Load-aware Routing for Non-Persistent Small-World Wireless Mesh Networks

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***Abstract*—Wireless mesh network is a distributed multi-hop relaying network. A large scale wireless mesh network typically has high value of network average path length which results in reduced throughput and increased delay in the network. Average path length can be reduced in the network by implementing a few long-links among the network node-pairs, and thus introduces the small-world characteristics in the wireless mesh networks. However, the conventional routing algorithms are not optimized for small-world wireless mesh networks. In this paper, we propose a Load-aware Non-Persistent small-world long-link Routing (LNPR) algorithm for small-world wireless mesh networks to achieve lower average transmission path length for data transfer sessions among a set of source-node and destination-node pairs in the network. LNPR uses load balancing strategy to better distribute the network traffic among the normal-links and the non-persistent long-links in the small-world wireless mesh networks for efficient use of long-links which are precious data transmission paths in the network. LNPR provides 58% to 95% improvement in call blocking probability and 23% to 70% in maximum load reduction with increment ranging from only 0.7% to 9% increase in average transmission path length. Small-world wireless mesh networks find numerous applications in rural and community networks for cost-effective communication.**

Keywords*—*Small-world wireless mesh network, long-links, average transmission path length, LNPR algorithm.

I. Introduction

WIRELESS mesh network (WMN) consists of three types of nodes: gateway mesh router, mesh router and mesh client [1]. Gateway mesh routers are connected to other communication networks or the internet through wired links. Wireless mesh routers are deployed in the WMNs as partially mobile or fully static nodes whereas mesh clients are dynamic nodes in the network. WMNs have many advantages such as low up-front cost, easy network maintenance and robustness in network operation. Average path length (APL) which is defined by the end-to-end hop distance (EHD) averaged over the network, has greater value in the context of WMN due to its regular network topology. To reduce the APL value of the WMN, EHD between source-node (SN) and destination-node (DN) has to be minimized. Therefore, long-links (LLs) can be established among the distant router nodes (as their positions are mostly static in the WMN) to reduce the APL and incorporate the small-world (SW) characteristics in the WMNs.

Small-world characteristics can be achieved by lowering the value of APL in a regular network. Milgram [2] first observed the small-world characteristics in his 1967 experiment where he concluded that people are connected to each other with "*six degrees of separation*," thus forming the small-worlds. In [3], the authors achieved SW characteristics by creating a few LLs by rewiring the normal-links (NLs) in a regular network which resulted in reduced APL, and low to moderate average clustering co-efficient (ACC), which is the measure of the connecting neighbor nodes averaged over the network. In [4]–[10], the authors created the SW characteristics by adding a few LLs in the network. However, the above LL creation strategies deal with static or permanent LLs, as the LLs are established permanently for the whole data-transfer session in the network.

We consider non-persistent LLs (NPLLs) in this paper where LLs are formed temporarily between nodes as and when traffic demands them. Therefore, after certain time interval, the LLs may change the directions of LL formation by creating connections among different node-pairs in the network. Therefore, to create NPLLs, we consider smart antennas to form directional beams for connecting the distant node-pairs in the network. Smart antennas [11]–[14] or adaptive array antennas can be used to dynamically track the distant nodes by smart signal processing in the network to form NPLLs by highly directional beamformer.

SW-WMNs find applications in the context of rural networks or community networks. In rural or community regions of operation, there are very limited access or no access of the infrastructure networks, therefore, the deployment of SW-WMNs can provide cost-effective connectivity throughout such regions.

In this paper, we propose LNPR algorithm in the context of SW-WMN. The algorithm better distributes the traffic load among the LLs and NLs, thus incorporate load-balancing in the network. The rest of this paper is structured as follows. **Section II** describes existing routing algorithms for WMN along with the difficulties to implement them in the context of SW-WMN. **Section III** describes LNPR algorithm for non-persistent SW-WMN. In **Section IV** performance results of the algorithm is presented in terms of different metrics, which is followed by conclusion in **Section V**.

II. Routing in SW-WMNs

Small-world characteristics can be achieved in a WMN by implementing a few LLs in the network as studied in [5]–[10], [15]. The LLs in the WMN can be implemented in two ways. In *persistent LL* creation, the locations of the LLs among SN and DN pairs do not change for the duration of operation in the WMN. Whereas, in *non-persistent LL* creation, the LLs change their positions after a stipulated amount of time. Therefore, smart antennas equipped with a few mesh routers in the WMN, create directional beams to make non-persistent LLs in specified directions depending on the traffic requirements.

Routing for WMNs [1] can be divided into two categories: (i) *reactive routing* [17] is based on the strategy of on-demand data path establishment from SN to DN (e.g. Ad-hoc On Demand Distance Vector Routing (AODV) [18] or Dynamic Source Routing (DSR) [19]), whereas, (ii) in *proactive routing* [20], the data path is computed independently of demand and routing information is updated at every node in the network (e.g. Destination-Sequenced Distance Vector Routing (DSDV) [21] or Optimized Link State Routing (OLSR) [22]). However, these routing strategies do not provide efficient solutions for SW-WMNs with NPLLs. Figure 1 explains one example situation where the conventional routing algorithms overload the non-persistent LLs to find the shortest paths among SN and DN pairs in the grid-topology based SW-WMN.

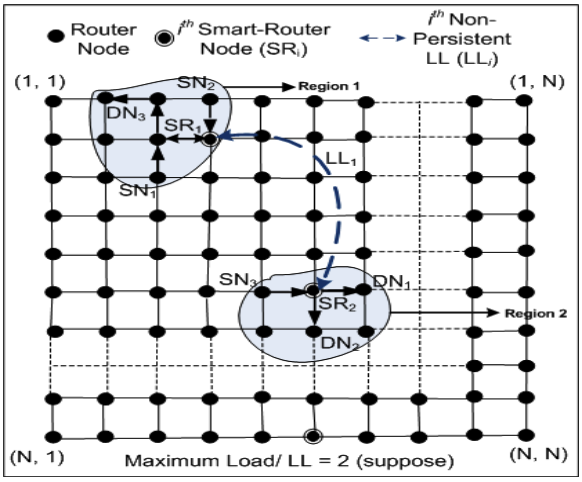

Fig. 1: Example Data Transfer Sessions among SNs and DNs in SW-WMN.

In Figure 1, smart-routers (SRs) are wireless mesh routers equipped with smart antennas which are capable of forming highly directional beam and changing the direction of beam adaptively to make non-persistent LLs in the SW-WMN. Therefore, for a specific time duration, non-persistent LLs can be made among SRs to transmit data packets among a set of SNs and DNs in the WMN. The conventional routing such as Link State Routing (LSR) [23] are based on the greedy strategy to find the shortest path between SN-DN pair. Hence, to find the shortest path, the routing strategies may choose the same LL repeatedly without considering the traffic load. Figure 1 also shows the data transmission session among three SN-DN pairs by using conventional routing strategies in the context of SW-WMNs.

In Figure 1, data transfer session is established between Region 1 and Region 2 where the data packets of SN_1 are transmitted to DN_1 through LL_1 which is created between SR_1 and SR_2. Similarly, the data packets from SN_2 is transmitted to DN_2 via LL_1. However, when SN_3 has to send data to DN_3, LL_1 is again used to deliver the data packets to DN_3 with minimal hops, as shown in Figure 1. Therefore, the path for data transfer session among different SNs and DNs may include the same LL. As a result, LLs may be highly overloaded, therefore, LLs should be used in such a way to avoid overloading. Hence, conventional WMN routing algorithms are not efficient in the context of SW-WMN.

A limited number of routing solutions exist in the context of SW-WMN to utilize the LLs in the network. In [10], the authors depicted a Small-world based Cooperative Routing (SCR) algorithm in the context of multi-hop wireless network, where, a few wireless nodes called cooperative nodes, have relaying capability to some distant cooperative nodes in the network. The cooperative nodes help to create long distant connections among SN-DN pairs by relaying the data packets to the distant DNs with cooperative capability, or to the nearest cooperative nodes of DNs. However, the global information is required to implement cooperative routing in the context of SW-WMNs. Moreover, the cooperative node has to transmit its own data and relay its neighbor's data, therefore, the bandwidth requirement is more to implement cooperative routing.

Jiang et. al. [16] considered data-mule or data ferry based NPLL creation in the multi-hop wireless networks. The data-mule which is mobile in the network, has the location information for the path it travels. Depending on the location information of the DN (i.e., whether the DN is on the way of the path traversed by the data-mule), the data-mule loads and dispatches the data to the DN or to the nearest node of DN in the network. However, the router nodes in the WMNs are mostly static or with less mobility, therefore, router nodes cannot be used as the non-persistent or dynamic LLs in the network.

In this paper we propose a Load-aware Non-persistent Small-World LL Routing (LNPR) algorithm for SW-WMNs. We consider a few non-persistent LLs among SR node-pairs and study the call block probability of NPLLs in the context of SW-WMN.

III. LNPR ALGORITHM FOR SW-WMNS

Here we describe LNPR algorithm which finds shortest path in a greedy way to transfer data from SN to DN in the SW-WMN without causing significant overloading of the NPLLs. The NPLLs are created among randomly deployed SR pairs in the SW-WMNs. The selection of SR pair in the network to create an NPLL is described later in this section.

LNPR incorporates load-balancing which results in better traffic distribution among NLs as well as NPLLs in the SW-WMN. The LNPR algorithm is depicted in Algorithm 1.

In Algorithm 1, from line 1 to line 21, we define all the variables which are used to describe the algorithm. Before applying LNPR algorithm, a few bidirectional NPLLs are deployed in SW-WMNs. The NPLLs are deployed among the SR node-pairs based on the path difference through NLs in the network. We denote the path traversed as the end-to-end hop distance through NLs (EHD_{NL}) in the SW-WMNs. To determine the edge-weight of an NPLL [part (A) of Algorithm 1], suppose, the p^{th} NPLL, we calculate the ratio of the average path length (APL) of the WMN with only NLs to the APL of the network including the p^{th} NPLL (from line 31 to line 32 in Algorithm 1). Therefore, by calculating the metric $NPLL_{EdgeWeight}$, we assign higher edge-weight to the more important NPLLs in the SW-WMN. Thus, the NPLLs can be used efficiently to create a path between SN and DN in the SW-WMN without severe overloading. However, the edge-weight for each NPLL is very small. Therefore, we consider a metric,

Algorithm 1 LNPR Algorithm for Non-persistent SW-WMNs

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1: USED ABBREVIATIONS AND INITIALIZATION:
2:
3: SN — Source node in the SW-WMN
4: DN — Destination node in the SW-WMN
5: SR — Smart-router node in the SW-WMN
6: NL — Normal-link in the SW-WMN
7: NPLL — Non-persistent bidirectional long-link in the SW-WMN
8: EHD — End-to-end Hop Distance between SN and DN (including NLs and NPLLs)
9: $EHD_{NL}(SN, DN)$ — End-to-end Hop Distance between SN and DN using only NLs
10:
11: $ConnectionLink(p)$ — $p^{th}$ link (NL or NPLL) between a node-pair
12: SF — Scaling Factor $\geq 1$
13: APL — Average Path Length $\rightarrow$ EHDs among all the pairs in the network
14: ATPL — Average transmission path length $\rightarrow$ Average of EHDs among SN-DN pairs in the network
15:
16: G — Graph including NPLLs
17: G´ — Graph including NPLLs with modified edge weights
18:
19: $k$ = Number of SR nodes in the SW-WMN
20: $MaxLoad_{NL}$ = Maximum traffic-load handled by each NL in the SW-WMN
21: $MaxLoad_{NPLL}$ = Maximum traffic-load handled by each NPLL in the SW-WMN
22:
23: (A) DETERMINATION OF NPLL EDGE-WEIGHT:
24:
25: $LowerLimit_{LL}$ = Lower boundary value for $EHD_{NL}(SN, DN)$
26: $UpperLimit_{LL}$ = Upper boundary value for $EHD_{NL}(SN, DN)$
27: for $i = 1 \rightarrow (k-1)$ do
28:     for $j = i+1 \rightarrow k$ do
29:         if $LowerLimit_{LL} \leq EHD_{NL}(i, j) \leq UpperLimit_{LL}$ then
30:             Create $p^{th}$ NPLL between $i^{th}$ and $j^{th}$ SR node pair
31:             Calculate APL($p$)
32:             $NPLL_{EdgeWeight}(p)$ = $(\frac{APL}{APL(p)}) \times SF$
33:             Assign $NPLL_{EdgeWeight}(p)$ to the $p^{th}$ LL in the SW-WMN
34:         end if
35:     end for
36: end for
37:
38: (B) DETERMINATION OF END-TO-END LOAD-BALANCED PATH:
39:
40: $m$ = Number of recursive calls to find shortest path
41: Assign $NPLL_{EdgeWeight}$ (Part (A) of Algorithm 1) to every possible NPLL in G, s.t., G $\rightarrow$ G´
42: $s$ = Number of randomly chosen SN-DN pairs in the SW-WMN
43: for $i = 1 \rightarrow s$ do
44:     Count = 0;
45:     while Count $\leq m$ do
46:         $r$ = Shortest path between $SN_i$ and $DN_i$ in $G´$
47:         for $j = 1 \rightarrow (r-1)$ do          ▷ Implementation of Load-balancing
48:             if $ConnectionLink(j)$ = NL then
49:                 if NL reaches $MaxLoad_{NL}$ then
50:                     Disable $j^{th}$ link for rest of the data transfer session
51:                 end if
52:             else if $ConnectionLink(j)$ = NPLL then
53:                 if NPLL reaches $MaxLoad_{NPLL}$ then
54:                     Disable $j^{th}$ link for rest of the data transfer session
55:                 end if
56:             end if
57:         end for
58:         if $ConnectionLink(j)$ = $MaxLoad$ for NL or NPLL then
59:             Count = Count+1;
60:         else
61:             break;
62:         end if
63:     end while
64:     if Path found in $G´$ between $SN_i$ and $DN_i$ then
65:         Transfer data packets between $SN_i$ and $DN_i$ through $r$
66:     end if
67: end for
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Scaling Factor (SF) to enhance the edge-weight uniformly for each NPLL in the network (line 33 in Algorithm 1).

To evaluate end-to-end path distance among a few randomly chosen SN-DN pairs [part (B) of Algorithm 1], shortest paths are measured with greedy approach. However, we incorporate the strategy of load-balancing in the LNPR algorithm (line 45 to 55 in Algorithm 1) to evenly distribute the load in the network.

Non-persistent deployment of LL which is mentioned in Algorithm 1, refers to the creation of LLs in a network which changes its position after a stipulated amount of time. SR nodes have the directional capability of beamforming in a particular direction. Hence, LLs are formed using SR nodes show non-persistency in SW-WMN. For the creation of an NPLL, SR node-pair has to satisfy the cut-off distance value between them in the WMN as shown in Figure 2.

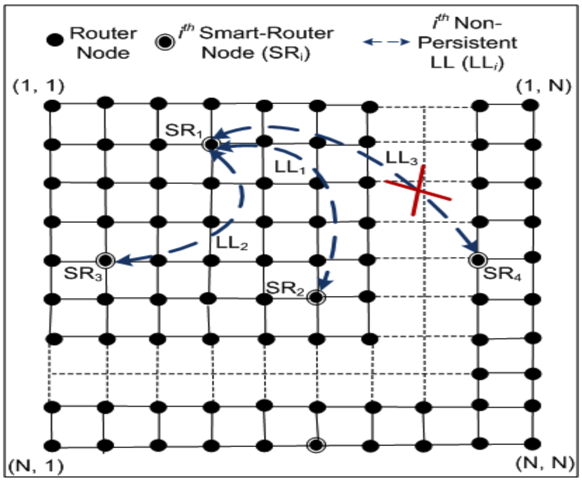

Fig. 2: Non-persistent LL Creation by Smart-Routers in WMN.

Figure 2 explains the NPLL creation strategy mentioned in part(A) of Algorithm 1. In the figure, SR_1 can make LLs either with SR_2 (LL_1 in Figure 2) or with SR_3 (LL_2 in Figure 2) for a stipulated time interval, as the EHDs among SR_1-SR_2 and SR_1-SR_3 are satisfying the cut-off value (i.e., 5 $\leq$ EHD $\leq$ 10). However, LL_3 between SR_1 and SR_4 is not created in the WMN (Figure 2) as the EHD is not satisfying the cut-off value.

In the context of NPLL creation, among the SR nodes in the square grid WMN, if multiple NPLLs are partially overlapped or assigned in the same orientation it may result in interference. In such interference scenarios, the interfering NPLLs share the NPLL bandwidth. For example, if two NPLLs are superimposed in the network, then the allotted spectrum for each of the overlapped NPLLs will be halved. While running part(B) of Algorithm 1, the bandwidth sharing is implemented keeping NPLL overlapping into consideration in order to make end-to-end load-balanced path in the network.

LLs are used for data session between SN and DN. An LL is used for data session till it reaches the maximum bearable load and after which it is disabled for data transmission between SN and DN. Further, greedy algorithm searches for another path for data transmission. Beam steering of the SRs to other reachable SRs are based on traffic demand and a scheduling strategy, description of which is out of the scope of this paper.

Since SRs are typically expensive, we implement LNPR algorithm in which LLs with more edge-weight are used rarely. Here, the edge-weight of a LL in SW-WMN is the ratio of APL of the network with and without the deployment of that LL as depicted in lines 31-33 in Algorithm 1. Therefore, an NPLL which results in a lower APL for the WMN, is assigned higher edge-weight in the network. The determination of edge-weight is shown in lines 31-33 in Algorithm 1. Moreover, we implement load-balancing to better distribute the traffic load throughout the network, which is depicted in Figure 3.

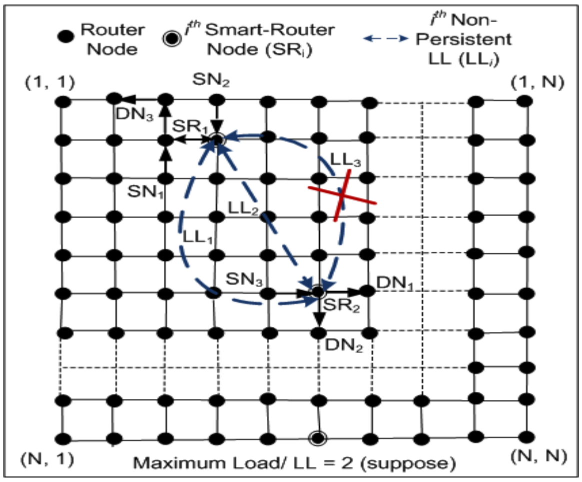

Fig. 3: Load Balancing Strategy for Non-persistent LLs in SW-WMN.

In Figure 3, the LL(LL_1) between SR_1 and SR_2 is used to make a data transmission path between SN_1 and DN_1. Therefore, the LL is used once to make a path in the SW-WMN. Now, for data transmission between SN_2 and DN_2, same LL(LL_2) is used second time and hence it reaches maximum load (considered as 2 here) bearable by any LL in network. However, during the data transmission from SN_3 to the DN_3, the nearest LL that can be used is situated between SR_2 and SR_1 (LL_3) as shown in Figure 3, which has already reached its maximum limit of data transfer (in Figure 3, we assume maximum load for each NPLL is two). Therefore, this LL cannot be used to deliver the data from SN_3 to the DN_3 with minimum EHD.

IV. Performance Results

We study the performance of our load-balanced routing algorithm LNPR, in the context of SW-WMNs. We create the simulation environment with MATLAB based simulation tool. The grid-network contains 100 mesh router-nodes positioned in a 10×10 square-grid topology. SR nodes are deployed randomly in the network (5% of the total number of nodes in the WMN) to create NPLLs. SNs and DNs pairs are randomly chosen from the grid WMN. We implement LNPR algorithm described in Section III for performance evaluation of the algorithm. The simulation is run for five set of values starting from ten SN-DN pairs to fifty SN-DN pairs. The values obtained from above, determine the impact of SF, CBP, maximum load handled by each NPLL and average transmission path length (ATPL) of the network. The simulation results are evaluated from the average of ten seed values and the standard deviation of observed values are shown as error bars in the result figures in this section.

A. Impact of Scaling Factor

To distribute the traffic-load better among NLs and NPLLs in the SW-WMN, we assign edge-weight with SF to each NPLL based on its impact (i.e., the influence of that particular NPLL in reducing overall APL of the network) on the square-grid network as can be seen on line 33 of Algorithm 1. Figure 4 shows the variation of CBP, the standard deviation (SD) of load in each possible NPLL, and ATPL of the network after implementing LNPR with various SF values (the simulation is run for SF = 1 to SF = 5 with 30 SN-DN pairs) in the SW-WMN. Each result is averaged over 10 runs.

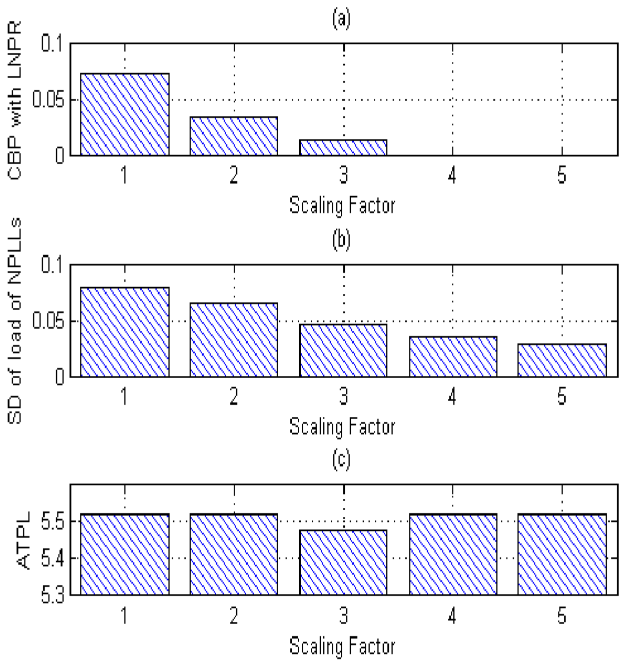

Fig. 4: Variation of Call-blocking Probability (CBP), Standard deviation (SD) of Load, and average transmission path length (ATPL) with LNPR for SF = 1 to SF = 5 (Number of SN-DN pairs = 30).

From Figure 4(a), we see that at SF = 3, CBP attains the lowest non-zero value as compared to SF = 1 for data transmission of 30 set of SN-DN pairs in the SW-WMNs. From Figure 4(b) it is noticed that the standard deviation of the load in NPLLs is the maximum for SF = 1. However, as the scaling factor is increased, the standard deviation of the load becomes smaller in the network. From Figure 4(c), we observed that ATPL value is the lowest at SF = 3. Hence, at SF = 3, the performance of LNPR algorithm is better as compared to the value of SF = 1 (for non-zero CBP) in the grid topology SW-WMNs.

B. Call-blocking Probability (CBP)

Call-blocking probability (CBP) is a metric which determines the probability of blocked call averaged over a data transmission session in the network. We evaluate r as the end-to-end shortest path from SN to DN in Algorithm 1, and if NLs exceed weighted $MaxLoad_{NL}$ or NPLLs exceed weighted

$MaxLoad_{NPLL}$ after m number of attempts, we conclude that call is dropped in the SW-WMN (Algorithm 1). Hence, CBP is calculated as the ratio of total blocked calls to the total number of call for data transfer session in the SW-WMNs. Figure 5 shows that reduction in CBP with LNPR as compared to CBP without LNPR for different sets of SN-DN pair ranges from 10% (50 SN-DN pairs) to 50% (10 SN-DN pairs) where with SF = 1 in the context of SW-WMN. The improvement in CBP is due to the better load balancing achieved by LNPR on NPLLs.

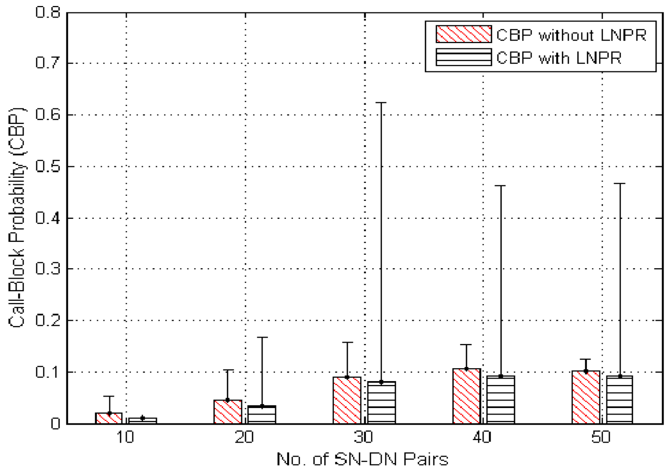

Fig. 5: Call Block Probability (SF = 1).

Figure 6 shows the result of CBP for SF = 3. It is observed from the figure that CBP with LNPR improves the call acceptance rates ranging from 58% (50 SN-DN pairs) to 95% (30 SN-DN pairs) as compared to CBP without LNPR.

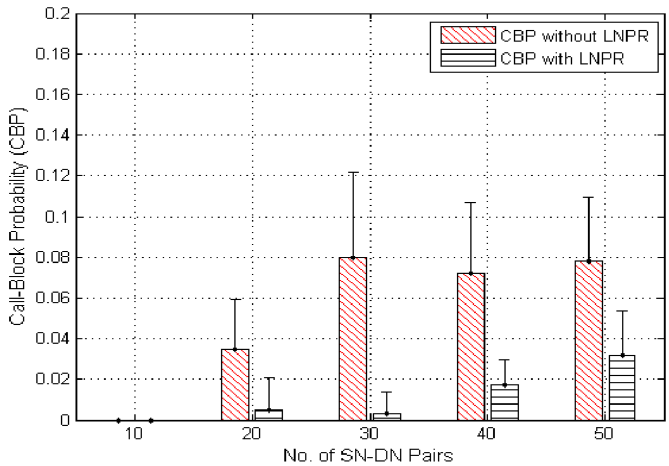

Fig. 6: Call Block Probability (SF = 3).

C. Load Balancing Observations

Figure 7 shows the maximum load on each NPLL with and without LNPR in the context of SW-WMN with SF = 1. We observe that for 10 SN-DN pairs, LNPR helps to reduce the maximum load by 8% whereas for 50 SN-DN pairs, maximum load is 63% lower. The improvement indicates that with increasing load, the impact of LNPR is high. Figure 8 depicts the variation of the maximum load with and without LNPR with SF = 3 as it is the optimum value of scaling factor. We observe that maximum load is same for NPLLs with and without LNPR, whereas when the SN-DN pairs increase from 20 to 50, decrement of the maximum load with LNPR for different sets of SN-DN pair ranges from 23% (20 SN-DN pairs) to 70% (50 SN-DN pairs) as compared to maximum load without LNPR in the SW-WMN. With SF = 3, it can be seen that the maximum load for LNPR is much lower than without LNPR.

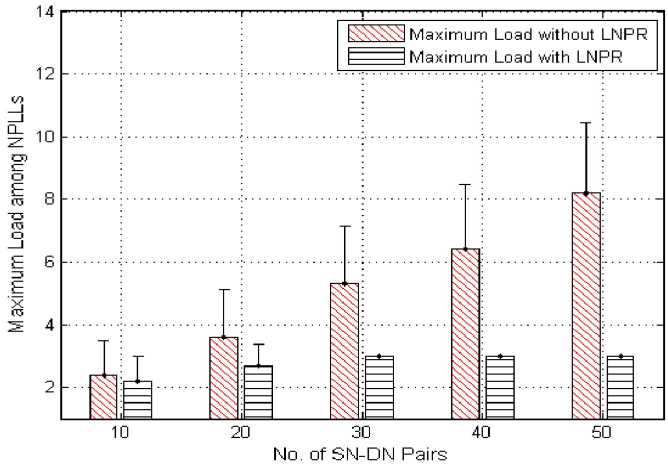

Fig. 7: Maximum Load of NPLLs with and without LNPR (SF = 1).

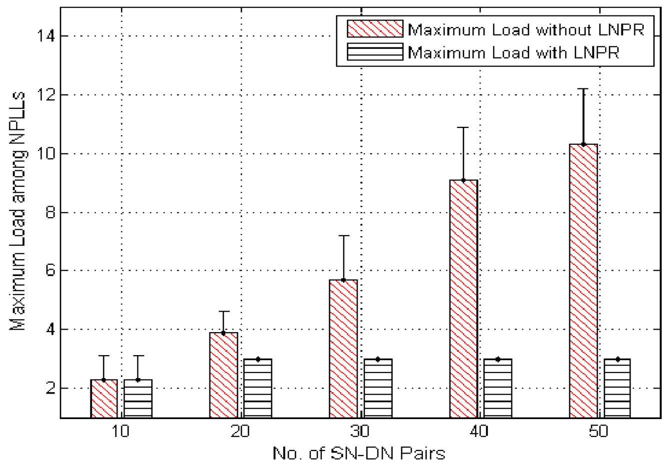

Fig. 8: Maximum Load of NPLLs with and without LNPR (SF = 3).

D. Average Transmission Path Length (ATPL) Observations

ATPL is the EHD between SN and DN averaged over a set of data transmission sessions for a stipulated time in the WMN. ATPL gives a measure of reduced path length with the help of non-persistent LLs in the SW-WMN. ATPL gives the measure of transmission path length for a set of data sessions whereas APL is defined as average path length of the whole network. Figure 9 shows the ATPL observations for various cases.

Figure 9 shows the ATPL values with NLs (Normal ATPL), small-world ATPL without LNPR (SW-ATPL without LNPR),

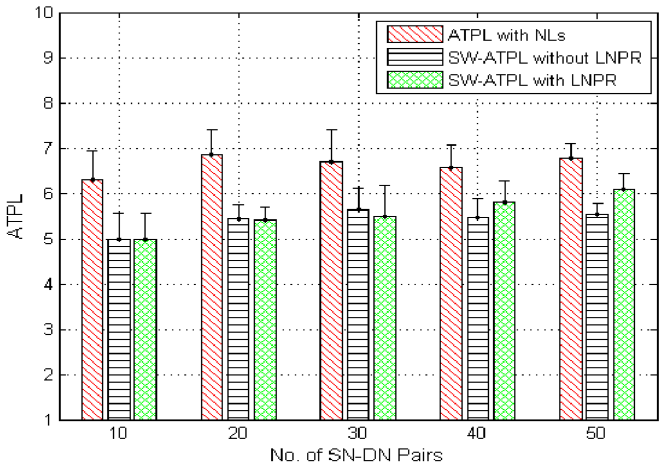

Fig. 9: ATPL with NLs, SW-ATPL without LNPR, and SW-ATPL with LNPR.

and small-world ATPL with LNPR algorithm (SW-ATPL with LNPR) for 10 SN-DN pairs to 50 SN-DN pairs of data transmission. From the figure, it is clear that after implementing NPLLs in the network, ATPL is decreased significantly compared to Normal ATPL. From Figure 9, to determine ATPL with NPLLs with different sets of SN-DN pairs, reduction achieved in ATPL is from 15% (30 SN-DN pairs) to 20% (10 SN-DN pairs) with respect to ATPL with only NLs in the network. However, when we implement LNPR algorithm, we observe that the value of ATPL is slightly increased. From Figure 9, it is observed that the set of SN-DN pairs increase from 10 to 50, only a small increment from 0.7% (20 SN-DN pairs) to 9% (50 SN-DN pairs) is observed in the ATPL value for our proposed LNPR algorithm compared to SW-WMN with NPLLs.

Therefore, the application of LNPR algorithm results in substantial distribution of the traffic-load which reflects in the maximum load distribution among the NPLLs and the minimization of the network call block probability. All the simulation results show overall performance enhancement in the context of grid-topology based SW-WMNs.

V. Conclusion

In this paper we proposed Load-aware Non-persistent small-world LL Routing (LNPR) algorithm in the context of SW-WMN which can be deployed to provide end-to-end connectivity in rural and community networks. LNPR search for the shortest paths among SN-DN pairs in the network by implementing a load-balanced greedy route finding approach. The efficiency of the LNPR algorithm has been measured with respect to different metrics, such as, (i) Impact of scaling factor (ii) Call Blocking Probability (iii) maximum traffic-load NPLLs, and (iv) ATPL observations. We observed that for each metric, performance enhancement has been achieved. Our results indicate that LNPR provides 58%- 95% improvement in call blocking probability and 23%- 70% in maximum load reduction with only 0.7%- 9% increase in ATPL.

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