywords*-Topology Control; PlainTC, QoS; simulation; wireless mesh**

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are often used as a cost-effective means to provide broadband connectivity in both areas without prior network infrastructure as well as areas where network infrastructure already exists. The most common type of WMN deployment is the Infrastructure WMN (I-WMN) [1] that comprises a two-tiered architecture (see Figure 1). A stationary backbone network comprising a Mesh Portal (MPP), Mesh Points (MPs) and Mesh Access Points (MAPs) dynamically form the upper tier via self organisation and self-configuration whilst the lower tier is comprised of client stations (devices) that may also be mobile.

Typical I-WMN usage scenarios include, amongst others, community and neighbourhood networking, enterprise networking, metropolitan area networks, transportation systems, building automation, health and medical systems and security surveillance systems [1]. The most common applications supported by rural WMNs are Web browsing, local telephony and local video-conferencing. These particular applications can be differentiated by the relative locations of the two communicating nodes. Communication occurring exclusively within the WMN is referred to as intra-mesh communications whilst communication either to or from a node outside of the WMN can be referred to as Portal-based communications with the most common form being Web browsing.

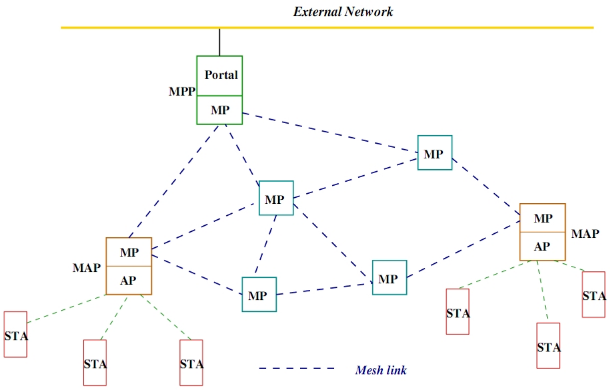


Figure 1. Infrastructure WMN architecture [3]

Despite the existence of either intra-mesh or Web traffic, the above-mentioned usage scenarios require some form of Quality-of-Service (QoS) to ensure fairness and the efficient usage of network resources. The I-WMNs may also be deployed in areas with unreliable (if any) power supplies such as in rural African settings where backbone nodes may be battery-powered [2]. Thus, QoS mechanisms that contribute to the overall energy-efficiency of the network are advantageous since even I-WMNs deployed in urban areas can benefit from increased energy-efficiency. Another major requirement for I-WMN QoS mechanisms are that they be as autonomous as possible, in keeping with the self-organising and self-configuring nature of the backbone network.

The wireless transceiver power output may be seen as a potential target for energy-efficiency measures since the transceiver is reported to constitute between 15% to 35% of the total energy consumed by a wireless device [4]. I-WMN deployments, however, often rely on the usage of maximum transceiver powers by the backbone nodes, thus resulting in several inefficiencies such as high levels of interference, increased contention for the shared transmission medium, a reduction in network capacity and unnecessary transceiver power consumption.

As a result of the inefficiencies associated with maximum power consumption in ad hoc networks, several Topology Control (TC) schemes have been developed that can be applied to the WMN backbone in order to maintain network connectivity whilst reducing interference, enhancing the network capacity and reducing transceiver power consumption. Within the context of TC, "power consumption" usually refers to the power consumed by a node's wireless transceiver. TC aims to enhance the QoS capabilities of the WMN backbone by optimising the transceiver powers of all backbone devices whilst maintaining network connectivity.

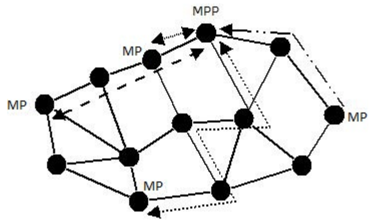
Several simulation studies [2], [5], [6], [7] have demonstrated the efficacy of TC in ad hoc networks with regards to maintaining network connectivity and reducing transceiver power output. Other simulation studies have demonstrated the positive effect of TC on Application Layer traffic performance [9], [10], [11], [14], [7], [8], [12], [13], [2], [15].

To the best of our knowledge, the overwhelming proportion of studies that investigate TC's effect on Application Layer traffic performance consider only intra-mesh traffic scenarios and thus do not consider the impact of TC on both intra-mesh and Web traffic scenarios[1], which have very distinctive differences.

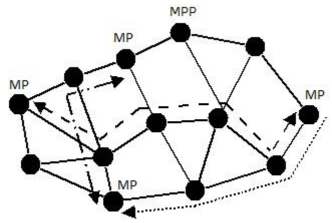
Intra-mesh communications may be either one-way or two-way, depending on the usage scenario. In the event of two-way intra-mesh communications, traffic flow in both directions is less heavily skewed in one direction. Web traffic, however, is highly skewed in the downlink direction (from the MPP to the MAP through which the requesting client station is connected to the I-WMN) such as in the case of browsing the World Wide Web. A graphical depiction of both inter- and intra-mesh communication scenarios can be found in Figures 2(a) and 2(b).

In this paper, the effect of a simple, autonomous TC scheme on the performance of both intra-mesh and Web traffic is evaluated via simulation. The evaluation reported in this paper indicates that the employed TC scheme degrades application performance and that the scheme may be more suited to applications that favour higher PDR for smaller network sizes whilst being more suited to applications that favour higher throughput rates for greater network sizes.

The remainder of this paper is organised as follows. Section 2 provides a review of existing evaluations of the effect of TC on Application Layer performance. Section 3 discusses the PlainTC TC scheme being employed for the evaluation. Section 4 details the simulation setup and measurement methodologies employed in this study whilst Section 5 contains the performance evaluation where the effect of the PlainTC TC scheme on both intra-mesh and Web traffic is discussed. Section 6 concludes the paper.



(a) Web traffic scenario



(b) Intra-mesh traffic scenario

Figure 2. I-WMN traffic scenarios

II. LITERATURE REVIEW

Several studies have shown that TC schemes have a mostly positive effect on the performance of Application Layer traffic. However, this positive effect has been mostly demonstrated in networks with intra-mesh traffic patterns. The effect of TC on the performance of Web traffic is, to the best of our knowledge, undetermined.

Studies depicting the positive impact of TC on Application Layer performance can be found in [9], [10], [11], [14], [7], [8], [12], [13], [2], [15]. The CONNECT and BICONN schemes described in [9] were found to produce up to a 227% improvement in throughput compared to the usage of maximum transceiver powers at all nodes.

Both single-path and multi-path intra-mesh traffic scenarios are considered in [11]. Traffic demands were assumed to be known in advance and transceiver powers were assigned such that node loads were maximised, thus aiding load-balancing and improving network capacity.

Multi-channel WMNs where considered in [14]. An interference-aware TC scheme was coupled with a bandwidth-aware routing protocol and the resultant combination produced a 57% improvement in the number of Application Layer data streams in intra-mesh traffic scenarios.

The scheme in [7] attempts to maintain at least one neighbour in each sector of the node's transmission range. This scheme (CBTC) was found to improve network throughput by 144% whilst an optimised version of the scheme

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[1] The *cbrgen* tool packaged within the commonly used ns2 simulator [16] only allows for the creation of intra-mesh traffic scenarios.

improved throughput by 294%. In addition, CBTC reduced latency by approximately 53% whilst the optimised version achieved an approximately 37% reduction when compared to maximum transceiver power usage.

The LMST scheme [8] improved the total number of Application Layer data packets delivered whilst also improving the energy efficiency of the data transfer. LMST was also found to reduce packet retransmissions.

The TAP scheme [12] was found to produce a 4% improvement in packet delivery compared to the maximum transceiver usage scenario whilst much more substantial improvements in throughput were recorded in [13].

The ABD and PRD schemes [13] increased throughput from approximately 100Kbps (at maximum transceiver power) to approximately 425Kbps when nodes were stationary.

The LM-SPT scheme described in [2] was able to match the throughput achieved when utilising maximum transceiver power output whilst LM-SPT's variants improved throughput even further in intra-mesh traffic scenarios.

The DT+SD scheme in [15] was evaluated using intra-mesh traffic and improved throughput by approximately 152%, lowered packet loss by approximately 36% and lowered delay by approximately 58% when compared to maximum transceiver power usage.

The schemes (Scheme-1 and Scheme-2) reported in [10] were evaluated in ad hoc networks possessing directional antennas. For short-range traffic (one-hop), both schemes were reported to reduce end-to-end delay by more than 50%. Improvements in packet loss ratio and throughput were also described. The work in [10], however, also depicted a scenario where Application Layer traffic performance was reduced. For long-range traffic (10 hops), both Scheme-1 and Scheme-2 were found to increase end-to-end delay and degrade throughput when compared to the maximum transceiver power usage.

III. PlainTC: A simple Topology Control Scheme

PlainTC is a simple TC scheme designed to be run on low-cost, resource-constrained I-WMN backbone nodes. Thus, PlainTC is not a distance- or location-based TC scheme but rather it employs neighbourhood information to maintain network connectivity. PlainTC employs the probabilistic Critical Number of Neighbors (CNN) method where the maintenance of the prescribed number of one-hop neighbours will achieve asymptotic connectivity as the network size increases.

The use of the CNN method provides several benefits to TC schemes designed for the I-WMN backbone, namely:

- it does not require the use of a Global Positioning System (GPS) chip or additional hardware
- it does not rely on accurate Physical Layer measurements such as signal strength and angle of arrival
- the CNN can be computed locally, allowing for a distributed TC scheme
- the maintenance of a CNN may result in cumulative transceiver power savings in the backbone
- the CNN results in bounded average node degree to lower channel contention

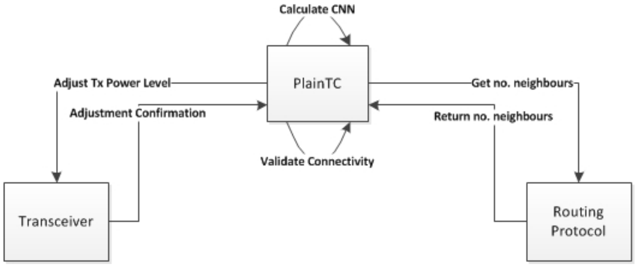

Figure 3. Interaction of PlainTC with other system elements

Several works proposing CNN strategies exist in the literature and PlainTC employs the strategy defined in [17]. This choice was informed by the increased fault-tolerance provided as well as the results of an evaluation conducted in [18].

PlainTC is designed to work in conjunction with either a proactive or hybrid routing protocol which is used to determine the network size. The network size is used to determine, according to the strategy defined in [17], the required CNN to be maintained. PlainTC subsequently iteratively, adjusts the node's transceiver power such that the required number of neighbours is maintained. This process can be seen in Figure 3.

PlainTC exhibits low computational complexity and produces minimal communication overhead which has lead to the successful prototyping of the scheme [19] on a low-cost, resource-constrained device that is also a popular I-WMN backbone device. This scheme has also been shown to be able to maintain network connectivity as well as produce cumulative transceiver power savings in both clustered and uniformly-distributed scenarios [20] as well as in a test-bed environment [19]

IV. Simulation Details and Measurement Methodology

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

A. Simulation Details

The ns-2 [16] software tool (version 2.34) is used to simulate I-WMNs that display the uniform node distribution pattern in networks with size varying from 20-120 nodes. The nodes were configured to use the Adaptive Auto rate Fallback mechanism that adjusts the data rate of a node as the transceiver power level changes. Other salient simulation details can be found in Table I.

Table I
SIMULATION DETAILS

Simulation Time	100 seconds
Network Size	20–120 nodes
Routing Protocol	OLSR
Traffic type	CBR with 80% of nodes as traffic sources (for both intra-mesh and Web traffic scenarios)
Traffic rate	4 pkts per second with a max. of 1000 pkts
Max. transceiver range	100m
Initial energy	0.01 Joule
Transmit Energy	0.6W
Receive Energy	0.3W

B. Measurement Methodology

The details of how the various performance metrics were recorded can be found here.

1) Network Connectivity: 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.

C. Packet Delivery Ratio (PDR)

PDR refers to the percentage of successfully delivered data packets from the total number of sent data packets. The average PDR of all traffic flows is reported.

D. Throughput

Throughput was measured as the rate of data received at the destination per second. The average throughput of all traffic flows is reported.

V. PERFORMANCE EVALUATION

This section presents the results of the evaluations performed.

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 PlainTC compares favourably with the Max. Power scenario even as the network size increased. PlainTC's ability to tolerate larger network sizes stems from maintaining an adaptive CNN that is based on the size of the backbone network.

Table II
NETWORK CONNECTIVITY

Network Size	Src-Dest Pairs (Max. Power)	Src-Dest Pairs (PlainTC)
20	380	38
40	1560	1560
60	3540	3539
80	6320	6317
100	9900	9898
120	14280	14277

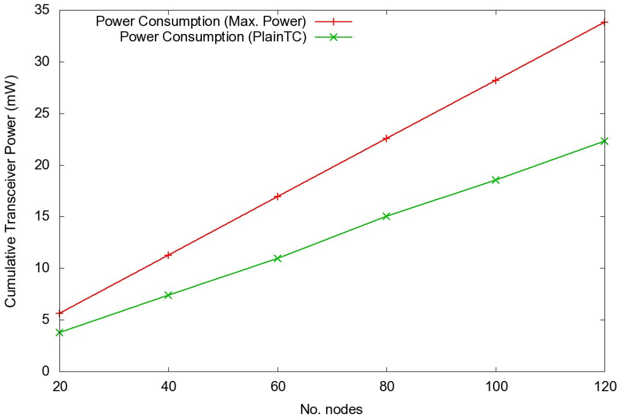

Figure 4. Cumulative Transceiver Power Output

B. Transceiver Power Consumption

The transceiver power consumed by PlainTC was compared against the Max. Power scenario. Figure 4 indicates that PlainTC is able to produce cumulative transceiver power savings and Table III shows that the extent of the achieved power savings remains largely unaffected by changes in the network size.

PlainTC's employment of the CNN connectivity strategy would suggest that the scheme should be producing greater power savings as the network size increases, but a closer inspection of the actual transceiver power assignment achieved (that was previously reported in [20]) showed that the power savings were mostly contributed to by a minority of centrally-situated nodes.

C. Packet Delivery Ratio

The influence of the PlainTC scheme on the PDR of both intra-mesh and Web traffic is discussed here. Figure 5 indicates that intra-mesh traffic achieves a higher PDR than Web traffic. This situation arises due to the bottleneck encountered the closer Web traffic gets to the solitary Internet Gateway. The most common manifestation of the bottleneck are buffer overflows at nodes in close proximity to the Internet Gateway thus resulting in the lower PDR for the Web traffic scenario. Intra-mesh traffic does not suffer from

Table III
PERCENTAGE POWER SAVINGS ACHIEVED

Network Size	PlainTC
20	33.5
40	34.3
60	35.4
80	33.3
100	34.3
120	34.1

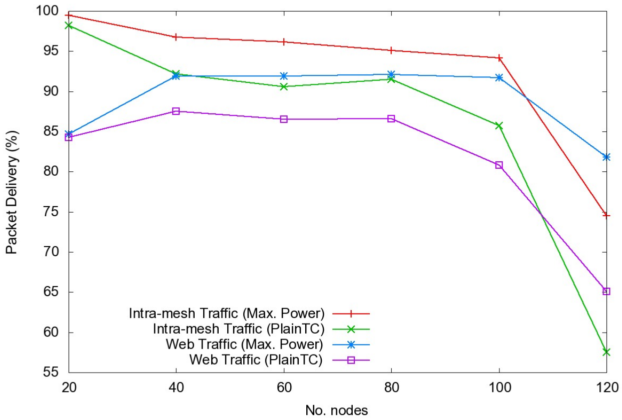

Figure 5. PDR achieved by intra-mesh and Web traffic

the existence of unavoidable bottlenecks due to the route redundancy that can be exploited.

PlainTC was found to degrade PDR in both the intra-mesh and Web traffic scenarios. This is most likely caused by the increased data rates achieved by nodes that employ lower transceiver power levels which exacerbates the buffer overflows that are already experienced. At the largest network size, PlainTC begins to achieve a higher PDR than Max. Power but further testing with even greater network sizes is required to validate this observation.

D. Throughput

The effect of PlainTC on the throughput achieved in both the intra-mesh and Web traffic scenarios is discussed here. Figure 6 shows that Web traffic achieved higher throughput rates than intra-mesh traffic despite having achieved a lower PDR than intra-mesh traffic. This is caused by the nature of the traffic flows where the intra-mesh scenario is more likely to experience delays in forwarding traffic due to the contention of the two opposing traffic flows that comprise a successful intra-mesh communication.

PlainTC was found to decrease the throughput achieved in both traffic scenarios. This degradation is not as severe as expected due to the higher data rates achieved whenever nodes were able to reduce their transceiver power levels.

VI. 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.

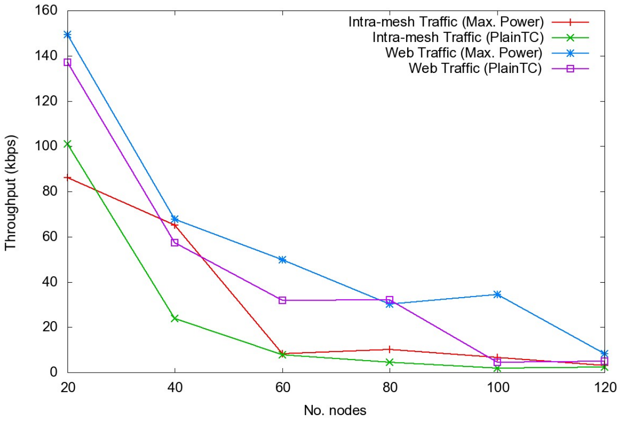

Figure 6. Throughput achieved by intra-mesh and Web traffic

These networks are deployed to support a variety of applications, the most common being a combination of Web browsing, local telephony and video-conferencing. In this paper the effect of a Topology Control scheme on the performance of Web traffic and local intra-mesh traffic is investigated via simulations.

The evaluation has indicated that the PlainTC scheme is able to maintain a high level of network connectivity whilst producing cumulative transceiver power savings. PlainTC was also shown to negatively affect the performance of the two traffic scenarios being considered. The results indicate that PlainTC may be more suited to smaller network sizes. This finding is largely a result of the higher data rates enabled by reduced transceiver power levels, where a higher data rate enables greater throughput but has the unfortunate side-effect of saturating node buffers leading to higher packet losses in some scenarios.

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REFERENCES

[1] I. F. Akyildiz and X. Wang, *Wireless Mesh Networks*. Chicester: Wiley, 2009.

[2] F. O. Aron, T. O. Olwal, A. Kurien, and M. O. Odhiambo, “Energy Efficient Topology Control Algorithm for Wireless Mesh Networks,” in *Proc. International Wireless Communications and Mobile Computing Conference*, Aug. 2008, pp. 135–140.

[3] X. Wang and A. O. Lim, “IEEE 802.11s Wireless Mesh Networks: Frameworks and Challenges,” *Ad Hoc Networks*, vol. 6, no. 6, pp. 970–984, 2008.

[4] P. Santi, *Topology Control in Wireless Ad Hoc and Sensor Networks*, Chichester: Wiley, 2005.

[5] N. Li and J. C. Hou, “Localized fault-tolerant Topology Control in wireless ad hoc networks,” *IEEE Transactions on Parallel and Distributed Systems*, vol. 17, no. 4, pp. 307–320, 2006.

[6] K. Wu and W. Liao, “Interference-efficient topology control in wireless ad hoc networks,” in *Proc. IEEE Consumer Communications and Networking Conference*, Jan. 2006, pp. 411–415.

[7] L. Li, J. Y. Halpern, P. Bahl, Y. M. Wang, and R. Wattenhofer, “A Cone-based distributed Topology Control Algorithm for wireless multi-hop networks,” *IEEE Transactions on Networking*, vol. 13, no. 1, pp. 147–159, 2005.

[8] N. Li, J. C. Hou, and L. Sha, “Design and Analysis of an MST-based Topology Control Algorithm,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 3, pp. 1195–1206, 2005.

[9] R. Ramanathan and R. Rosales-Hain, “Topology control of multihop wireless networks using transmit power adjustment,” in *Proc. IEEE INFOCOM*, Mar. 2000, pp. 404-413.

[10] Z. Huang, C. Shen, C. Srisathapornphat, and C. Jaikaeo, “Topology Control for Ad hoc Networks with Directional Antennas,” in *Proc. International Conference on Computer Communications and Networks*, Oct. 2002, pp. 16–21.

[11] X. Jia, D. Li, and D. Du, “QoS Topology Control in Ad Hoc Wireless Networks,” in *Proc. Joint Conference of the IEEE Computer and Communication Societies*, Mar. 2004, pp. 1264–1272.

[12] P. Hu, P. Hong, J. Li, and Z. Qin, “TAP: Traffic-aware topology control in on-demand ad hoc networks,” *Computer Communications*, vol. 29, no. 18, pp. 3877–3855, 2006.

[13] P. Siripongwutikorn and B. Thipakorn, “Mobility-aware topology control in mobile ad hoc networks,” *Computer Communications*, vol. 31, no. 14, pp. 3521–3532, 2008.

[14] J. Tang, G. Xue, and W. Zhang, “Interference-Aware Topology Control and QoS Routing in Multi-Channel Wireless Mesh Networks,” in *Proc. ACM MobiHoc*, May 2005, pp. 68–77.

[15] H. Jang and R. Fang, “Interference-aware Topology Control in Wireless Mesh Network,” in *Proc. International Conference on Mobile Technology, Applications & Systems*, Sep. 2008, pp. 1–7.

[16] The Network Simulator -ns-2. [Online]. Available: http://www.isi.edu/nsnam/ns/

[17] F. Xue and P. Kumar, “The Number of Neighbors Needed for Connectivity of Wireless Networks,” *Wireless Networks*, vol. 10, no. 2, pp. 169–181, 2004.

[18] P. Mudali, T. C. Nyandeni, N. Ntlatlapa, and M. O. Adigun, “A Test-Bed Evaluation of Connectivity Strategies for Infrastructure Wireless Mesh Networks,” in *Proc. Southern African Telecommunications and Network Applications Conference*, Sep. 2010. [Online]. Available: http://www.satnac.org.za/proceedings/2010/engineering.htm

[19] P. Mudali, T. C. Nyandeni, N. Ntlatlapa, and M. O. Adigun, “Design and Implementation of a Topology Control Scheme for Wireless Mesh Networks,” in *Proc. IEEE Africon*, Sep. 2009, pp. 1–6.

[20] P. Mudali, M. B. Mutanga, M. O. Adigun, and N. Ntlatlapa, “Evaluating Transceiver Power Savings Produced by Connectivity Strategies for Infrastructure Wireless Mesh Networks,” in *Proc.International Conference on Wireless and Mobile Computing*, June 2011, pp. 215–220.