

Modeling Wireless Mesh Networks for Load Management

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Abstract—Developing a simulation model for multi-hop multi-gateway wireless mesh networks (WMNs) is a challenging task. In this paper, a multi-hop multi-gateway WMN simulation model is developed in a step-by-step approach. This paper presents a MATLAB Simulink-based simulation model of Wireless Mesh Network (WMN) designed for easy optimization of layer 2. The proposed model is of special utility for the simulation of scheduling of GateWay (GW) and packet within a multi-hop multi gateway wireless network. The simulation model provides the flexibility of controlling the flow of packets through the networks. Load management among the GWs of WMN is performed in a distributed manner wherein the nodes based on their local knowledge of neighborhood beacons optimize their path to a GW. This paper presents a centralized Load Management Scheme (LMS). The LMS is based on the formation of Gateway Service Sets (GSS). The GSS is formed on basis of equal load distribution among the GWs. The proposed LMS is then analyzed for throughput improvement by leveraging the MATLAB Simulink model developed in the paper. A throughput improvement of almost 600% and a 40% reduction in packet loss was observed through simulations thus indicating the efficacy of the proposed LMS. The uniqueness of the simulation model presented in this paper are its scalability and flexibility in terms of network topology parameters.

Keywords—MATLAB; Simulink; multi-hop; wireless mesh network (WMN); gateway; simulation model; load management

I. INTRODUCTION

Nearly always good research methodology is supposed to culminate with performance analysis and simulation study. Research in wireless networks carries no exception. In this paper, a system model is presented to simulate the WMNs. The model is designed in a manner such that it supports the flexibility to increase or decrease the number of GateWays (GWs) within the mesh as well as supports the increase and decrease in the number of hops for a particular router. This results in providing a very simple lightweight model for the optimization of layer 2. This model can be applied easily for GW scheduling in a very quick and efficient manner.

Designing a multi-hop multi gateway WMN model is a tough challenge. In such a mesh network there are multiple parameters to be handled. A very popular example is the IEEE 802.11s mesh architecture [1]. Another example is the Zigbee mesh architecture [2]. In a mesh architecture, the model has to be developed in such a way that the simulations can be performed on a wide variety of scenarios. Specifically, the model should be able to generate scenarios wherein the number of gateways can be varied. At the same time, the model should also have the capability to increase/decrease the number of

Mesh Routers (MRs). The model should also be able to depict the three-level hierarchy of a WMN as presented in Fig. 1 and Fig. 2 of this paper. In this paper, a WMN model is developed which comprises all the aforesaid properties efficiently. Such a model can be used by researchers to apply their solutions easily. The contribution of this paper is to provide a platform and insight which can be used by the scientific community to build their WMN models in a better and more efficient manner using Simulink.

In this paper, a load management technique is applied to reduce congestion in GWs of WMN. In multi-GW WMNs, there is no mechanism available to schedule a fixed set of MRs to GWs. This causes either contention or congestion of GW [3,4]. In this paper, a GW scheduling technique is applied by creating a fixed Gateway Service Set (GSS). GSS is defined as assigning an equal number of MRs to each GW. This will result in avoidance of delay due to repeated computation of nearest GW by MRs. This will also reduce GW congestion by avoiding unfair allocation of MRs to GWs. Such an LMS is then used to analyze the performance of load sharing in various scenarios of WMN. The pertinent point is that the simulations to analyze the proposed LMS could be performed with ease due to the flexibility provided by the proposed simulation model.

II. LITERATURE REVIEW

Most of the research about WMNs generally opts for the ns2 [5] simulator which is an unlicensed open-source simulator. Among the licensed simulators, the top choices are Qualnet and Simulink [9]. Simulations are of two types – Discrete events and continuous ones. Discrete event simulations are suitable for models where parameters do not change until the occurrence of some event. Continuous event simulations are suitable for models where parameters change continuously and do not require the occurrence of any event for the occurrence of change [6]. In [7], the authors have defined and compared different types of simulation models based on event and time. A characteristic feature of a good model is its scalability. The model of WMN should allow flexibility in changing the network topology quickly and easily. An analysis of different types of network simulators is presented in [8].

The model of a WMN comprises three types of nodes – GWs, MRs, and End Nodes/client nodes. GWs provide Internet access to MRs and end nodes. There can be multiple GWs that connect the network to the Internet. The difference between MRs and End nodes is that MRs can redirect traffic to GWs, whereas End nodes just connect to the nearest available MR. Unlike MRs, the End nodes cannot connect to a far-off node

that is out of communication range of a GW. Most of the WMNs follow the generic architecture recommended by the IEEE 802.11s standard [1].

An abundance of literature is available on wireless network simulations using Simulink [9,10,19]. But in most of these papers, the researchers are unable to consider multi-hop multi-gateway WMNs such that the number of GWs is more than 5 and the number of routers more than 20. In [9], the authors have simulated multi-gateway mesh networks. Although the authors of [9] analyze multi-GW association in WMNs, the simulation model comprised only two GWs and 14 MRs. The authors in [10] have simulated WMN with 100 MRs but have not considered more than one GW. This limits their analysis to WMNs with only a single GW. In [11], the authors have used the ns2 simulator to simulate a network with 50 nodes but with only a single GW. The authors in [12] have considered WMN with up to 5 GWs and 50 MRs. But the topology of WMN has not been modified throughout the simulation process.

In this paper, a step-by-step process is presented to develop a WMN on Simulink. Thereafter, the model is used to analyze the performance of the WMN when there is an increase in the number of GWs and MRs systematically. In the process, there is an attempt to achieve a balanced approach for ensuring a fair allocation of MRs among multiple GWs. Therefore, to each GW an equal number of MRs is assigned. The uniqueness of the model presented in this paper is that it is scalable and flexible in terms of network topology parameters. In this model, very easily the number of MRs can be increased and decreased. The same applies to GWs wherein the number of GWs can be increased and decreased with ease.

Finally, this model is applied to analyze a fair GW scheduling technique. This paper proposes to allocate a fixed set of MRs to a GW thus forming a GSS. The GWs are deployed such that each GW receives an equal number of MRs which is in its wireless coverage area. These MRs assigned to a GW might be directly within its communication range or through another MR as mesh topology [1]. This will result in the mitigation of delay in the computation of the path to a GW. Since most of the traffic is to or from the Internet, GWs become a major source of traffic within WMN. This results in congestion of the wireless links to GWs and congestion due to queuing delays in GWs. This occurs since some GWs might have a larger number of MRs associated with them compared to some other GWs in WMN, which might be idle due to no traffic through them. In [13], the authors have identified that the available capacity of a GW reduces by $O(1/n)$ where n is the number of users. The presence of many users results in GW bottleneck and was termed as a 'bottleneck collision domain' in [13]. In [14,16] the authors have attempted mitigation of GW bottleneck with a proposal of performing cooperative caching among the MRs to avoid packet loss. Most of the load balancing techniques focuses on route optimizations. Since most of the time routes are formed on basis of the information about the neighborhood of a node, these are not very optimal techniques. It is also observed by [15] that such techniques consume network resources and bandwidth due to repeated attempts for route requests and route response packets. A very recent paper in this direction is by [17]. In this paper, the authors have attempted to balance load by optimizing the

Adhoc On-Demand Distance Vector (AODV) Routing Protocol. AODV is a very popular routing protocol in WMNs. This is because most of the optimization techniques in WMN are derived from the adaptations of MANET technologies. In the case of MANETS, assigning a fixed service set to GW is not possible due to peer-to-peer routing. But in the case of WMNs, especially IEEE802.11s WMNs, such an assignment is possible because WMNs are a hybrid of fixed and mobile infrastructure. Therefore, this paper proposes a mechanism in which each GW can be assigned its own GSS thereby reducing the network traffic for route determination. This technique also results in a fast and efficient delivery mechanism because the MRs do not have to keep computing the shortest path to a GW when there are multiple GWs in the vicinity. In [18] the authors have performed a detailed survey and have concluded that the WMNs are here to stay for a long time. In [18] the authors also note that the WMN model should become more and more flexible in a manner that allows for the nodes to move from one gateway to another seamlessly. This paper attempts to provide such flexibility while performing the load sharing among gateways through a fair assignment of MRs to GWs.

III. NETWORK ARCHITECTURE OF WMN

Fig. 1 presents a conventional WMN with three levels of nodes. For more details on WMN and its architecture one may refer to [19] in which authors have explained in detail different types of WMNs based on various IEEE standards. At the first level is the GW node which connects to the Internet. In IEEE802.11s standard [1], it is called the Mesh Portal Point (MPP). But in this paper, a more generic term called the GW node is used. The GW node is connected to many routers which are called the Mesh Points (MPs) in IEEE 802.11s. But to keep the term generic, it is called the Mesh Router (MR). Finally, the end nodes are the client devices, for example, a laptop, smartphone, or a sensor. These are called the Mesh Clients in IEEE 802.11s. In this paper, they are referred to as End nodes.

The WMN architecture in Fig. 1 is extended further to a real-world scenario in Fig. 2. The difference between Fig. 1 and Fig. 2 is that in Fig. 1 none of the GWs have a fixed Gateway Service Set (GSS) whereas in Fig. 2 each GW has been assigned a fixed number of MRs.

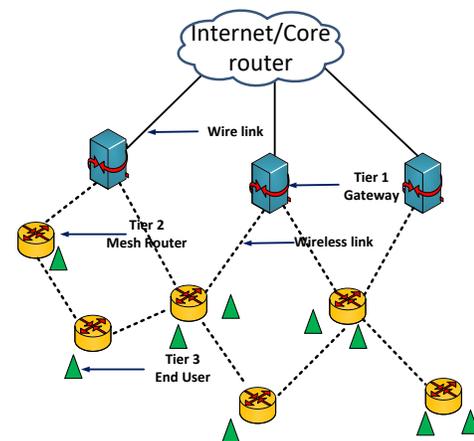


Fig. 1. Three Tier WMN Architecture.

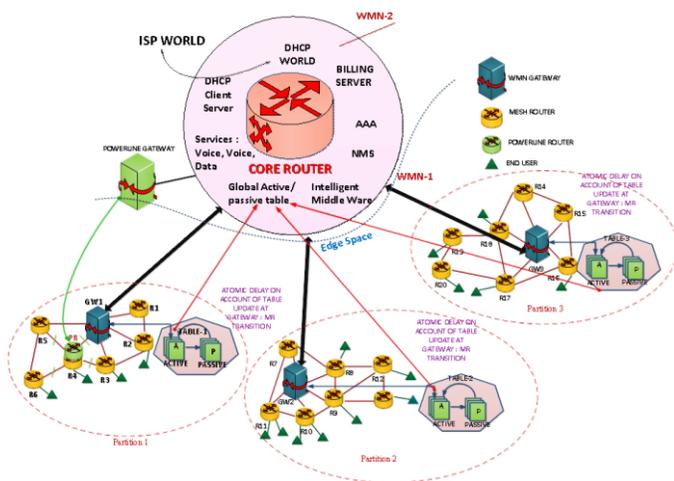


Fig. 2. Schematic of a Real-World WMN Scenario.

In Fig. 2, the MRs and the GWs are connected through wireless links and there are wired connections between the GWs and the core router. Each GW locally maintains an Active Passive Routing (APR) table which is explained later in this section. It is important to note that there might be many WMNs connected and served by the same Internet Service Provider (ISP). To illustrate this, there are two labels indicating WMN-1 and WMN-2 in Fig. 2. Both the WMNs are shown connected to the same ISP and core router. Fig. 2 depicts a dashed line that separates the ISP space and the edge space. The edge space marks the beginning of the WMN space or the Local Area Network (LAN) space.

The next section presents how this model can be used to implement fair scheduling of GWs within a WMN. The proposed scheduling of GWs through the judicious management of the routing table is called Load Management Scheme (LMS). The usage of the term LMS is justified because the scheduling of GWs aims at the reduction of processing load on GWs. A particular GW can hand off its extra load to a neighboring GW by simply changing the MR entry from active to passive, in its routing table. At the same time, the GW receiving the load will change the entry of the MR from passive to active. Therefore, by managing and changing the routing table, a fair allocation of GW to MRs can be maintained.

IV. COMPONENTS OF WMN

The core router is a router that connects the edge network to the Internet. The major functionality of the core router is to streamline the Internet traffic as per the bandwidth demand without a loss in performance [16]. In this paper, the core router is entrusted with the main functionality of meeting the bandwidth demand at the edge routers (GWs in this case). Fig. 2 depicts the Core Router sub-block. The major components of a core router are Internet Service Provider (ISP), Core Router, Authentication, Authorization, and Accounting (AAA) server, Billing server, Network Management System (NMS) Server, Voice, and Video data services, DHCP Server, Global Active/Passive Routing (APR) Table and Intelligent Middle Ware (IMW).

Although the APR Table and IMW may not be a part of the core router in conventional WMN, the proposed LMS requires this additional software to be installed at the core router. The IMW and its components are discussed in more detail in a later section. The components of Edge Space define the components of WMN and are described next.

A. GW

This is the connection point to provide Internet connectivity through the Core router. The GW is connected to the core router through a wired medium or high bandwidth.

B. MRs

The GW is associated with a set of MRs labeled from R_1 to R_6 . Each MR has a wireless connection to either another MR or the GW. An MR is connected to another MR or GW if they are within transmission range of each other. If an MR is not in the transmission range of the GW, it can still reach the GW through multiple hops by using another MR which is within the transmission range of GW. An MR is not allowed to send a packet to GWs other than its associated GW even if there are other GWs that are in its transmission range. The MR-GW association is decided through the APR table depicted alongside each GW in Fig. 2.

C. Local APR Table

This is the most important data structure of the proposed LMS residing at the GW. This table facilitates mapping the GSSs of WMN. Each GW has two main columns in its APR table namely, the active column and the passive column. The active column contains the list of all those MRs that are associated with the GW whereas the passive column keeps the list of all those MRs that are in the transmission range of the GW but are not associated with it. While configuring the WMN, the GW routing table is configured such that the GSSs obtained from the Greedy Graph Partitioning Algorithm (GGPA) are mapped onto the routing table of each GW. This means all those MRs that belong to a GSS are made active in the routing table of GW.

Table I is the routing table of the GW belonging to GSS 1 depicted as partition 1 in Fig. 2. In Table I, the active column contains MRs labeled $R_1, R_2, R_3, R_4, R_5,$ and R_6 . The MRs labeled R_7 and R_{11} are associated with GW_2 as shown in Fig. 2. But because they are within the transmission range of GW_1, R_7 and R_{11} are listed under the passive column of Table I.

TABLE I. APR TABLE FOR GSS 1 (PARTITION 1 IN FIG. 2)

Active	Passive
R_1	R_7
R_2	R_{11}
R_3	
R_4	
R_5	
R_6	

When a GW gets overloaded, some MRs must be offloaded to a neighbor GW. This process becomes remarkably simple with the proposed APR table of the GW. If GW2 becomes overloaded, then it can offload MRs labeled R7 and R11 to GW1 by changing the APR table entry of GW1 and GW2.

TABLE II. APR TABLE OF GW OF GSS1 AFTER RECEIVING MRs FROM GSS 2 FOR LOAD SHARING

Active	Passive
R ₁	
R ₂	
R ₃	
R ₄	
R ₅	
R ₆	
R ₇	
R ₁₁	

Initially, the APR table of GW1 appears like Table I and after offloading of MRs labeled R7 and R11 to GW1, the modified APR of GW2 is depicted in Table II. Interestingly, the transition process at the core router involves only updating the entry of the APR table of receiving and sending GWs.

D. The Intelligent Middle Ware

The core router shown in Fig. 2 executes an IMW explained in this section. The IMW residing on the Core router of Fig. 2 has two modules namely load monitoring and load sharing. The load monitoring module periodically estimates the load demand of each GW. Based on this estimation, the module decides whether the load on GW is excess or not. The basis of this calculation is based on comparing load demand to the capacity of GW. A discussion on computing the capacity of GW is presented in [16,20]. If the load demand exceeds the capacity of GW, then a particular GW is overloaded. Demand at each GW is computed by the load monitoring module by recording the number of MRs connected through the GW and the applications that they are executing.

The load sharing module has two components to support load sharing with neighboring GWs. Load sharing with wireless GWs is invoked when the load monitoring module raises an overload alert. The load sharing module checks the stability condition (whether any neighboring GW is having less load and is willing to receive MRs from the overloaded GW). If the stability condition is satisfied, then from an overloaded GW, an MR with a high bandwidth demand is shifted to a neighboring GW with a nominal load. Accordingly, the APR tables are updated.

V. SIMULATION MODEL OF THE PROPOSED LMS OF WMN

Since this research is focused on routing optimization for load balancing, this study requires simulation to be built around the multi-hop routing mechanism of mesh. In this paper, the Simulink blocks are developed to suit the requirement of IEEE 802.11s MAC which is the main module of interest to this paper. To develop this model, the network architecture evolved in the previous section is used. The

coming sections explore this process and after the explanation of the individual blocks, the complete integrated model is presented. Fig. 3 represents the sub-blocks required for the implementation of the proposed LMS. The simulation model has the following four major modules namely Packet Generator, Core router, MR Mobility, and MPP GW.



Fig. 3. Simulation Models of Sub Blocks for LMS.

These blocks follow the network architecture depicted in Fig. 2. It can be recalled that in the network architecture of Fig. 2, the core router routes packets to the respective GWs. Thereafter the GWs forward the packets to the destined MR through multiple hops. Finally, the destined MR forwards the packet to the client/customer device. The simulation model uses a packet generator to generate traffic and this traffic constitutes the input to the core router. Each packet has a destined MR identified by an IP address. The core router module maintains a global APR table for each of the GWs of WMN.

The MR-mobility module simulates the transition of MRs from one GW to another. Since the MR transition effect percolates to the core router, this block is kept located between the GW and the core router block in the hierarchy. For this, the MR mobility block receives signals from the GW about the completion of the transition. It must then send a signal to the core router to resume packet flow from the packet generators, in case the MR transition is complete. The core router in turn issues a signal to the packet generator to resume packet generation.

The MPP GW module defines the operations of GW. The GW model also has a sub-model that simulates the end-user/customer device which operates on the normal IEEE 802.11x [21] standard. This simulation also comprises the client hand-off/handover process between two MRs. A detailed discussion of the layout of each block is presented in the coming sub-sections. The block layout is followed by a screenshot of the actual Simulink model used in the simulation. More details on the process of designing the Simulink block are presented in [22].

A. Packet Generator Module

A packet generator is modeled as a random packet generator that generates packets with labels for specific GWs. The packet generator has five major blocks as depicted in Fig. 4, namely, Set Attribute, Free running counter, Time based entity generator, Repeating Sequence Stair, and FIFO Queue.

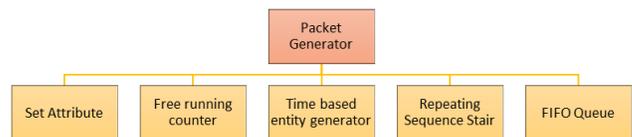


Fig. 4. Block Hierarchy of the Packet Generator Model.

Set attribute block gets packet generated. The free-running counter block is for data generation. Repeating sequence block is to define the length of the data block. Time-based entity generator defines the rate at which packets are generated. Finally, packets are delivered to the core router through the FIFO queue. A screenshot of the final packet generator Simulink block comprising these sub-blocks is shown in Fig. 5. The output of the packet generator is fed to the core router. This module is explained in the next subsection.

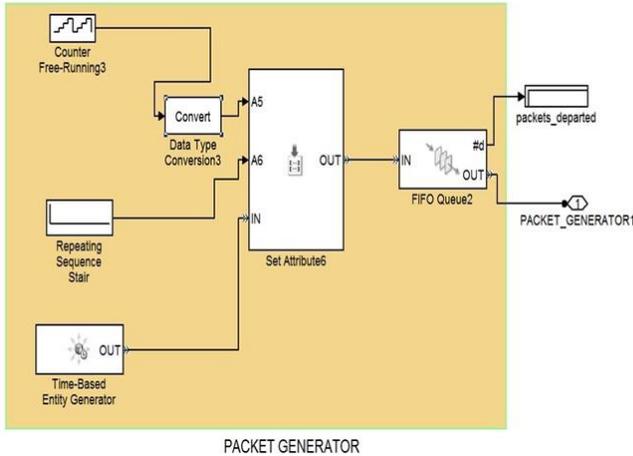


Fig. 5. Simulink Model of Packet Generator.

B. Core Router Module

The function of a core router is to route the packet coming from the packet generator to respective GWs. From its global APR table, the IMW checks for the destination MR and the GW associated with the destination MR. Then the packet is routed to the associated GW of destination MR. The core router has six major blocks as depicted in Fig. 6.

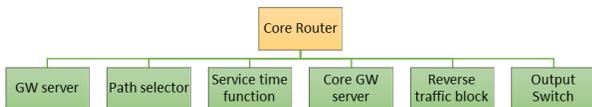


Fig. 6. Hierarchy of the Core Router Block.

- 1) *GW server* receives packets from respective ‘packet generators’ which are to be fed to ‘path selector’.
- 2) A *reverse traffic block* is used to model traffic from GWs and MRs to the core router.
- 3) *Path selector* sorts all the GW packets along with power line packets and reverses traffic packets.
- 4) *The service time function* computes the time taken for path selection (routing) to respective GWs. The referred service time is computed by dividing the length of the packet by the capacity of the core router. For example, if the length of the packet is 512 bits and the capacity of the core router is assumed to be 100 Mbps, then the service time for each packet is 512 ns.
- 5) *Core GW server* serves each packet in-service time defined by the service time function. The health of the core router is monitored in the “core GW server” by analyzing

Channel Utilization, Average delay, Number of packets departed, Number of packets dropped, Average wait time, and packet delay.

6) *Output switch* sends packets to their destined GWs: The functionality of the Core router block along with these components is depicted through a Simulink model shown in Fig. 7.

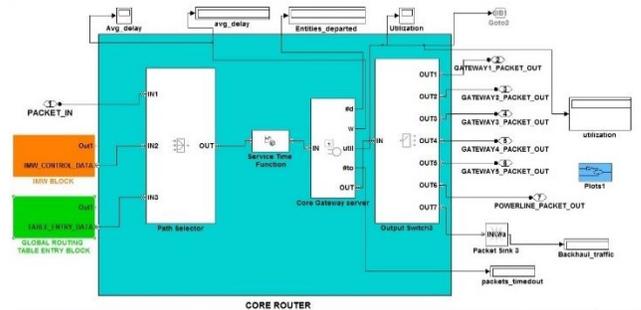


Fig. 7. Simulink Model of Core Router.

C. MR-Mobility Module

MR Mobility module simulates the MR hand-off and hand-over from one MR to another MR just like client mobility in an IEEE 802.11x network. When an MC moves out of an MR access area, the MR hands over the MC traffic to the MR which is accessible to the MC. This delay is added to the total packet response time. A Simulink model of MR mobility is shown in Fig. 8. It can be observed that the MR mobility module has two major blocks.

- MR delay model.
- GW Channel model.

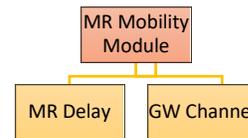


Fig. 8. Functional Blocks of MR Mobility Model.

1) *MR delay model*: The MR delay block simulates delay due to the transfer of MR from one GW table to another. This is an atomic process involving a delay in updating the global APR table at the core router and the local APR tables at the sending and receiving GW involved in MR transition. This block consists of a packet generator sub-block as shown in Fig. 9.

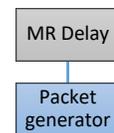


Fig. 9. Sub-blocks of the MR Delay Block.

The packet generator block induces reverse traffic from the GW towards the core router. In this paper, the word ‘traffic’ indicates the traffic from the Internet (packet generator) to the MRs whereas ‘reverse traffic’ is defined as packets from the

MR towards the Internet. This reverse packet, when generated by the packet generator module of the MR delay block, indicates invoking of load sharing. When the reverse traffic packet reaches the main packet generator module through the core router, it blocks the packet generator till the time the MR transition takes place (delay in updating the local and global APR table). Once the MR transition is over, another reverse packet is generated from the MR delay block towards the core router and the packet generator resumes the forward traffic. Fig. 10 depicts the MR delay block comprising the packet generator sub-block.

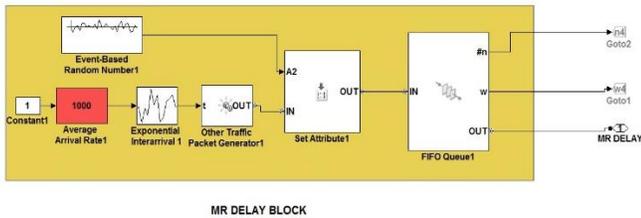


Fig. 10. Simulink Model of MR Delay Block of MR Mobility Module.

The packets generated by the MR delay block are forwarded to the ‘GW Channel Model’, explained in the next section, which incurs channel processing delay.

2) *GW channel model of the MR mobility block*: The GW Channel block of the MR mobility module models the channel between the GW and Core router. The sub-blocks of the channel model are depicted in Fig. 11.

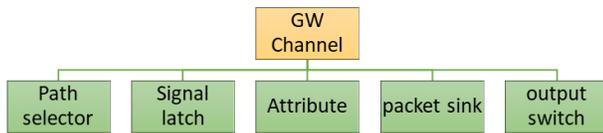


Fig. 11. Sub Blocks Comprising the Channel Model Block.

a) *Path selector*: This module is used to receive packets from the core router (in case of forwarding traffic) and MR delay block (in case of reverse traffic).

b) *Signal latch*: Path selector uses ‘Probabilistic signal latch model’ to select packets.

c) *Attribute*: The service time in processing packets in a single server is calculated by the ‘Attribute Function’ block.

d) *Packet sink*: The data packets are routed to the respective GW or core router in case of backward traffic using the ‘Packet sink’ block.

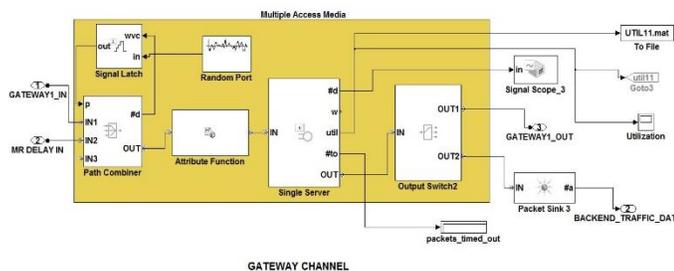


Fig. 12. Simulink Model of GW Channel Block of the MR Mobility Module.

e) *Output switch*: The packets are sorted by ‘Output switch’ which checks the packet header and routes the packets to the respective destination GW or routes the packet back to the core router if it is a backward packet requesting a traffic block. Fig. 12 depicts the final Simulink block of the channel model representing all the above-listed sub-blocks.

3) *The final MR mobility Simulink block*: The final MR mobility Simulink block comprising its major sub-blocks the MR delay block of Fig. 10 and channel model of Fig. 12 is shown in Fig. 13.

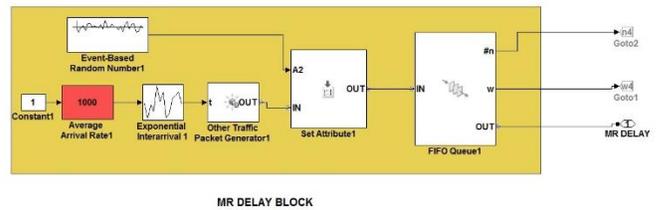


Fig. 13. Simulink Model of MR Mobility Module.

D. GW Module

The GW module segregates and routes the packet destined to a particular MR. The structure of the GW module is depicted in Fig. 14.

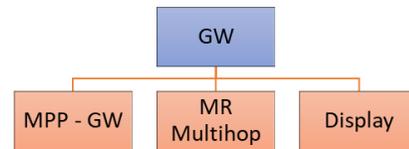


Fig. 14. Hierarchy of the GW Model.

As depicted in Fig. 14, the GW Model has two major blocks:

- MPP GW
- MR Multi-Hop (Multi-Hop of MR)

1) *MPP-GW sub block of the GW*: MPP-GW model further comprises the sub-blocks shown in Fig. 15.

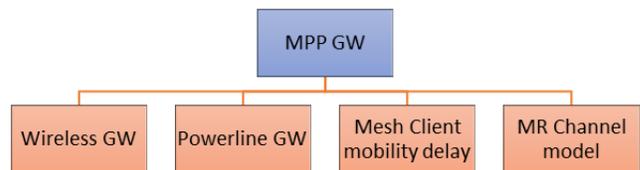


Fig. 15. Sub Blocks of the MPP-GW Block.

This block has four major sub-blocks:

a) *Wireless GW*: This model has a ‘set attribute’ block that receives packets from the core router and forwards them at a pre-defined data rate (bandwidth) to the channel model through the ‘FIFO queue’ block.

b) *Power Line GW*: The power line GW gets the packets directly from the core router. It uses the same ‘set attribute’ block to define the data rate. The ‘FIFO queue’

block gets input about the MRs chosen to transit to the power line. This block is attached to the core router and it routes the traffic from the core to the MRs specifically attached to the power line. The MRs attached to the power line GW can be identified using the global APR table at the core router.

c) *Mesh Client Mobility delay*: This block has two parts. One part simulates the end-user device, and the other part simulates the mobility of the client. The end-user device acts as either a source or a sink for the traffic flow. Therefore, the end-user device is modeled as having two parts- the packet generator part which is the source, and the sink which consumes the packets which are received through its connected MR. The mobility of the client is modeled by introducing a handoff-handover delay whenever the mobile client moves from one MR transmission range to another.

d) *MR Channel model*: This model simulates the channel between the GW and the MRs. The channel model is responsible to induce the client's mobility delay. This is the delay involved in hand-off and hand-over when an end-user moves from one MR to another MR. This is different from the MR mobility delay which involves delay incurred during the transition of MRs for load sharing.

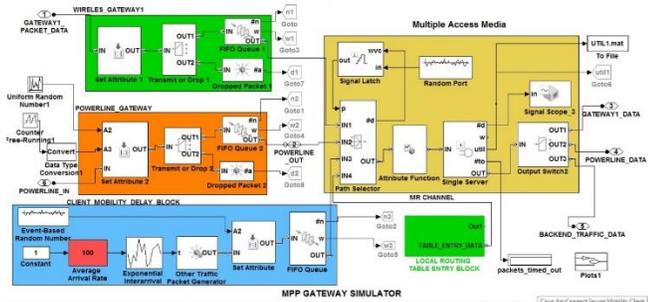


Fig. 16. MPP-GW Simulation Sub Block of the GW Simulator Block.

The sub-blocks listed in Fig. 15 are shown in the final Simulink block of the MPP-GW model block in Fig. 16.

2) *Multi-Hop MR of GW*: The ‘multi-hop MR’ sub-block receives packets from the MPP-GW block and records variation in-service time due to the increasing number of hops. This block consists of two sub-blocks as depicted in Fig. 17.

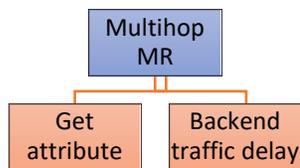


Fig. 17. Sub Blocks of the Multi-hop MR Block.

These blocks are:

a) *Get attribute*: It refers to MR where it receives service time from the respective GW. The service time of the packet will be almost doubled for every hop.

b) *Backend traffic delay*: This block simulates the processing delay incurred by the mesh management traffic. Although this traffic does not contain the actual data packets, mesh management packets are also important. The Simulink block of multi-hop MR simulation is shown in Fig. 18 which depicts the ‘get attribute’ and ‘delay’ sub-blocks listed in Fig. 17.

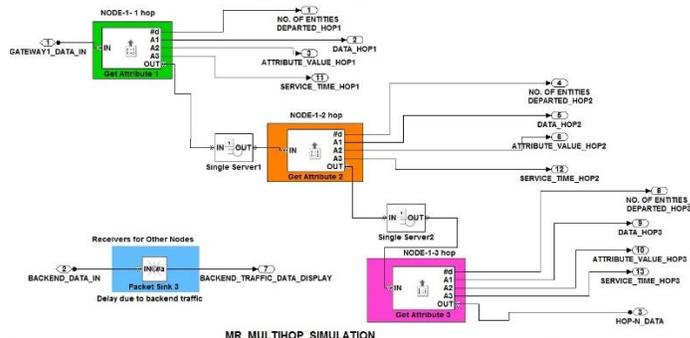


Fig. 18. Multi-hop Simulation Sub Block of the GW Simulation Block.

3) *Display block*: Since this is the final and the last block of the simulation model, it displays parameters such as ‘number of packets departed’, ‘Average waiting time’, and ‘service time’.

E. Final GW Simulation Block

Fig. 19 depicts the final GW simulation block comprising the MPP-GW and the MR multi-hop simulation blocks.

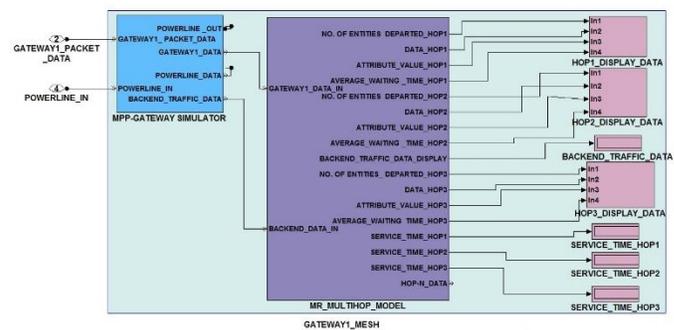


Fig. 19. GW Simulation Block.

F. System-Level Simulation Block

The system-level simulation model is shown in Fig. 20. This model depicts the packets generator module, the core router module, the MR mobility module, and finally the GW module. The process flow can be mapped onto the final simulation model in Fig. 20. This model will be used in the next section to derive various performance results and to investigate the various system parameters. The framework of this model follows the schematic architecture proposed in the network architecture diagram in Fig. 2. The next section presents the results obtained through the system-level simulation block of LMS shown in Fig. 20.

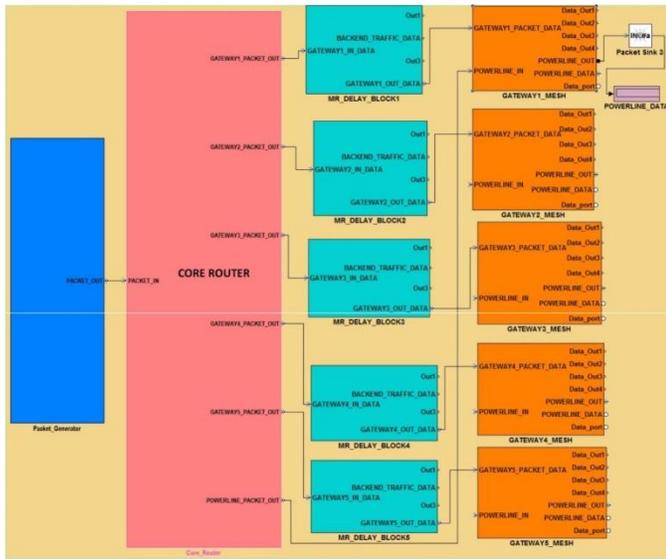


Fig. 20. System-Level Simulation Block of LMS.

VI. ASSUMPTIONS AND PARAMETERS FOR MATLAB MODEL

In the previous sections, a simulation model of the proposed LMS was developed using MATLAB, and Simulink blocks. This model is used to analyze the performance of the proposed LMS. Various test cases for performance analysis are created to compare the performance of the WMN with the proposed LMS and the conventional WMNs with no load management feature. Throughout the simulation process, the simulation parameters are chosen as per Table III.

The traffic flow is assumed to be Markov distributed. The core router is assumed to be connected through a high-speed wire link. Therefore, its capacity is 100 Mbps which is the usual capacity of a high-speed fiber backhaul. The communication range of 250 m and carrier sensing range of 550 m is the most used value in the simulation of the IEEE 802.11 standard. This assumption is based on the ns2[5] and Qualnet’s physical layer adaptation of the IEEE 802.11 standard and 914 MHz Lucent WaveLAN DSSS wireless card [23].

TABLE III. SIMULATION PARAMETERS

Parameter	Value
Number of GWs	1 - 15
Number of MR	Varying (100 – 300)
Maximum number of Mesh Clients	250
Mean Packet arrival rate	0.01s (100 packet/s)
Mean hop delay	0.01s
Flow rate	Markov Model
Packet Size	64 bytes
Core router capacity	100Mbps
GW Capacity	2 Mbps
Transmission range of MR & GW	250m
Carrier sensing range	550m

Initially, a formulation is derived to compute the throughput from the simulation results. Thereafter this formulation is applied to obtain the throughput in the following section. First, a simple WMN is simulated without load management or GW scheduling. The throughput of this WMN is recorded. Thereafter the GW scheduling is performed, and the throughput is computed again. The performance of a conventional WMN is compared with a WMN with GW scheduling on basis of throughput, packet delay, and packet dropped parameters.

VII. ANALYSIS OF THE THROUGHPUT OF A WMN WITH THE PROPOSED LMS

This section investigates the throughput of WMN after applying each step of the proposed LMS. To compare the performance, it is necessary to create two WMN models namely Conventional WMN without LMS and WMN with proposed LMS. It can be observed that both these models can be derived from the system-level simulation model in Fig. 20 by making slight modifications in the IMW block.

A. Creation of a Simulation Model for Conventional WMN without LMS

To create a model of such a WMN, the simulation model of Fig. 20 is modified slightly. The IMW block as well as the Global APR table as explained in previous sections is disabled. The MRs are assigned to the GWs randomly and the respective APR tables of GWs are created accordingly. Thereafter, there is neither load monitoring nor load adjustments throughout the simulation period. This is the closest approximation to the conventional model of WMN without LMS.

B. Creation of Simulation Model of Load Management with Load Sharing

To obtain this model, the IMW block is modified such that all the blocks are enabled, and load monitoring is performed. Whenever the steady-state load condition is violated, the WMN performs load-sharing as explained in the IMW earlier. Since one of the major comparison parameters is the system throughput performance, the next subsection explains how throughput is calculated from the system utilization graph obtained through the simulation.

C. Process of Throughput Computation from the System Utilization Graph

This section explains how the throughput is calculated using the system utilization graph obtained from the MATLAB simulation. The system utilization graph is a part of the results displayed by the display block of the System-level simulation model in Fig. 20. It represents the average channel utilization of the entire WMN. The throughput computation is based on the following system parameters.

Core router bandwidth = 100 Mbps.

GW bandwidth = 2 Mbps.

Packet size=512 bits.

The throughput is determined using the relation.

$$\text{Throughput} = \text{Bandwidth} * \text{Utilization}.$$

D. Throughput Analysis with Load Sharing

This section presents the analysis of a WMN having the capability of load sharing incorporated in it. For uniformity and ease of comparison, the same scenarios of the previous section are reconsidered. For the simulation, the maximum capacity of GWs is assumed to be 2 Mbps. The first simulation on a WMN with load-sharing features pertains to the studies on the variation of throughput as a function of the number of MRs. As can be seen from the results of Fig. 21, initially the throughput improves with the increase in the number of MRs. The improved throughput is due to the fair scheduling of WMN. Regarding the throughput performance, it is interesting to note that the performance profiles exhibit a steep rise and slow decay characteristics.

It is worth mentioning here that a very similar trend was observed in [24] when they performed a similar study on fifth-generation cellular networks. It was observed by them that increasing the number of devices resulted in a decrease in data rates. They concluded that until better technology is devised, this decrease is bound to continue. This indicates that when a WMN gets congested and when all its GWs are utilized to their full potential, the throughput shall begin to drop. The relationship between the capacity of a WMN and the capacity of GW can be written as:

$$\text{The capacity of a WMN} = (\text{Capacity of GWs}) \times (\text{Number of GWs}).$$

E. Comparison of a Conventional WMN and a WMN with Proposed LMS

This section compares the throughput obtained in a conventional WMN without LMS with the throughput obtained in a WMN with the proposed LMS feature. The simulations have been performed keeping the total number of MRs fixed to 100 in each of the WMN scenarios but the number of GWs has been varied. This helps to study the effect of increasing the number of GWs on the throughput of WMN, keeping the number of MRs constant.

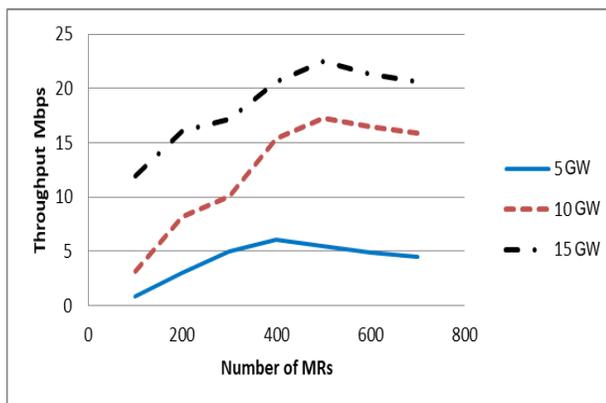


Fig. 21. Throughput of WMN with a Fixed Number of GWs and a Varying Number of MRs.

The results in Fig. 22 depict a continuous increase in the throughput after the application of the proposed LMS. The percentage increase in throughput of a WMN with 5GW 100MR after load sharing is 869%. In the case of a WMN with 10 GW 100 MR, the percentage increase is 893% after load sharing. For a WMN with 15GW 100 MR, the percentage increase in throughput is 1000% after load sharing!!!

The only difference in the simulation scenario between the Fig. 22 and Fig. 23 is the change in the total number of MRs to 200. Additionally, Fig. 23 also compares the throughput of a WMN obtained with a total number of 5 GW and 100 MRs.

The results of Fig. 23 reveal that a WMN with the same number of GWs but with a relatively larger total number of MRs exhibits better throughput performance. The throughput improvement of a WMN with 15GW 200MR is 1036% after load sharing. For a WMN with 10GW 200MR, the throughput improvement is 811% after load sharing. For a WMN with 15GW 200MR, the throughput improvement is 102.7% after load sharing. It can be noticed that if the number of MRs is fixed and only the number of GWs is increased, the gain in throughput is not as significant after performing load sharing. This is because when the number of GWs is increased but the number of MRs is fixed, then the GSS of every GW gets a lesser number of MRs. This results in a smaller number of MRs per GW and thus implying a relatively lesser gain in throughput.

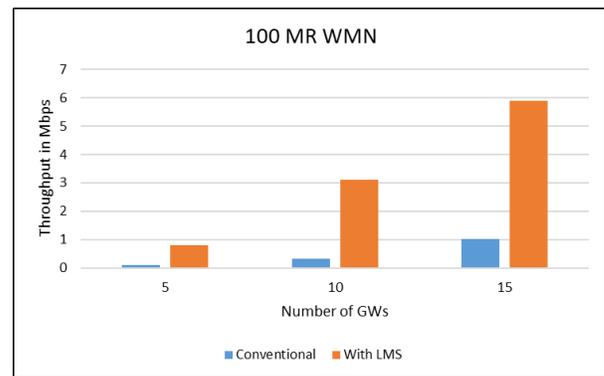


Fig. 22. Throughput Improvement of 100 MR WMN with Varying Number of GWs.

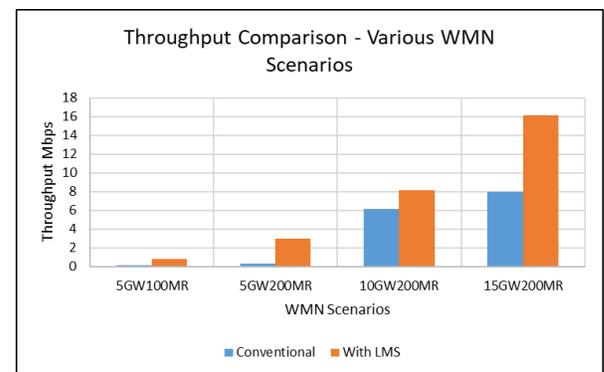


Fig. 23. Throughput Performance of LMS for Different WMN Scenarios.

The next section compares the parameter of packet drop before and after applying load sharing.

F. Analysis of Packet Loss

Since the proposed LMS relieves the congestion of GWs, it results in a reduced packet loss thereby leading to overall improved performance of a WMN. For the simulation, a WMN of 100 MRs is considered. Fig. 24 presents a comparative summary of the results obtained for the packet loss parameter. For the simulation results showed in Fig. 24, the total number of MRs remains constant at 100 while the number of GWs is varied from 5 to 15. The results of Fig. 24 depict an average 40% reduction in the packets dropped after applying the proposed LMS. This confirms the progressive improvement attributed to each constituent process of the proposed LMS thereby demonstrating the best performance.

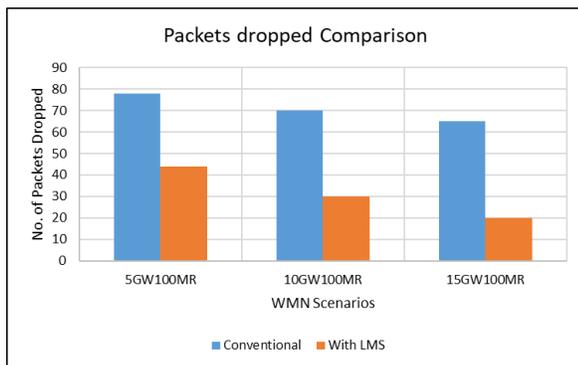


Fig. 24. Comparison of Packets Dropped With and Without LMS.

VIII. CONCLUSIONS AND FUTURE WORK

This paper has demonstrated the step-by-step process in the development of a simulation model of WMN using Simulink. The proposed simulation model was used to analyze the performance of the LMS proposed in this paper. It was found that there was an average 600% increase in the throughput of WMN after applying the LMS. The model also depicts a reduction of 40% in the number of packets dropped. The model is designed to facilitate the flexibility to increase or decrease the number of GWs within the mesh to support the increase and decrease in the number of hops for a particular router. The presented model will be helpful for researchers to analyze proposed techniques that involve many variations in the topology of WMN. The proposed model is also useful for the simulation of scheduling of Gateway and packet within a multi-hop multi gateway wireless network. This paper discusses the MATLAB model of conventional WMN and the implementation of the Load Management Scheme (LMS) on it. Using the proposed model, this paper has presented a comparative analysis of the throughput performance of WMN with and without the LMS. The uniqueness of the model presented in this paper is that it is scalable and flexible in terms of network topology parameters.

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