Design and Implementation of a Topology Control Scheme for Wireless Mesh Networks

P. Mudali*, T.C. Nyandeni*, N. Ntlatlapa†, and M.O. Adigun*
*Department of Computer Science
University of Zululand, South Africa
Email: pmudali@pan.uzulu.ac.za
†Meraka Institute, CSIR, South Africa

***Abstract*—The Wireless Mesh Network (WMN) backbone is usually comprised of stationary nodes but the transient nature of wireless links results in changing network topologies. Topology Control (TC) aims to preserve network connectivity in ad hoc and mesh networks and an abundance of theoretical results on the effectiveness of TC exist. Practical evaluations of TC schemes that provide gradual transceiver power adjustments for the WMN backbone are however in their infancy. In this paper we investigate the feasibility of power control in a popular WMN backbone device and design and evaluate an autonomous, light-weight TC scheme called PlainTC. An indoor test-bed evaluation shows that PlainTC is able to maintain network connectivity, achieve significant transceiver power savings and reduce MAC-level contention but that no significant reductions in physical layer interference were realised. The evaluation has also highlighted the danger of associating power savings with network lifetime. Further larger-scale experiments are required to confirm these results.**

Keywords - Topology Control, implementation, WMN, test-bed

I. INTRODUCTION

Infrastructure Wireless Mesh Networks (WMNs) are a subclass of ad hoc networks that possess a two-tier architecture consisting of an access and a backbone network. Client devices connect to the mesh backbone which is typically self-organizing and self-configuring. These backbone nodes (comprising Mesh Points and Mesh Access Points) collaborate amongst themselves to maintain network connectivity and deliver traffic to the intended destinations.

Despite the stationary nature of the infrastructure WMN backbone, maintaining network connectivity is made difficult by the transient nature of wireless links, making them unreliable when deployed [1], [2], [3]. Traditionally, network connectivity is assured by ensuring that each device in the WMN backbone utilizes its maximum transceiver power. The disadvantages of this approach are the high levels of interference, increased contention for the transmission medium, a reduction in network capacity and unnecessary energy consumption. In the African context, any power savings are welcomed and operating a network at maximum power consumption is an ill-afforded luxury for reasons expressed in [5]. The African context also constrains WMN deployments (and their associated QoS mechanisms) to those that are as autonomous as possible due to the lack of technical expertise in rural areas.

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. Power consumed by the wireless transceiver is reported to account for between 15% to 35% of the total energy consumed by the device [4]. TC aims to enhance the QoS capabilities of the WMN backbone by optimizing the transceiver powers of all backbone devices whilst maintaining network connectivity.

Several simulation studies [5], [6], [7], [8] have demonstrated the efficacy of TC in Ad hoc networks but the effectiveness of TC when implemented on real-world, resource-constrained WMN backbone devices is (to the best of our knowledge) in its infancy. TC implementations for the laptop [10] and sensor [11] platforms are available but these devices are not typical infrastructure WMN backbone nodes. A study reported in [9] used a commercially-available wireless router platform, but these were arranged in a string topology, which is unrealistic for the rural African deployment scenarios being considered.

In this paper a TC scheme for a WMN backbone comprising of commercially available Linksys WRT54GL routers (which are popular WMN backbone devices) is proposed and evaluated. The proposed scheme is designed to maintain network connectivity by relying on data gathered by a proactive routing protocol.

The scheme was tested on an indoor tes-bed and the evaluation indicates that maintaining network connectivity by attempting to maintain a Critical Neighbor Number (CNN) achieves reduced transceiver power usage and MAC-level contention for the wireless medium. The results also indicate that attempting to maintain a CNN may cause any achieved power savings to be a result of the logical location of the backbone nodes in a realistic setting.

The remainder of this paper is organized as follows. Section 2 investigates the feasibility of transceiver power control by the Linksys WRT54GL wireless router. In section 3 we provide the details of our proposed Topology Control scheme and discuss the indoor test-bed that was used to evaluate this scheme in

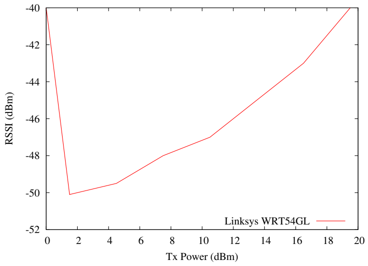

Fig. 1. Received RSSI values for varying transceiver powers

Section 4. The measurement methodology is presented in section 5 whilst the evaluation results are contained in section 6. Section 7 reviews other implementations of Topology Control schemes. Finally, the work is concluded in section 8 where avenues for future work are also given.

II. FEASIBILITY OF TRANSCEIVER POWER CONTROL IN LINKSYS WRT54GL DEVICES

Studies establishing the ability of off-the-shelf wireless cards to provide transceiver power control have been conducted in [16]. We will attempt to establish, using a similar methodology to [16], whether the Linksys WRT54GL router is capable of transceiver power control. In addition we will determine the latencies involved when changing power levels.

A. *Ability to change Transceiver Power Output*

The OpenWRT [18] firmware installed on the router allows for the adjustment of the transceiver power output. The firmware specifies a power output of 19.5dBm by default and after experimentation we adopted the use of a 3dBm increment or decrement. This value is a compromise between the time taken to reach the necessary power level and ensuring that power consumption is minimized.

One Linksys WRT54GL router broadcast frames at 1-second intervals while a laptop was used to capture the frames and log the associated RSSI values. The Linksys router was configured to increase its transceiver power output by 3dBm every two minutes. Figure 1 depicts the association between the Linksys router's transceiver power output and the RSSI values logged by the laptop. The RSSI values presented are the average of five runs.

It can be observed that the Linksys device exhibits a gradual increase in received RSSI as the transceiver power is increased. Attempting to set the transceiver power to 0dBm proved fruitless as the device automatically reverted to the maximum power.

B. *Latency during Transceiver Power Level Adjustment*

The second component of this feasibility study determined the latency involved when changing between transceiver power levels. The router was set up to alternate between the min. and max. power levels every two minutes.

The router was observed to change transceiver power levels almost instantaneously but required approximately 6 seconds before stabilizing at the required level. This latency was a result of the process involved when changing power levels. With this particular device, the new power level needed to be stored in the NVRAM (non-volatile random access memory) partition and the wireless settings needed to be reloaded before the power level change was effected. The RSSI values were observed to stabilize once this process completed.

The Linksys WRT54GL router is a popular WMN backbone device and its ability to perform power control means that TC schemes can be developed for those WMN deployments that utilize these devices as backbone nodes. The next section presents our proposed TC scheme.

III. PROPOSED SCHEME

This section presents the design and implementation of our proposed TC scheme, PlainTC (see Figure 2) .

A. *Maintaining Network Connectivity*

The most fundamental aspect of any TC scheme is its ability to maintain network connectivity. Two main approaches may be used in this regard, either maintaining the Critical Transmission Range (CTR) or the Critical Neighbor Number (CNN). Examples of these works can be found in [4].

The CNN refers to the minimum number of neighbors that should be maintained by each node in order for the network to be asymptotically connected. This approach to maintaining connectivity is adopted for use in the proposed scheme because only knowledge of the network size is required to determine the CNN. This information can be easily obtained from a proactive routing protocol such as OLSR [15]. The CNN may also result in heterogeneous transceiver power outputs, potentially maximizing power savings and interference gains. The CNN is also less affected by the distribution and position of the network nodes and there is no need to assume a GPS-enabled router. The CNN also increases gradually with network size and is thus able to tolerate delays in the propagation of topology updates and network size (if a proactive routing protocol is used). Thus, maintaining connectivity via a CNN reduces human intervention (if a proactive routing protocol is employed) which is of fundamental importance in the rural African context.

Prior research has proposed several CNN values and tests conducted on our indoor test-bed have indicated that setting the CNN to the upper-bound of the inequality proposed in [17] (and shown in Equation 1),

$$0.074 log(n) < k < 5.1774 log(n) \qquad (1)$$

where n is the number of backbone nodes, was sufficient to ensure backbone network connectivity in this instance despite the assumption made in [17] that the nodes are uniformly distributed. Note that additional experimentation is required to determine whether this inequality is suitable for general usage.

B. *Other Design Criteria*

The proposed scheme dubbed PlainTC (and shown in Figure 2) attempts to conform to the set of ideal design properties proposed in [4] . A discussion of the design properties follows.

```
$no.nodes \Leftarrow olsr.getRoutingTableSize()$
$CNN \Leftarrow \lceil 5.1774 log(no.nodes) \rceil$
$max\_tx\_power \Leftarrow 78qdBm$
$min\_tx\_power \Leftarrow 1qdBm$
$tx\_power\_change\_level \Leftarrow 3qdBm$
if $current\_tx\_power \leq max\_tx\_power$ then
  if $current\_no\_neighbors > CNN$ then
    if $(current\_tx\_power - tx\_power\_change\_level) \geq min\_tx\_power\_level$ then
      $current\_tx\_power \Leftarrow current\_tx\_power - tx\_power\_change\_level$
    end if
  end if
  if $current\_no\_neighbors < CNN$ then
    if $(current\_tx\_power + tx\_power\_change\_level) \leq min\_tx\_power\_level$ then
      $current\_tx\_power \Leftarrow current\_tx\_power + tx\_power\_change\_level$
    end if
  end if
end if
```

Fig. 2. Algorithm of Proposed Topology Control Scheme, PlainTC

1) Fully Distributed: The lack of centralized control in the WMN backbone necessitates a distributed approach and this lends itself to the practical relevance of the proposed TC scheme.

2) Localized: According to [4], three types of information can be collected and used as the basis of a TC scheme: location information, direction information and neighbor information. The Linksys WRT54GL device contains neither a GPS nor the native ability to determine the relative direction of incoming and outgoing transmissions. The device does however possess the ability to collect low-quality [4], neighbor-based information by inspecting the routing table built by the proactive routing protocol being employed.

3) Small Node Degree: The work in [4] also promotes the maintenance of a small physical node degree but in practical settings it is difficult to determine the number of neighbors within radio range. Determining the logical node degree is easier because the number of HELLO messages received from unique sources can be determined if a reactive routing protocol is employed. If a proactive routing protocol is employed, then the routing table can be inspected for the number of one-hop (or *n*-hop) neighbors.

C. Implementation Architecture

The popularity of the Linksys WRT54GL router as a WMN backbone device is due to its native use of a Linux-based firmware. This has led to the development of alternative firmwares that offer mesh functionality, with OpenWRT [18] foremost amongst them.

The OpenWRT firmware is a stripped-down version of the Linux OS that caters for the limitations imposed by the Linksys hardware. The firmware contains embedded Linux tools and allows user-space packages to interact with the NVRAM partition that the Linkys WRT54GL device provides.

The 64KB NVRAM partition stores configuration variables that span the entire logical protocol stack and is thus a potential source of cross-layer optimization data.

A vertical architecture is adopted for the implementation of PlainTC. This choice is motivated by the architecture of the OpenWRT firmware and the existence of the NVRAM partition, thus enabling the logical implementation architecture shown in Figure 3. The nature of PlainTC and the existence of the NVRAM partition allow for the following implementation benefits:

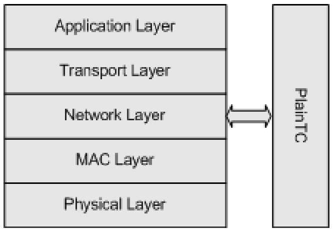

Fig. 3. Proposed Logical Architecture

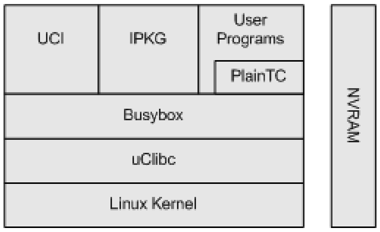

Fig. 4. Implementation Architecture, adapted from [19]

(i) the de-coupling of PlainTC scheme from the traditional protocol stack layers
(ii) cross-layering (if required),
(iii) no new interfaces between layers being required, and
(iii) no new protocol messages that require defining

OpenWRT's architecture allows PlainTC to be straightforwardly translated into a user-space implementation as shown in Figure 4. No modifications to the firmware are required resulting in a loose-coupling between the firmware and PlainTC and conforming to the logical implementation architecture in Figure 3.

The resultant interaction between PlainTC, the proactive OLSR routing protocol, the OpenWRT firmware and the NVRAM partition is depicted in Figure 5. PlainTC (in its present form) relies on the topology information collected during OLSR's normal operations. The total number of backbone nodes and the number of neighbors can be used to determine the appropriate CNN to be maintained. If the transceiver power output requires modification then the OpenWRT firmware interacts with the NVRAM partition to achieve the desired transceiver power level.

IV. TEST-BED SETUP

The mesh test-bed consists of 14 nodes placed in an 6m x 4m area as shown in Figure 6. The node placement is determined by the availability of plug points (which is somewhat analogous to the coupling of nodes with existing infrastructure in real-world deployments) and each node in the mesh backbone consists of a mains-powered, Linksys WRT54GL router with the OpenWRT firmware used to provide mesh functionality. The Linksys WRT54GL routers possess a 200MHz processor, 16Mb of RAM, 4Mb flash memory and a Broadcom 802.11b/g radio chipset. The wireless chipset

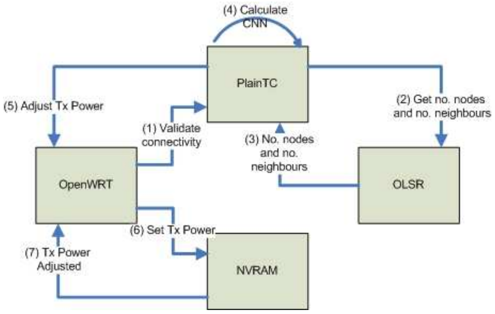

Fig. 5. PlainTC's Interactions with other System Elements

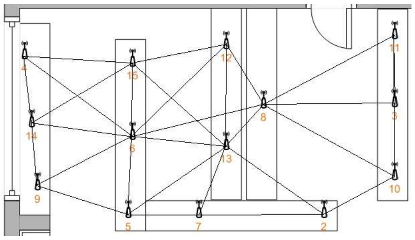

Fig. 6. Testbed Layout at Max. Tx Power

allows transceiver power output levels to be set from 0 to 19.5dBm, which is the maximum power output recommended by the manufacturer. Each node is connected via Ethernet through a switch to a central server.

This network was operated in 802.11g mode on channel 6 in order to mitigate against interference caused by a separate WLAN that is operational within the building.

V. MEASUREMENT METHODOLOGY

The goal of the performance evaluation is to determine whether PlainTC maintains network connectivity whilst reducing transceiver power consumption and interference in the process. In addition, PlainTC's resource consumption is also measured.

All evaluation data was collected at the central server via the node's Ethernet ports, thus having no effect on the wireless interface. The impact of network size on all metrics (besides the resource consumption metrics) was determined by randomly switching-off edge nodes at five minute intervals. The following measurement processes were used for each of the metrics being measured.

1) Network Connectivity: Network connectivity is best measured at the Network Layer and thus the availability of routes between all source-destination pairs is a reliable indicator of network connectivity. Routes to and from all network nodes are available whilst utilizing maximum transceiver powers, resulting in a maximum of 182 (14 x 13) possible source-destination pairs at the Network Layer. Network connectivity, after applying PlainTC, is assured if routes for all possible source-destination pairs can still be found. Standard *ping* packets are sent between each source-destination pair and the availability of paths is determined when the ping utility reports replies from the destination.

TABLE I
NETWORK CONNECTIVITY

Network Size	Src-Dest Pairs (Max Tx Power)	Src-Dest Pairs (PlainTC)
8	56	56
9	72	72
10	90	90
11	110	110
12	132	132
13	156	155
14	182	180

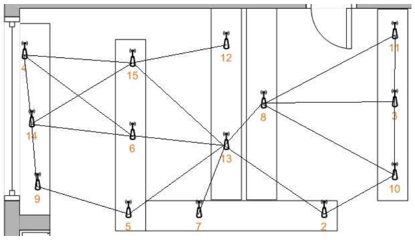

Fig. 7. Resultant Test-Bed Topology after applying PlainTC

2) Transceiver Power Consumption: The transceiver power levels for each testbed node are logged every minute using the *wl* utility. These values are summed to produce the total transceiver power consumption of the network. This value is compared to the maximum transceiver power consumption.

3) Interference: The interference levels experienced by each node are also logged every minute and the average interference levels are determined. The *wl* package is used to report the noise levels experienced.

4) CPU Load and Memory Consumption: The resource consumption of PlainTC is of vital importance in real-world implementations. Both the CPU load and memory consumption are recorded using the *top* utility.

VI. PERFORMANCE EVALUATION

The results of the performance evaluation of the proposed TC scheme are presented here.

A. Network Connectivity

The number of source-destination pairs connected using the maximum transceiver power was compared to the number of pairs connected using PlainTC. Table I shows that PlainTC was able to maintain network connectivity as there was little observed difference in the number of available source-destination pairs subsequent to its application on the test-bed network.

The network size was also observed to not affect PlainTC's ability to maintain network connectivity due to the attempts to maintain a CNN that is based on the network size. The resultant test-bed topology (with all 14 nodes) is depicted in Fig 7.

B. Power Consumption

Each test-bed node initially utilized a maximum transceiver power output of 89mW, resulting in a linear transceiver power

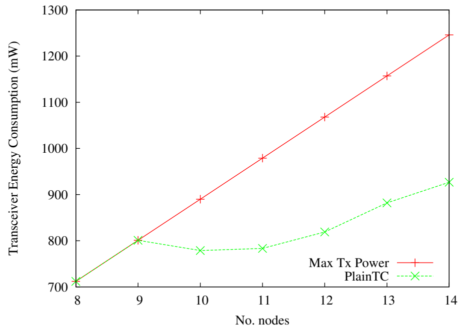

Fig. 8. Power Consumption

TABLE II
PERCENTAGE POWER SAVINGS ACHIEVED

Network Size	% Transceiver Power Saved
8	0
9	0
10	12.5
11	20
12	23.3
13	22
14	25.6

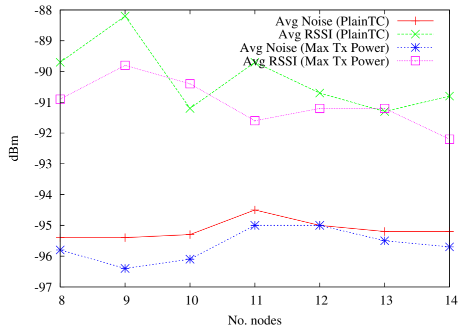

Fig. 9. Measured Interference

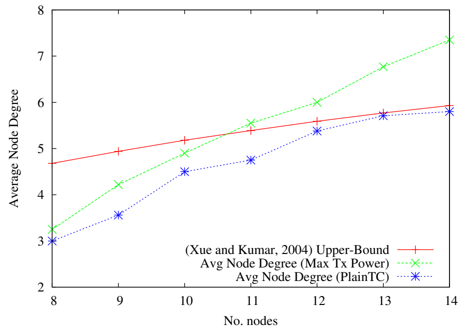

Fig. 10. Node Degree

increase as the network size increased. As shown in Figure 8, PlainTC achieved significant power savings as the network size grew. When the maximum number of test-bed nodes were switched on, a 25.6% reduction in total transceiver power consumption was achieved (see Table II).

It was interesting to note that the power savings achieved were contributed to by a maximum of 5 network nodes and these nodes were mostly situated at the logical center [20] of the network. These "central" [20] nodes had the highest numbers of one-hop neighbors and, due to the CNN connectivity strategy employed, were not required to use their maximum transceiver powers.

This result also illustrates the often incorrect correlation between power savings and the corresponding prolonging of network lifetime. In this instance, if the test-bed nodes were battery-powered and network traffic loads were evenly distributed, the network lifetime would not have been prolonged because extending the network lifetime would have required *all* the nodes to have achieved transceiver power savings.

C. *Interference*

The Received Signal Strength Indicator (RSSI) is a simple indicator of the link quality, which is largely determined by interference levels. Higher RSSI values are indicative of improved link quality and lower interference impact, if the transceiver power remains constant.

Despite the transceiver power savings produced, PlainTC made almost no impact in reducing noise levels and only a marginal improvement in signal quality was realized, see Figure 9. The lack of improvement in noise levels could possibly be attributed to the earlier observation that only a minority of network nodes achieved transceiver power reductions. It would seem that either the number of nodes that achieved power reductions was not sufficient to improve the overall interference level at the physical layer, or that the interference effect of the other WLAN resident within the building cannot be discounted.

PlainTC was however able to reduce contention at the Medium Access Control sub-layer whilst attempting to maintain a CNN. Figure 10 shows that an increase in network size produced a convergence between the node degree maintained by PlainTC and the theoretical upper-bound on node degree proposed in [17], resulting in contention for the transmission medium being minimized for the network connectivity strategy employed.

D. *Resource Consumption*

PlainTC was observed to consume 368Kb of memory (2.3% of total memory) and approximately 0.3% of the Linksys WRT54GL device's processing capability. Due to the localized nature of the scheme, no discernible differences in memory consumption and CPU load were observed as the network size was varied.

VII. LITERATURE REVIEW

A recent study reported in [9] implemented a Topology Control scheme on commercially available wireless routers. The scheme utilised the CTR approach to maintain network connectivity which requires knowledge of node positions. The CTR approach to TC is not feasible for rural African deployments because of the human intervention required to log node positions, compute the CTR and then set all network nodes to maintain this CTR value, as described in [9].

Other implementations of TC exist but these are limited to the laptop and sensor platforms which are not typical WMN backbone nodes. The implementation of TC schemes for the laptop platform has been reported in [10]. COMPOW, CLUSTERPOW and MINPOW have been developed and evaluated on laptops using plug-in Cisco Aironet 350 series wireless cards. Each of these three schemes maintains six routing tables, one for each power level supported by the wireless card. All three schemes are executed locally and use information collected by the routing protocol. Most implemented routing protocols send beacon messages at either one-second [14] or two-second intervals [15] which means that constant power level changes are inevitable if up-to-date routing tables at all power levels are to be maintained. The Linksys WRT54GL's lack of pre-defined power levels and the requirement to maintain multiple routing tables make these works inappropriate.

TC schemes developed for the sensor platform tend to be sleep-based eg GAF [12], CEC [13] and ASCENT[11]. These schemes are inappropriate for the WMN back-bone due to the need to maintain route redundancy and the presence and dependence of client devices on back-bone nodes.

VIII. CONCLUSION AND FUTURE WORK

In this paper we have established that the Linksys WRT54GL router, a popular WMN backbone device, possesses the ability to control its wireless transceiver power output. This has lead us to propose PlainTC, an autonomous, light-weight Topology Control implementation. PlainTC (in its present form) uses information obtained from a proactive routing protocol to maintain network connectivity by maintaining a Critical Neighbor Number (CNN). The evaluation of PlainTC on an indoor WMN test-bed has indicated that this scheme is able to maintain network connectivity, reduce transceiver energy consumption and reduce MAC-level contention. The findings also suggest that any transceiver savings achieved using the CNN connectivity strategy are produced by "central" nodes that initially possess a greater number of neighbors than nodes towards the network edge. The evaluation also highlighted the danger of associating power savings with the lengthening of the network lifetime.

Several issues remain however. Firstly, a larger scale test-bed evaluation is required that also evaluates PlainTC's effect on network traffic. Secondly, we intend devising a strategy to maintain the CNN whilst utilizing a reactive routing protocol. Lastly, we are investigating the possibility of using information from other network layers to optimize PlainTC's performance.

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