On Tree-Based Routing in Multi-Gateway Association based Wireless Mesh Networks

Stefano Maurina
School of Computer Science and Informatics,
University College Dublin (UCD)
Belfield, Dublin 4, Ireland
stefano.maurina@gmail.com

Roberto Riggio & Tinku Rasheed
CREATE-NET
via alla Cascata, 56/D
38123 Trento, Italy
name.surname@create-net.org

Fabrizio Granelli
DISI – University of Trento
via Sommarive 14,
I-38050 Trento, Italy
granelli@disi.unitn.it

[1]**Abstract—There is an increasing acceptance for Wireless Mesh Networks (WMN) as the potential 'last-mile' access technology running media-rich applications with stringent quality of service (QoS) requirements. As WMNs are envisioned to provide high bandwidth broadband services to a large community of users, the Internet Gateway which acts as a central point of attachment for the mesh routers is likely to be a potential bottleneck because of its limited wireless link capacity. We propose TBMGA (Tree-Based with Multi-gateway Association), a novel routing protocol that elegantly balances the load among the different Internet gateways in a WMN. With TBMGA, we combine the flexibility of layer-2 routing with the self-configuring and self-healing capabilities of MANET routing. TBMGA switches the point of attachment of an active source-serviced gateway depending on a global metric estimated based on the average queue length and expected availability at the Internet gateway. The protocol is evaluated using simulations and we observe that the proposed scheme is able to efficiently balance the traffic between multiple gateways.**

Keywords: Wireless Mesh Network, Proactive Protocols, Link Quality Metrics, Tree-based Routing, Load Balancing, Multi-Gateway Association.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) have recently emerged as a solution for providing last-mile Internet access [1]. Several such networks are already in use, including testbeds and commercial deployments. The form of mesh networks that are of most commercial interest are often called Infrastructure-mesh networks and consists of mesh routers which form the mesh network backbone; gateways which provide the network with Internet connectivity, and the end-users devices (as shown in Figure 1). End-user devices do not participate in the packet relaying. Mesh routers are rarely mobile, and usually does not have power constraints. The most significant application of such networks is to provide broadband Internet access to static or mobile hosts in areas where wired infrastructure is either difficult or economically infeasible to deploy or, more in general, as flexible and low-cost extension of wired infrastructure networks.

One of the distinguishing aspects of WMNs is the multi-hop forwarding or relaying of packets over the wireless links for communication between the mesh routers. The mesh routers are equipped with multiple wireless interfaces operating in orthogonal channels. Here, the network consists of two types of links: access links to end-user devices and mesh-relay links between mesh routers to form the packet transport backbone. Routing protocols should effectively provide paths through the mesh network and react to dynamic changes in topology, so that the mesh routers can communicate with each other even if they are not in direct wireless range. The design of the mesh backbone is an important factor to guarantee minimal congestion in the presence of dynamic traffic aggregation from access links.

WMNs have a relatively stable topology except for occasional node failures or additions. Practically all the traffic flows are aggregated and forwarded either to or from a gateway. Gateways connect directly to the fixed network and therefore constitute traffic sinks and sources to WMNs. Such a multipoint-to-point architecture introduces two main bottlenecks affecting WMN capacity which are the gateway bottleneck and the client communication bottleneck respectively. Apart from significant capacity reduction, the single gateway architectural model also introduces other issues such as fairness problems and security risks. In [4], the authors discuss an alternate communication model for WMN, in which mobile devices are allowed to connect through more than one of the available gateways. This multiple association is shown to provide several advantages including capacity benefits, fairness improvements, diversity, failure resiliency and better security, apart from allowing for dynamic congestion control and delay-loss guarantees.

In Infrastructure WMNs, the principal focus is on offering the best throughput and the most commonly adopted strategy is to use reactive routing protocols with link-quality metrics [10]. As the traffic is primarily concentrated along the paths directed toward the Gateways (we can safely assume that the traffic between mesh nodes is negligible), tree-based routing is prominently adopted in WMNs. The high traffic load (being the WMN a backhaul for the Internet) and the tree-based routing may cause congestion along the traffic paths and hence require efficient load balancing and fairness schemes.

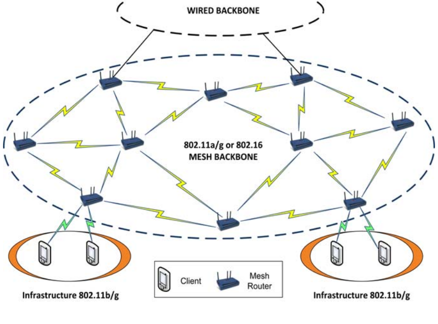

Figure 1: Infrastructure/backbone WMNs.

In this paper, we propose a Tree-Based with Multi-gateway Association (TBMGA) routing protocol which is intended for Infrastructure WMNs employing multiple gateways to connect to the Internet. TBMGA is a novel routing protocol that elegantly balances the load among the different Internet gateways in a WMN. With TBMGA, we combine the flexibility of layer-2 routing with the self-healing and self-configuring capabilities of MANET routing. We switch point of attachments of active source-serviced gateway depending on a global metric estimated

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based on the average queue length and expected availability at the Internet gateway. The protocol is evaluated using simulations and we observe that the proposed scheme is able to balance the traffic efficiently between gateways in a mesh network.

The paper is structured as follows: in Sec. II, we discuss the relevant prior works. We introduce the TBMGA protocol and the related assumptions in Sec. III. Section IV presents the evaluation results. Finally we draw our conclusions in Sec. V.

II. RELATED WORKS AND DISCUSSIONS

Proactive ad hoc routing protocols [10] do not take into account that traffic distribution in Infrastructure WMNs is mainly directed towards or from a wired network. Tree-based routing protocols well capture this feature, and attract increasing attention as a possible routing solution for WMNs. Nevertheless, the skewed distribution of traffic toward gateways can greatly decrease network performance due to the non-efficient spatial usage of wireless bandwidth which leads to heavily congested routes and bottlenecks at the Gateways. This results mainly in waste of wireless bandwidth and higher end-to-end delays. To mitigate unbalanced distribution of traffic and hence improve network performance in terms of total throughput and end-to-end delay, we propose a multi-gateway association through which a mesh node forwards a flow toward a gateway considering both the link quality metric and a Gateway Load Balancing scheme.

There are two approaches for building a WMN [3]. The first one is the use of a MANET routing protocol. The two most successful and representative of two different approaches, reactive and proactive, are respectively AODV [7] and OLSR [8]. These protocols are usually implemented as routing daemons that run at layer 3 (routing layer). Packets are routed toward the destination based on their IP address, similarly to what happens in the Internet. The disadvantage is that other Layer-3 protocols, such as IPv6 cannot be used. The connectivity of the nodes and the topology of the network are constantly monitored and the routes are determined dynamically. MANET protocols are therefore robust to changes in the network.

The second approach is the Wireless Distribution Service (WDS) [5]. WDS provides forwarding functionality for extending the range of an AP, i.e., it allows Access Points to act as repeater. WDS is standardized by IEEE-802.11, but is not implemented by all the manufacturers. Besides, different products are rarely compatible with each other since some part of the standard are not fully specified. The routing is done at Layer-2. This means that packets are routed according to the MAC address destination regardless of the upper Layer protocol like IP, IPv6, DHCP, etc. This offers greater flexibility and a wide range of solutions. Nevertheless, the routing is usually static with the neighbour MAC addresses entered manually in each Access Point. Thus, we lose the dynamic, self-configuration and self-healing features of MANET protocols. With TBMGA we try to combine the flexibility of layer-2 routing with the potentiality of MANET routing. The nodes are identified by the MAC address of the wireless network card. The routing done in layer-2 implies that on top of it, the typical protocols and software can be used, like DHCP for address assignment, HTTP/TCP/IP for Internet browsing, and UDP/RTP/IP for video streaming.

III. TBMGA PROTOCOL OVERVIEW AND OPERATION

TBMGA is a proactive routing protocol which builds and maintains new- routes from gateways toward each node of the network during fixed intervals. Being a proactive routing protocol, TBMGA deals with route table management. There are three types of tables: the Gateway Routing Table (GWRT), the Mesh Node Routing Table (MNRT) and the Cache Routing Table (CRT).

TBMGA has been designed to allow the clients to connect to a wired network (in particular the Internet) but not to communicate directly among each others. Once the routes are established, the nodes must be aware of the distribution of the load and the current free capacity at the gateways to achieve good performance, load balancing and fairness. For this purpose, TBMGA is associated with a Gateway load balancing scheme, detailed in Section III.A. During the time interval between each route discovery, nodes keep on exchanging probe packets for the purpose of estimating the ETX metric [9][10], which is used during route discovery. ETX is not sensitive to the load and this is necessary to avoid route flapping.

Root Announcement (RANN), Route Reply (RREP), and Unicast packets are the message types defined by TBMGA. The tree topology formation begins when the root (Gateway) starts periodically (proactively) sending out the Root Announcement (RANN) message by increasing the sequence number with every announcement. The RANN are sent by the Gateways in broadcast and the dissemination covers the entire network. To avoid uncontrolled spread of RANNs, each mesh node stops to rebroadcast the same RANN (same combination of Gateway Address and Sequence Number RANN) after a predefined time since it has received a new RANN even if it has a better metric. During this processing of the RANN message, each node learns the new route toward each gateway (each node receiving a RANN caches a route back to its originator). To make the gateways aware of the new routes, the nodes unicast an RREP message along the new paths to each gateway. The final result of this node discovery process is the creation of a tree from every gateway to every mesh node as depicted in Figure 2.

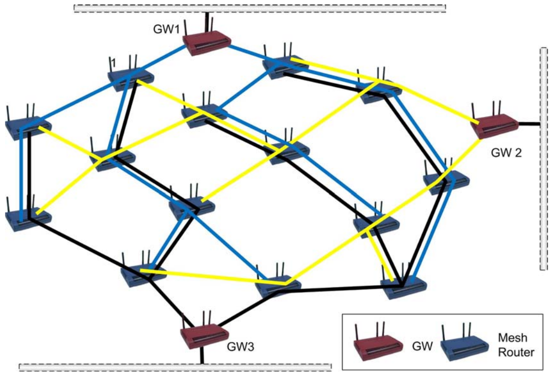

Figure 2: Three gateways building the trees throughout the network

Each Gateway broadcast the RANN message in a proactive manner, where by at a fixed time, it is possible to build new update routes towards all the nodes of the networks according to the ETX metric. Any Mesh Node receiving a RANN behaves as represented in Figure 3:

- It refreshes the ETX metric of the RANN packet
- It checks the Gateway Address and the SN and looks up in its Route Cache Table
- If the combination is not still present in the Cache (new Gateway or known Gateway with new SN), it caches the mesh node it received the announcement from as the potential parent toward that Gateway, starts the Timer in the

Route Cache Entry and rebroadcasts the RANN with the updated cumulative metric

- If the combination is already present in the Cache (same GW Address and SN) and the Timer field is not still elapsed, it checks if the ETX metric of the new RANN is better than the one already stored. If it is better it updates the Cache with the new information and rebroadcasts the RANN with the updated cumulative metric. If the ETX metric is worse, it discards the RANN
- If the combination is already present in the Cache (same GW Address and SN) but the Timer is already elapsed, it discards the RANN

When the Timer in a Route Cache Entry ends, the Mesh Node updates the corresponding Gateway Routing Table (GWRT) entry with the new metric and the next hop to the Gateway. In this way, at the end of RANN dissemination, each node learns the best route to the Gateway; which originated the RANN.

The procedure described above permits the Mesh Nodes to know the best route toward a Gateway. Anyway, to guarantee a two-way communication, the Gateway must be aware of the new routes to reach the Mesh Nodes. To perform this task, each Mesh Node, after having chosen its parent node toward a Gateway, Unicast an RREP along the new path to the Gateway:

- When the Timer in a Route Cache Entry ends, the Mesh Node updates the corresponding Gateway Routing Table (GWRT) Entry with the new metric and next hop's MAC Address to the Gateway
- At the same time the Mesh Node sends to its next hop toward the Gateway a Route Reply (RREP) message with the Gateway's address as the destination address
- Each intermediate mesh node that receives the RREP forwards the message to its selected parent node toward the Gateway contained in the RREP and updates the corresponding Mesh Node Routing Table (MNRT) Entry with the next hop's MAC Address toward the MN originating the RREP
- When the RREP arrives to the root, the Gateway updates its Routing Table Entry for the Mesh Node which has sent the RREP with the next hop MAC Address towards that node

Note that an RREP is never sent by a node on behalf of other mesh nodes like it can happen in MANET routing protocols like AODV. This ensures that the discovered path metric is current, since the route request and the route reply traverse the complete path from the gateway to each node and collect the current metric values. Once the next-hops from/to the Gateways are computed, the data packets can be routed toward the destination through Unicast packets. The source node will encapsulate the Ethernet payload in a Unicast packet. The intermediate nodes will simply forward the Unicast packet according to its destination MAC address.

III A. GATEWAY LOAD BALANCING

As stated in [4], the availability of multiple Gateways does not imply a direct and linear increase of network performance. The presence of more Gateways can be reflected as a network capacity benefit only with the adoption of a suitable load balancing technique. This is mainly due to the uneven load distribution experienced across a real network caused by the not uniform geographical dislocation of end-users and by the differences in the traffic generated by different clients.

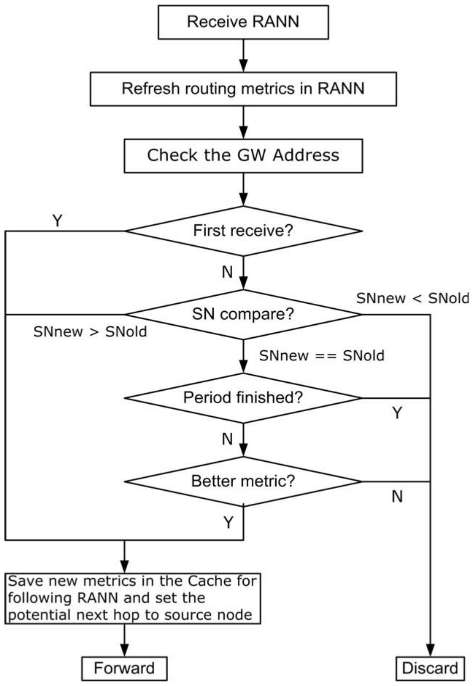

Figure 3: process followed by a mesh node upon receiving a RANN.

Gateway Load Balancing provides a natural and elegant way to spread the traffic over different paths toward a set of gateways [14]. With TBMGA, since every MN conserves the next-hop toward each Gateway in its GWRT table, this process is particularly straight-forward. The proposed gateway load balancing scheme is tailored to suit our needs from the LDAB algorithm, presented in [3]. LDAB tries to reach load balancing and fairness among the nodes monitoring the queue length at the gateways over a fixed time period. If the average queue's length exceed a certain threshold, the GW indicates to its active source (sources with high traffic) to connect to other GWs if possible. The choice to redirect only the active source and not all the flows connected to the GW is very important to avoid route flapping, which is a common problem of many load balancing approaches.

We modified this approach to adapt the way in which the active sources are chosen. If we simply base our choice according to the volume of the traffic generated by the MNs, we could switch a MN that is only one hop far away from its current GW, and as such it should reasonably stay connected to it. We considered taking into account both the traffic rate, the loss ratio and the number of hops to the GW. Two MNs, transmitting approximately with the same rate, will be given different weights based on their distance to the GW and the loss ratio along the path. In this way, we increase the likelihood to keep the MNs in proximity of a GW connected to it while switching the ones far away but most probably closer to other GWs. To accomplish this, we consider as "the active sources", the MNs with the highest value *[(MN's ETX metric)*(MN's rate)]* where the ETX metric allows to consider both the number of hops and the packet loss.

The pseudo-code in Figure 4 summarizes the main steps carried out by the load-balancing algorithm. Each GW keeps checking its queue length. In case the average queue length exceeds a fixed threshold during a time window, the GW identifies the one with the highest value among the MNs currently connected to it. At this point, it sends a *CHANGE_Pkt* request to this MN asking to switch to another GW if possible.

```
At a GW:
sending
If (the average queue length for a time period (Monitor_Cycle) > Threshold)
  Identify the MN sending to me with the worst (ETX metric*rate)
  Send a CHANGE_Pkt message to switch GW, if possible
End if
receiving
If a GW_REQ arrives from a MN:
  If (the average queue length < Threshold)
    Admit this node sending a GW_REP to it
  End if
End if

At a MN:
sending
When a CHANGE_Pkt arrives from the default GW:
  For (each GW in the GWRT != default_GW)
    Send in sequence, according to the best ETX metric,
    a GW_REQ with the MN's estimated traffic
  End for
receiving
The first GW replying with a GW_REP to a GW_REQ becomes the new default_GW
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Figure 4: Pseudo code for the gateway load balancing algorithm

When receiving a *CHANGE_Pkt*, the MN looks up an alternative gateway in its table. If other Gateways are available, the MN sends, in sequence, according to the best ETX metric, a Gateway Request (*GW_REQ*) message with the MN's estimated traffic to all of the other gateways. The Gateways receiving the *GW_REQ* check their availability to admit the new MN against the MN's estimated traffic. If a GW can afford the new MN, it replies with a Gateway Reply (*GW_REP*). The MN will associate with the first GW replying. After the reception of the *GW_REP*, the MN redirects all of its further traffic flows toward its new Gateway.

If however, a MN is not accepted by any other GW, it keeps on sending its flows to the current default GW. In such a case, the GW will send the *CHANGE_Pkt* to another MN serviced by it, always according the *{(MN's ETX metric)*(MN's rate)}* criterium.

IV. SIMULATION EVALUATION

The OMNET++ [15] network simulator has been used to evaluate the TBMGA protocol[2]. We ran the simulation for 300 seconds. We used IEEE 802.11g as the underlying MAC protocol. The backhaul is always composed of 13 fixed MNs, while the number of Gateway varies from 1 to 2 as depicted in Figure 5. The traffic is generated by three clients who transmit at different rate. The packet size was set to 512 bytes.

In Figure 6, we compare the Packet Delivery Ratio (PDR) at different rates and using a variable number of Gateways ranging from 1 to 2. The X-axis represents the average rate of the three flows, e.g., in the 800 Kbps case we used 600 Kbps, 800Kbps, and 1000Kbps respectively for flow 1, 2 and 3. When using a single Gateway, the PDR decreases quite rapidly as the rate of the flow increases. This is due to all the three flows being connected to the same gateway which leads to heavily congested paths particularly in proximity of the Gateway. The ETX metric which avoids routes with high loss rate is not sufficient to mitigate the lack of proper resources usage. With the introduction of more Gateways, we can exploit the Gateway Load Balancing feature to reduce the congestion along the routes. We can observe the PDR improving at every rate once we introduce the second gateway.

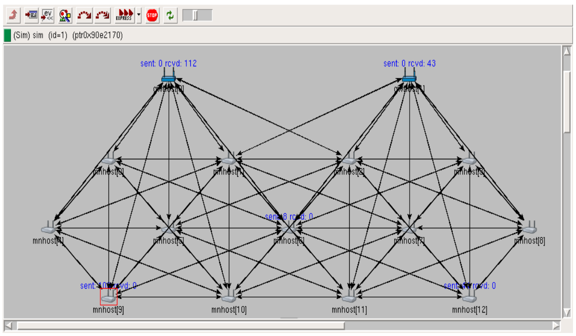

Figure 5: Scenario used in simulations

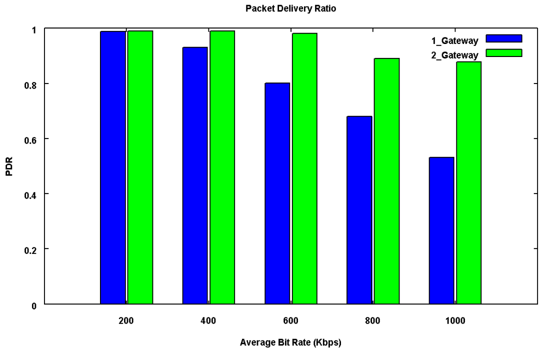

Figure 6: Packet Delivery Ratio at different rate and number of Gateways

As expected, we can observe the same trend for the end-to-end delay. Figure 7 compares the average end-to-end delay of packets for different bit-rates and with the number of Gateway ranging from 1 to 2. The introduction of more Gateways implies the traffic to be split along different paths, so that we get a better spatial usage of wireless bandwidth and consequently a decrease in the number of congested routes. As a result, the average end-to-end delay decreases.

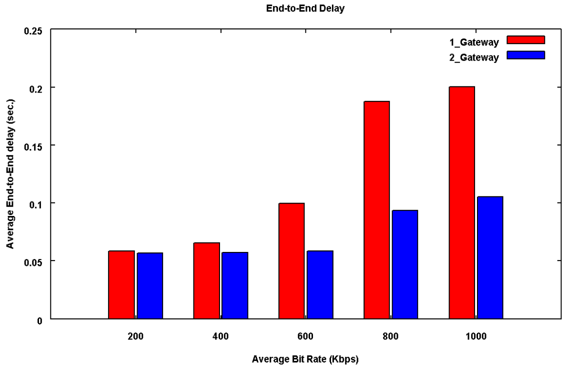

Figure 7: Average End-to-End delay at different rate and number of Gateways

The following results show the comparison between the instantaneous incoming rates that we get at the gateways with the instantaneous outgoing rate generated by the mesh nodes. Clients MN9, MN6 and MN12 generate traffic flows f1, f2 and f3 at the rate of 720, 240 and 480 Kbps respectively. We start the flows 45 seconds after the beginning of the simulation. We consider the sum of the incoming rate at the GWs and the sum of the outgoing rate at the MNs. In the ideal situation, these two parameters should be very close. Nevertheless, since we are coping with multi-hop wireless networks, there could be a lot of packets dropped due to potential buffer overflows. The problem is not only due to the high concentration of traffic at a gateway, that leads to saturation, but more generally it can be observed all over the path from a MN to a GW due to the shared nature of the wireless medium. The presence of multi-

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[2] The source code of the implementation is made available at *http://www.wing-project.org/directions:mesh_routing/*

gateway is hence important not only to alleviate the burden at the gateway, but also to spatially differentiate the routes followed by the flows en route to the gateways.

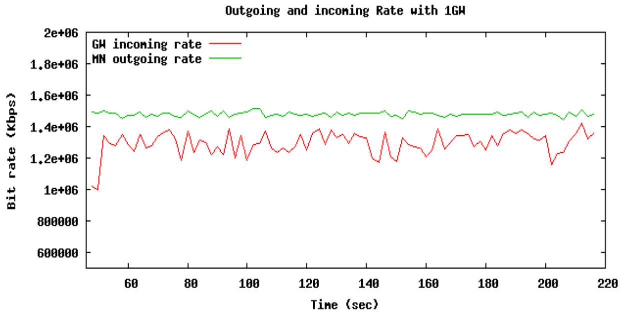

Figure 8: Instantaneous rate generated by the MNs and received at the GW

The scenario used for the simulations is the same as in Figure 5. The first test was carried out using only one GW1. As expected, as in Figure 8, the multi-hop backbone is not able to deliver all the packets generated by the MNs, due to saturation and congestion along the common links and at the GW which leads to MAC buffer overflow and thus packet drops.

In the second test, we used two GWs. The presence of the second gateway allows the use of the multi-gateway association and of the load balancing algorithm. The situation is highly improved as shown by the overlapping of the two curves (as in Figure 9). The incoming rate at the GWs and the outgoing at the MNs being almost the same imply that the numbers of packets dropped along the paths to the GWs are diminished. The presence of multiple gateways permits to balance the traffic load over different GWs, and also possibly along the routes followed by the packets on their way to the GW, with the obvious consequence to reduce the per-node contention period for accessing the wireless medium, and thus reducing the number of MAC buffer overflows.

V. CONCLUSIONS

Wireless Mesh Networks (WMNs) are a rapidly maturing technology to provide Internet access to static and mobile wireless devices in areas with limited wired connectivity. In this paper, we presented the Tree-Based with Multi-gateway Association (TBMGA) routing protocol, intended for Infrastructure Wireless Mesh Networks. With TBMGA, we combined the flexibility of Layer-2 routing with the self capabilities of MANET routing. We switched the point of attachments of active source serviced gateway depending on a global metric estimated based on the average queue length and expected availability at the Internet gateway. The protocol is evaluated using simulations and it is observed that the proposed scheme is able to balance the traffic efficiently between gateways in a mesh network. As future work we plan to implement and test the TBMGA protocol over a real-world deployment using the WING wireless mesh network Testbed [16].

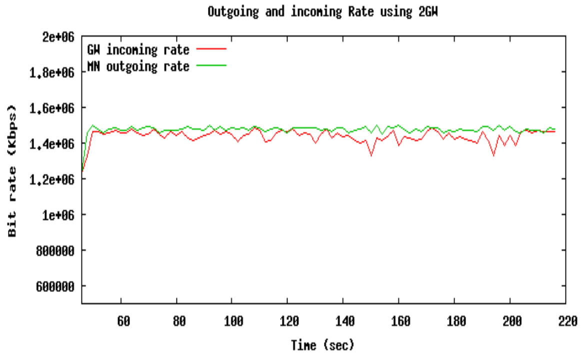

Figure 9: Instantaneous rate generated by the MNs and received at the GWs.

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