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# New Link Addition Strategies for Multi-Gateway Small World wireless Mesh Networks

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***Abstract*—Small-world network concept deals with the addition of a few Long-ranged Links (LLs) in a network to significantly bring down the average path length (APL) of the network. Existing small-world models do not consider the presence of multiple gateways and, therefore, we propose Multi-Gateway Aware LL addition Strategy (M-GAS). Further, the presence of multiple gateways brings forth the additional issue of traffic load balancing. We modify the M-GAS to propose Load balanced M-GAS (LM-GAS) for load balancing in small-world WMNs. For uniform and random placement of gateways, we present results from M-GAS and LM-GAS strategies. Our results provide early insights in achieving high load balancing in small world WMNs.**

## I. INTRODUCTION

A typical Wireless Mesh Network (WMN) consists of three classes of nodes: wireless clients, mesh routers, and gateway nodes. A wireless client connects with one of mesh routers over one-hop for its communication. Mesh routers (or simply ‘nodes’) form a multi-hop wireless mesh backbone for relaying traffic from (to) clients to (from) gateway nodes. Gateway nodes provide connectivity to the Internet via a backhaul (satellite, wired, etc) connection, relaying clients traffic to/from the Internet. There are several advantages for WMNs: self configurability, high fault-tolerance, and high network deployment flexibility. However, WMNs suffer from many disadvantages too. Rapid throughput degradation with path length, poor capacity scaling with larger networks, and wireless channel related performance issues are some examples. In applications such as medical emergency response, a large network may under-perform due to the lack of scalability. One method that can help reduce the path length, thereby providing better capacity, energy efficiency, and end-to-end delay, is the concept of small-world networks [1]. In this work, we study the benefits of small-world concept in multi-gateway WMNs by considering the real constraints of wireless networks such as the transmission range of radio links and limited availability of radios per mesh router node.

### A. Network Models and Related Work

In Watts-Strogatz (WS) model [1], a small-world network is constructed by probabilistically *rewiring* the network links. In Newmann-Watts (NW) model [2], new Long-ranged Links (LLs) are added with probability $p$. In Kleinberg model [3], the probability of having an LL between two nodes is inversely proportional to their euclidian distance. In [4]–[6], the authors studied the application of small-world concept in wireless networks. However, the existing small-world models [1]–[6] have many shortcomings for application in WMNs. The WS model is impractical for WMNs because it requires rewiring existing links, which is very complex to achieve in wireless networks. While one can apply NW and Kleinberg models in the wireless context, they do not consider the limit of number of radios or their bandwidth that impacts the number of LLs and the traffic they can carry. Further, wireless networks cannot realize LLs of arbitrary lengths due to technological, transmit power, or cost constraints.

The authors of [4] and [5] studied small-world network benefits in wireless networks by adding LLs between randomly chosen node pairs whose distance is from $[2, r]$ hops, where $r$ is the maximum distance in hops. However, such an LL addition method is not beneficial in multi-gateway WMNs because it may either create a traffic imbalance or not improve the APL to the gateway (G-APL). In [6], a few shortcut wires are added to improve energy efficiency of wireless sensor networks. Their model is quite different from the above discussed models (and our model) because they use wires for realizing LLs and assume each LL originates from the sink node. In [7], three LL addition schemes, Random LL Additional Strategy (RAS), Gateway Aware LL Addition Strategy (GAS), and Gateway Aware Greedy Strategy (GAGS), were proposed. However, the solutions in [7] work only for reducing the G-APL for a single-gateway scenario, therefore, those solutions may perform worse in a multi-gateway scenario.

In comparison to the above, in our work, our LL addition strategy explicitly considers the presence of multiple gateways and attempts to improve the G-APL and the gateway traffic load difference. We separate LLs into intra-region and inter-region LLs and use the RAS and GAS schemes from [7].

## II. MULTI-GATEWAY SMALL-WORLD WMNS

In this work, we present LL addition strategies based on the Constrained Small-World Architecture for Wireless Networks (C-SWAWN) [7]. The C-SWAWN model is referred to as C-SWAWN($R_S, R_L, K_{LL}$) where the parameters $R_S$, $R_L$, and $K_{LL}$ represent transmission range of nodes, the maximum range of LL, and the number of LL radios per node, respectively. For GAS and GAGS strategies in [7], $\Delta_h$ denotes the minimum difference in the shortest path lengths to gateway for any two nodes we want to connect by an LL. The gateway node does not have any LL radios and, therefore, all traffic has to reach the gateway through its one-hop neighbors. An LL can be realized between a pair of nodes with help of highly

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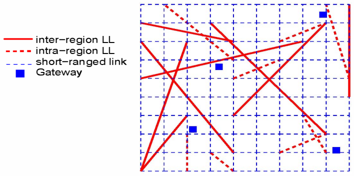

Fig. 1: Multi-gateway small world WMN topology.

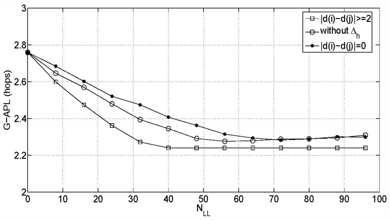

Fig. 2: G-APL v/s $N_{LL}$ for uniform gateway placement (M-GAS).

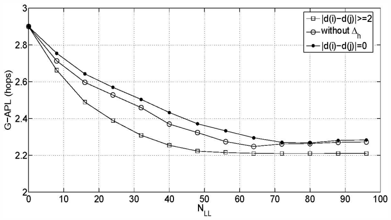

Fig. 3: G-APL v/s $N_{LL}$ for non-uniform gateway placement (LM-GAS).

directional point-to-point radios and, therefore, we assume that the interference between two LLs is negligible. Also LLs are bi-directional and their assignments do not change dynamically. Of all the strategies defined in [7], the GAGS was found to be better performing. However, GAGS was designed for a single gateway WMN because the $\Delta_h$, defined in GAGS scheme associated with C-SWAWN model, is measured for two nodes as the difference in the path length to a single centralized gateway. Therefore, we propose a Multi-Gateway Aware LL addition Strategy (M-GAS) in this paper.

### A. *Multi-Gateway Aware LL addition Strategy*

In multi-gateway small-world WMNs, each node routes its traffic to the gateway closest to it in terms of number of hops. The set of such nodes routing their traffic to a gateway is called a region. Unlike in a single-gateway small-world WMN, the LL addition in a multi-gateway small-world WMN is more complex. That is because, an LL can be added as an intra-region LL or inter-region LL and the same strategy cannot be used for both these. An LL is called intra-region or inter-region LL based on whether the LL is added between two nodes belonging to the same region or different regions, respectively. The addition of inter-region or intra-region LLs can impact the trade-off between traffic load balancing and the G-APL.

For intra-region LLs, a pair of nodes ($i$ and $j$), both in the same region, is randomly chosen and checked for three constraints for adding an LL between them. The first constraint is the euclidean distance $r$, between nodes $i$ and $j$, lies between $R_S$ and $R_L$. The second constraint is each of the two nodes should have an LL-radio unoccupied for the LL. The third constraint is the added LL should result in improvement of G-APL. In order to ensure the third constraint, we impose a condition: $|d(i) - d(j)| \geq \Delta_h$, where $d(i)$ or $d(j)$ is the shortest hop distance between nodes $i$ or $j$ and the gateway of $i$ or $j$, respectively, and $\Delta_h$ is the minimum difference in the shortest path lengths to the gateway for any two nodes we want to connect by an LL. $\Delta_h$ is a controllable parameter whose minimum value is two. We repeat the process of adding intra-region LLs till either we reach the number of LLs we want to add in each region or the network saturates with LLs, (*i.e.,* we cannot add any more LLs due to constraints on $R_L$, $K_{LL}$, and $\Delta_h$). The number of LLs beyond which we cannot add any more LLs in a WMN is called network saturation point ($N_{sat}$) [7].

For adding inter-region LLs, a pair of nodes ($i$ and $j$) is randomly chosen with $i$ and $j$ in different regions. They are checked for certain constraints for adding an LL between them. The first two conditions being the same as for intra-region LL addition, the third condition has a slight difference. $|d(i)-d(j)| \geq \Delta_h$, where $d(x)$ is the number of hops between WMN node $x$ and $G(x)$, over the shortest path. $G(x)$ is the nearest gateway associated with the node $x$ with respect to the number of hops. The fact that an inter-region LL is added between WMN nodes belonging to different regions forces us to evaluate the impact of the $\Delta_h$ in the following cases: (i) $|d(i) - d(j)|$ =0, (ii) $|d(i) - d(j)| \geq \Delta_h$, and (iii) without $\Delta_h$.

### B. *Load-balanced M-GAS*

In a multi-gateway WMN, gateways may face traffic load imbalance. The use of M-GAS may not help balance the traffic load among the gateways. Therefore, we propose a modification of the M-GAS, called Load balanced M-GAS (LM-GAS). The LM-GAS is used for adding LLs when gateways are placed non-uniformly in a region or when the uniformly placed gateways face non-uniform traffic load.

In this strategy, for adding inter-region LLs, a pair of nodes, $i$ and $j$, is randomly chosen such that they are present in different regions and checked for certain constraints for adding inter-region LL between them. These constraints are similar to those for adding inter-region LLs in M-GAS, however, the third condition is modified. Two nodes $i$ and $j$ lying in different regions can be connected only if either $|d(i) - d(j)| \geq \Delta_h$ and $|n[G(i)] - n[G(j)]| \geq \Delta_n$ where $G(i)$ is the gateway of the node $i$ and $n[G(i)]$ or $n[G(j)]$ is the gateway traffic load, in terms of the number of WMN nodes, associated with $G(i)$ or $G(j)$, respectively. In other words, $\Delta_n$ is the minimum difference in the load of two regions whose nodes can be connected by inter-region LLs. Intra-region LLs are added in a method similar to the method for adding intra-region LLs in M-GAS. By such a change in the policy, we ensure that the regions with large difference in their load are connected through inter-region LLs, and the $\Delta_h$ and $\Delta_n$ constraints ensure that traffic from the overloaded region will flow to the less loaded region.

## III. PERFORMANCE RESULTS

We study performance of the multi-gateway LL addition strategies based on the C-SWAWN model, in terms of metrics G-APL and standard deviation (SD) of traffic load among the

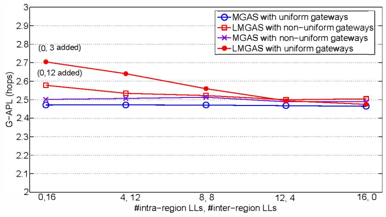

Fig. 4: G-APL v/s intra- and inter-region LLs ratios.

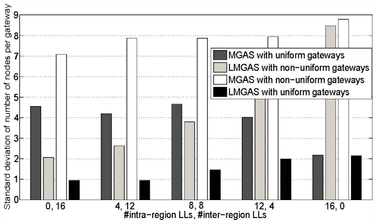

Fig. 5: Gateway traffic load v/s intra- and inter-region LLs ratio.

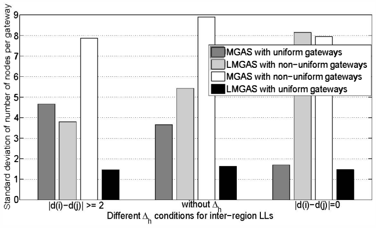

Fig. 6: Gateway traffic load vs different $\Delta_h$ cases in LM-GAS.

gateways, by carrying out detailed simulation experiments. We consider a multi-gateway network scenario with four gateways, in which 100 nodes are arranged in a grid pattern over an area of 1000 m × 1000 m in a simulator platform developed using MATLAB. Each WMN node routes its traffic to the gateway closest to it in terms of number of hops. In case there are more than one such gateway with equal distance, it randomly picks one. For the case of uniform placement of gateways, a gateway is placed each at the weighted center of each region (quarter), so without adding any LLs, the load on each gateway is 25 nodes and the network is in a balanced load condition. For non-uniform placement, gateways are arranged, with one gateway randomly located in each region, such that it resembles a real-world scenario. Such a gateway placement, in our scenario, gives the number of nodes per gateway as 27, 21, 35, and 17 for the four gateways as illustrated in Figure 1. Such a positioning of gateways gives a standard deviation of 7.8 in gateway traffic load. The results shown in plots are averaged over 20 seeds. Unless otherwise mentioned, the default values used for simulations are $K_{LL} = 2$, $R_S = 100\ m$, $R_L = 800\ m$, $\Delta_h = 2$ and $\Delta_n = 2$.

Figures 2 and 3 show the performance of M-GAS and LM-GAS, respectively, for the three cases of $\Delta_h$. In both the strategies, there is more improvement in G-APL with $|d(i) - d(j)| \geq \Delta_h, (\Delta_h = 2)$, compared to other strategies ($|d(i) - d(j)| = 0$ and without $\Delta_h$). Therefore, the constraint $\Delta_h$ ensures every added LL improves the G-APL. Further, the G-APL reduction is better in non-uniform gateway placements when using LM-GAS because nodes in a given region, that are located farther from their gateway may have higher chances of having an LL to a node, that has shorter path to its gateway, in another region.

For Figures 4 and 5, we added 16 LLs and varied the number of LLs added as intra- or inter-region ones. G-APL remains constant as long as the total number of added LLs is the same. That is, the G-APL savings contributed by the addition of an intra- or inter-region LL is the same. However, there is a small increase in the G-APL with fewer number of inter-region LLs, in Figure 4, with LM-GAS. That was due to the fewer number of inter-region LLs added, compared to the inter-region LLs attempted, in LM-GAS where with uniform and non-uniform cases only 3 and 12 inter-region LLs, respectively, were added. As a result, the G-APL is observed to be higher when more inter-region LLs are attempted for LM-GAS.

In Figure 5 we plot the traffic load SD among the gateways. It is observed that our LM-GAS strategy helps in balancing the load to a large extent as more inter-region LLs are added. For M-GAS, the inter-region LLs do not help in improving the load-balancing and less SD is observed when all added LLs are added as intra-region LLs. In either uniform or non-uniform gateway load cases, LM-GAS is found to be performing best.

For Figure 6, we added eight intra- and inter-region LLs, (total 16), using the M-GAS and LM-GAS strategies (with $\Delta_n$=2). The network load is more balanced when the LLs are added using the scheme with $|d(i) - d(j)| = 0$ for M-GAS in uniform case. That is because, non-zero value of $\Delta_h$ can result in artificial traffic load imbalance in uniformly loaded networks. For non-uniform traffic situation LM-GAS scheme with $\Delta_h \geq 2$ works best as larger value of $\Delta_h$ helps off load traffic from a heavily loaded regions to lightly loaded regions. Therefore, LM-GAS scheme is indeed useful for better load balancing in real-world multi-gateway small-world WMNs.

## IV. CONCLUSIONS

We extend the existing C-SWAWN model for multiple gateway WMNs and propose two LL addition strategies- M-GAS and LM-GAS. We found that the LM-GAS performs better for balancing the gateway traffic load without compromising the G-APL.

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