On Multi-Gateway Association in Wireless Mesh Networks

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***Abstract*— Most traditional models of wireless mesh networks involve a mobile device connecting to the backbone through one of the available gateways in a wireless mesh network. In this paper, we present an alternate model, in which mobile devices are allowed to connect through more than one of the available gateways. We call the model Multi-Gateway Association (MGA). We present arguments for why such a model can result in better capacity, fairness, diversity and security when compared to the default single-association model. We also identify the primary challenges that need to be addressed when using multiple-gateway associations, and propose solutions to handle these challenges.**

I. INTRODUCTION

Wireless Mesh Networks (WMNs) constitute a specific class of multihop wireless networks that have recently received research focus. Some application scenarios envisioned for such networks are campus wide networks, community networks, hospital networks and rural area networks. WMNs have several economic advantages, such as the possibility of using free unlicensed spectrum and the ease of construction,expansion and maintenance.This has generated considerable interest and attention from the industry.Further, in areas which do not have an already existing wired infrastructure (such as rural areas), these form the only data communications technology.There have been several successful commercial deployments in recent years [1], [2], [4], [5], [6]. Thus wireless mesh networks have an immense potential to succeed as an ubiquitously viable wireless technology.

Although WMNs are currently seeing initial deployments, there are several issues that need to be addressed before they can succeed as the future wireless technology. These issues can be categorized into issues that are prevalent in multihop wireless networks and issues that are specific to WMNs. There are several issues with multihop wireless networks and they have been well documented in the literature [16], [17]. These issues apply to WMNs as well. However, there are several new advantages and disadvantages of WMNs when compared to a general multihop wireless network.

The capacity of a WMN is significantly reduced due to the additional bottlenecks created by the nature of the traffic pattern. The two main factors are the gateway bottleneck and the client communication bottleneck. Since all traffic is directed towards the gateway and the gateway has a fixed bandwidth that has to be shared by all its clients, the throughput per client is reduced as the number of client nodes increases. In addition, when several clients associate with a single router (access point) in obtaining a path towards the gateway, the available client communication bandwidth has to be shared by all the clients as well. These are additional constraints that reduce the capacity due to the multipoint-to-point nature of the traffic. With WMNs, fairness among clients is also a significant issue. While nodes near a gateway typically enjoy a high share of the gateway capacity, nodes farther away have a significant capacity degradation. In addition, with the gateway as the single entry point of all data into the wired internet, the security risk is higher because the environment around the gateway is a single area where an eavesdropper gets access to packets of all flows served by the network.

However, mesh networks have several advantages inherent in their architecture compared to generic multihop wireless networks.Some of the dominant advantages are as follows. With a static routing infrastructure, the possibilities of route failures is greatly reduced. Moreover, the problems of connectivity are reduced due to the redundant deployment of mesh routers. The high node degree of a mesh architecture also provides advantages such as loss-resiliency and reduced probability of path failures. Thus, self healing is also made possible. Although mesh architectures come with several advantages, leveraging the advantages fully depends on the central challenges being addressed effectively. These challenges are exacerbated by several practical problems that occur due to the high and varying user density, improper association, improper load balancing, unbalanced resource allocation, etc. Given these set of problems of conventional WMNs, we investigate the benefits that can be obtained by moving away from a single-association model. Specifically, we consider the gateway association problem where a client associates with more than one gateway in order to transport its traffic to the backbone Internet and likewise from the backbone Internet. The essential contributions of this work are as follows:

- We present a new association model for WMNs called Multiple-Gateway Association (MGA) and evaluate its benefits and trade-offs both qualitatively and quantitatively.
- We identify the essential challenges that need to be addressed in order to leverage the benefits of multiple-gateway association.
- We propose a layer 3.5 solution to tackle the problems and leverage the benefits of the proposed model.

The rest of the paper is organized as follows. Section II describes the proposed model and also lists the assumptions made in this paper. Section III motivates the use of multiple-gateway association from the four main perspectives of capacity, fairness, diversity and security. In Section IV, we identify the key challenges that need to be addressed in order to truly leverage the benefits of multiple-gateway association. Section V describes the proposed solution suite, its mechanisms and interactions in the protocol stack. In section VI, we evaluate the performance of the proposed solution using simulations. Section VII presents related work and Section VIII concludes the paper.

II. MODEL AND ASSUMPTIONS

We consider a multi-hop wireless network with three sets of nodes: clients, mesh routers and gateways. Every mobile client connects to the router nearest to it in finding a path towards a gateway. The gateways, routers and clients all use omni directional antennas and operate on the same channel with the same capacity C. The clients do not perform any co-operative relaying and only serve as sources for their own traffic. Data is directed only from the gateway to client nodes or vice versa and not between clients.

For the single-gateway association, every client node chooses the gateway nearest to it for its association and directs all its traffic towards this gateway alone. We call this model Single Nearest Gateway Association . This model will be used throughout the paper for comparison purposes and referred to as SGA .More sophisticated single gateway association mechanisms such as based on load can be devised. However, we contend that the flow splittability inherent in MGA innately comes with the several advantages outlined in Section III, and established in prior works [8], [9].

In the Multiple-Gateway Association model (MGA), we consider every client node to choose more than one gateway for its communication. The specific number of gateways and the exact gateways that each client will associate with will be elaborated later on.

III. MOTIVATION

Multiple association can provide several benefits.This section provides illustrative scenarios for each benefit using flow graphs[1]. The four main categories of benefits are as follows:

A. Capacity

The use of multiple gateway association can provide significant capacity benefits. While, it is well known that the gateway bottleneck is the dominant reason for capacity constriction in a mesh network [11], the introduction of multiple gateways does not enable a straight-forward increase in capacity. Network capacity can increase linearly with the number of gateways only with proper load balancing and resource provisioning. Thus proper association, which prevents the formation of bottlenecks and distributes the network load evenly, is needed to realize the linear capacity increase. In this section, we argue that multiple gateway association is a practical necessity for achieving the capacity gains possible with the deployment of multiple gateways.

While several studies about the performance of protocols assume that load is uniformly distributed throughout a network, it is seldom the case in practice. The two main reasons for highly uneven load across a network domain are:

- Uneven client distribution: Users are in general unevenly distributed throughout a network. Further, the distribution also changes with time. In a mesh network covering a large area, density of users follows a profile, with separations at different granularities. For instance, a community mesh network for a city, would have a large concentration of users in office buildings as opposed to roads and other spaces. Within an office building, the density is typically higher in conference rooms and laboratories, as opposed to break-rooms and lobbies.
- Uneven user demands: The user demands could vary widely within a given network domain. Even in the wired Internet, it is known that the traffic consists of several short flows and few long flows. Thus, demands of users are also highly varying.

These two factors cause a strong difference in the aggregate load imposed on each gateway and thus some gateways are loaded beyond capacity whereas some gateways are severely underutilized.

The impact of the above two practical effects is illustrated in Figure 1. The figure shows a mesh network consisting of two gateways, 14 routers and 14 clients. The scenario depicts a highly ‘cluttered hotspot’ like environment with all 14 clients in the region shown. A single association strategy such as nearest gateway association would lead to sharing of the capacity of the gateway G1 by all the users. In such a scenario, the gateway is unable to meet user demands, and consequently, every user achieves a small share of the gateway capacity. On the other hand, we observe that the other gateway G2 is severely underutilized. In this scenario we can observe that a two-fold increase in capacity is possible by the use of multigateway association. In such scenarios, with a general number of gateways g, it is easy to observe that the best case improvement achievable through multi gateway association is $g - 1$ times that of single association. Thus multi-gateway association not only relieves congestion at some gateways but can also distribute and balance the load, leading to a network-wide improvement. The insights gained from this scenario can be generalized as follows. Consider a mesh network with g gateways, where the capacity of the i^{th} gateway is C_i and the aggregate load on that gateway is GL_i.

- Observation 1: With single nearest gateway association, the total network throughput NT_s is given by $NT_s = \sum_{i=1}^{g} min(GL_i, C_i)$
- Observation 2: With multiple gateway association, the total network throughput NT_m is given by $NT_m = min(\sum_{i=1}^{g} GL_i, \sum_{i=1}^{g} C_i)$
- Observation 3: Theoretically $NT_m >= NT_s$

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[1] The set of active edges carrying flow traffic in the network.

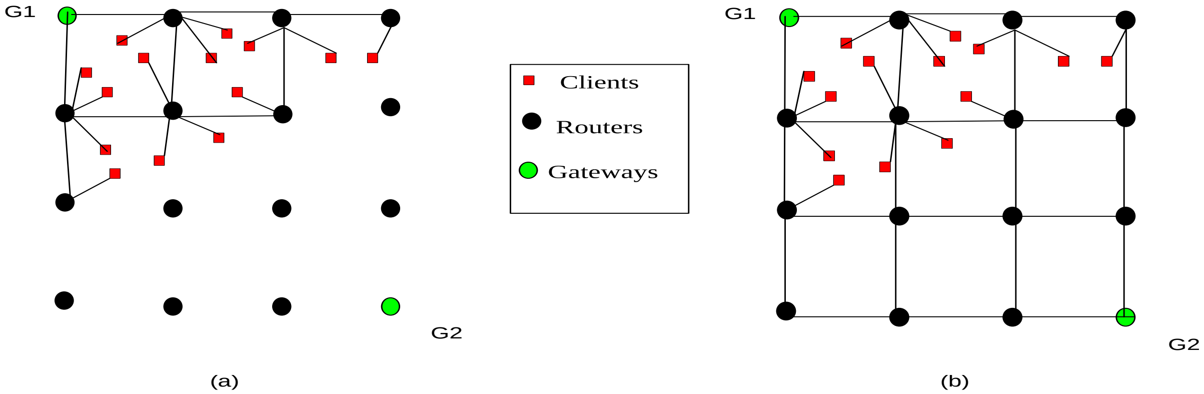

Fig. 1. Capacity Benefit -Illustrative flow graph

- Observation 4: For cases where the density of users is highly varying, leading to formation of hotspots(i.e for some practical cases), $NT_m >> NT_s$ as long as the path lengths to different gateways do not vary significantly and both routing and medium access control mechanisms do not incur distributed inefficiencies.

Observations 1 and 2 follow from the fact that the throughput follows the load as long as it is below capacity. Observation 3 follows from the nature of the *min* function and from the fact that all entries GL_i and C_i are non-negative. It is also to be noted that GL_i can take any value between 0 and a large value, given by the maximum aggregate load in the network. In cases where the individual GL_i vary differently, taking values greater than C_i and sometimes taking very small values, the benefits of multi-gateway association are significant. As an illustration consider Figure 1. In this case, i is 2 and GL_1 is $14L$,where L is the average load per client. Further GL_2 is 0. It is clear that the maximum total throughput achievable is $2W$, where W is the bandwidth of each of the gateways.

The capacity benefits of MGA occur whenever there is underutilization and overloading of gateways at different points in the network.In networks with heterogenous demand and availability of resources, simple shortest path routing leads to improper load balancing. MGA ,on the other hand,enables proper redistribution of resources from regions of the network that experience under-utilization to regions that have high demands. Thus, we conclude that there exist several situations in which the use of multiple gateway association brings significant capacity benefits.

B. *Fairness*

Multi-gateway association leads to a direct fairness benefit. The fairness problem in mesh networks has two dimensions.

- Problem 1 - Path length differences to the gateway: Since different users are at different distances from the gateway, the degradation of capacity due to hop length difference is different depending on the proximity of the user to the gateway. This causes clients near the gateway to unfairly achieve a large throughput compared to clients far away from the gateway.
- Problem 2 - Capacity differences at the associated gateway: Even when the average hop length of each client to the gateway is the same, there is difference in the per client share depending on the number of users sharing a gateway. Thus with improper association, some clients may have the complete bandwidth available for its exclusive use, whereas other users may receive only a small portion of the available capacity of the gateway.

Multi-gateway association primarily reduces the impact of the second problem above.However,it is also possible to reduce the first problem. To illustrate this we consider the scenario shown in Figure 2. The mesh network consists of two gateways connected at diagonal ends of a square grid with other 14 points in the grid occupied by routers. The figure shows 15 clients 14 of which are in the half of the grid closer to gateway G1 and the other client is in the other half. The use of nearest single gateway association causes the 14 clients to associate with G1 whereas the client 15 associates with G2. The fairness problem is evident from this case. While the first 14 clients need to share the bandwidth available at gateway G1 amongst themselves, each of them can at best achieve only $\frac{W}{14}$. However, the client 15 has the entire bandwidth of gateway G2 (namely W) available to it. Thus the unfairness manifests as a throughput ratio of 14!. Thus, as long as the aggregate load on each gateway is different, fairness problems of type 2 will occur. Thus it is not sufficient if the number of users connected to each gateway is the same but the aggregate load must be the same at each gateway. Multi-gateway association helps facilitate such a condition.

Multi gateway association also relieves the impact of problem 1. With single nearest gateway association, users located far away from the gateway must experience relatively lesser throughputs compared to users near the gateway. However, with multi gateway association although a user may be near a gateway, he would be far from the other gateways (assuming gateways are symmetrically and uniformly deployed). Thus each user would have the same average hop length to the

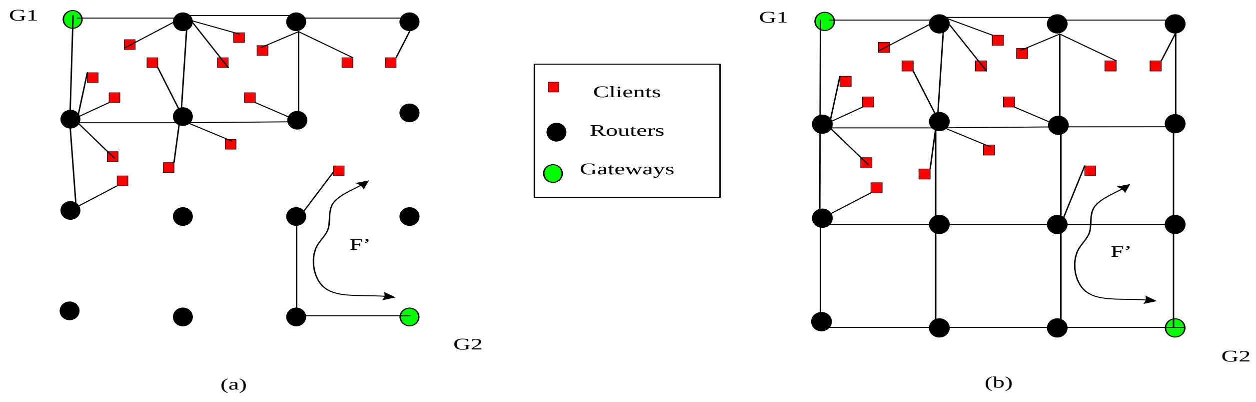

Fig. 2. Fairness benefit-Illustrative flow graph

gateways. This reduces the effects of the spatial bias of the mesh architecture.

C. Diversity and loss resiliency

The need for reliability is more severely felt in the context of mesh networks compared to conventional wireless networks such as cellular networks. The end-to-end success probability is significantly lesser than a single link probability, due to the multihop wireless transmission involved. This necessitates reliability mechanisms not just at the link layer but also at higher layers. In this subsection we present both argumentative and quantitative results to indicate why the MGA model is much better than a single-association model from the point of view of higher end-to-end success packet probability. In the MGA model, the traffic from each client can leverage two important facts:

- Paths to different gateways have statistically different end-to-end packet success probabilities.
- The probability of more than one path having low success probabilities simultaneously is very low.

As an illustration of the diversity benefit we consider the scenario shown in Figure 3. The mesh network shown consists of 2 gateways, 14 routers and 14 clients as in the previous cases. However, now we incorporate the lossy nature of links as well. The links shown by dotted lines indicate lossy links. In Figure 3(a), we see how the SGA approach suffers significantly because of the lossy nature of the links to the nearest gateway. However, with multi-gateway association this problem is reduced significantly as seen in Figure 3(b). Thus the resulting flow graph is better connected and provides better throughput.

Path Diversity improves performance in the presence of both hard and soft losses. By hard losses we refer to the failure of a gateway. On the other hand soft losses include channel dependent errors, buffer drops, etc. With a single association, there is a fixed probability of success supported by the links that make up the path to the nearest gateway. However, the use of multiple paths to different gateways boosts the success probability by g times, where g is the number of gateways to which a client associates. With the assumption of independent losses on paths to the different gateways, the probability that a packet will be lost is reduced from p_1 to $p_1 \cdot p_2 \ldots p_i \ldots p_g$ where p_i is the end-to-end packet loss probability of the i^{th} path to a gateway. Thus, it can be seen that an order of p^g benefit is obtained by associating with g gateways. However, the exact ways to achieve this benefit are still open. Adding controlled redundancy by appropriate protocol design, while simultaneously ensuring non-degradation of the throughput and also ensuring sufficient success rate, is required to achieve the theoretical benefit mentioned above. Thus, the true purpose of a mesh architecture of routers for providing loss resiliency is meaningless without multiple gateways intelligently and simultaneously utilizing them for the diversity benefit.

D. Security

Multi-gateway association also provides several security benefits compared to the single association case. The capabilities and strategies of the adversary need to be several times stronger in a multi-association context,than in the single association case to achieve the same compromise of security. In general, mesh networks have higher security threats because of the nature of the traffic flow. All data is concentrated around the gateway and thus the gateway serves as a single point which exposes the entire network to attack. With a mesh network an adversary positioned at the gateway can bring down the entire network. It is in this context, that multi gateway association has significant benefits. The number of intercepted packets is an important factor in breaking cryptographic keys.For instance, [14], [7] show how vulnerable 802.11 based networks are.Further, it has also been shown, how a cryptographic key of some length can be easily broken by intercepting and processing a few thousands of packets. Since a single association concentrates all packets of a client at a single gateway, it is easier for an eavesdropper to decode the key. However, with multi gateway association the number of packets that can be intercepted by an adversary positioned at one gateway is reduced g fold. As an illustration, consider the scenario shown in Figure 4. Assuming an eavesdropper is

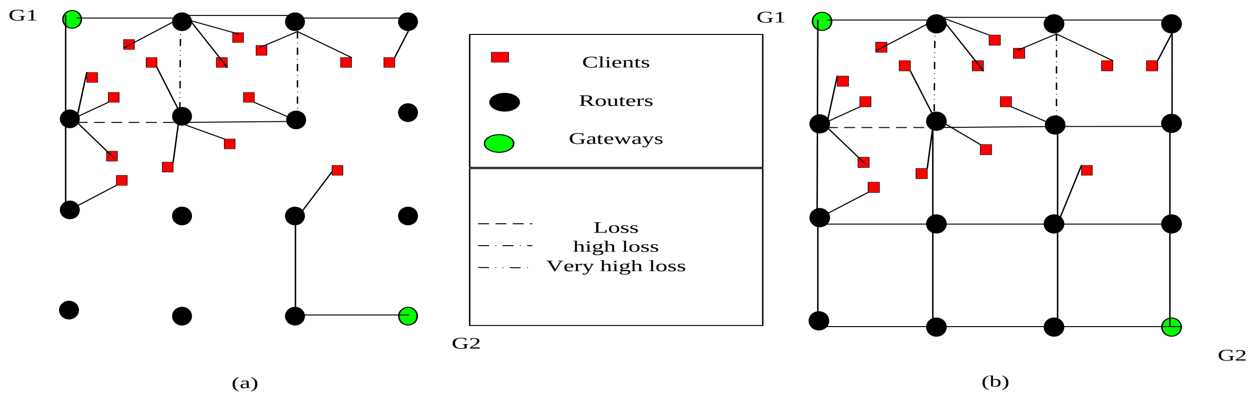

Fig. 3. Diversity benefit- Illustrative flow graph

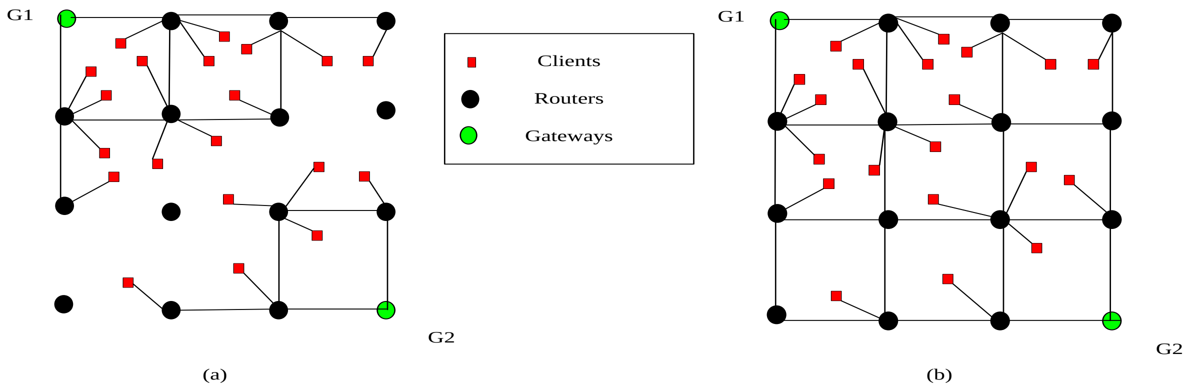

Fig. 4. Security benefit - Illustrative flow graph

located near gateway G1, it can be seen that he can gain access to all the packets of all the clients with single association. However with multi-gateway association, he gets access to only half of the packets of each client. Thus the time he needs to wait in order to process the packets of a particular client is doubled. A simple strategy such as changing the keys during this time, will render the eavesdropper's efforts useless.

E. Other benefits

The MGA model also allows to dynamically perform congestion control in the network. Using co-operation among the gateways, it is also possible to enhance capacity and security when compared to a single gateway scenario. Also, the multiple paths can be leveraged for delay and loss guarantees.

IV. CHALLENGES

In the previous section, the benefit of multi-gateway association towards several performance metrics was highlighted. In this section, we consider the key challenges that need to be addressed in order to ensure that the benefits of multi-gateway association are truly leveraged.

The key algorithmic challenges can be classified under the four main components.

1) Architectural Model: Since multi-gateway association causes packets to a single destination to reach the wired Internet through different gateways, some architectural support is needed in order to combine the packets from different paths and ensure reliable *first in first out* (FIFO) delivery to the end destination. This may require that reassembly of split packets occur at a node in the Internet which collects packets of a single flow from different gateways that the flow uses. Thus at least some wired nodes may need to use intelligent algorithms to combine the split traffic from different gateways, which might not be feasible. This is true for upstream traffic. Even for downstream traffic, the appropriate gateways should be used as ingress points for the wireless mesh infrastructure. Thus the architectural model to support multi-gateway association must consist of "super-gateways" which serve as aggregation points or distribution centers for the traffic between the mesh network gateways and the wired Internet backbone.

2) Gateway Characterization: Gateway characterization is the process by which the loss, delay and throughput statistics of a client's path to the different gateways is obtained for decision making. Specifically, the data rate supportable by the gateway, the packet loss probability on the end-to-end path to the gateway, and the end-to-end delay for that path are parameters that must be known for determining the association. Depending on the values obtained, the appropriate number of gateways for each client and the exact gateways to which each client should associate are also determined. The specific question to be answered in this respect is: *What are the loss, delay and rate statistics of the paths from each client to each gateway?* The algorithmic challenges here would include estimating this information in a distributed and localized manner.

3) Gateway association: Once the statistics of the different possible associations are known, the next challenge is to decide how many and which specific gateways each client must associates with. In particular, the key factors to be considered are: (i) load on each gateway, (ii) hop length of the path to the gateway, (iii) end-to-end loss probability, and (iv) available bandwidth at each gateway. For optimal performance, it is necessary that there is at least some level of independence(i.e difference) in the estimation of the gateway capabilities at different clients. This would prevent catastrophic effects when all clients sense a gateway as available and mutually contend for it thereby reducing the overall benefit. Within this component, the allocation or splitting of data rates among several possible gateways needs to be determined. The right allocation must not only consider the available bandwidth at the gateways but also the effect of hop length and losses. Hop length information is needed specifically in order to determine the nearest gateways. When the quality of the links comprising an end-to-end path is different, end-to-end statistics must be used to determine "relative goodness" of the paths to different gateways.

4) Scheduling: While the super-gateway is responsible for reassembly if packets arrive out of order, it can be shown that relying solely on out-of-order delivery will not result in effective aggregation of the resources along the multiple paths used [9]. Hence,the scheduling of packets to different gateways is an important problem and needs to be done with the aim of improving overall throughput by striving for FIFO delivery without relying on reassembly. Specifically, transport protocols like TCP require FIFO delivery for good and reliable performance. The scheduling algorithm operates on an input of a queue of packets generated by the source. The output of the algorithm is the slot schedules for the packets within a reference block. Since run-time scheduling is difficult to achieve in practice, a balance is needed between the granularity of network state change, granularity of information collection and the number of packets considered at a time for scheduling. Accurate scheduling decisions also require support from the MAC, PHY layers to obtain the average end-to end delay for each packet (including all contention, queuing, transmission and propagation delays).

V. ARCHITECTURE AND ALGORITHMS

Having identified the challenges of user association in multi-gateway mesh networks, we proceed to describe the components of our solution namely the architecture and algorithms that enable one to leverage the benefits of intelligent gateway association and control.

A. Architecture

As highlighted in the previous section, architectural support is needed for enabling multi-gateway association. In our model, we consider the use of a single router (called super-gateway) which serves as an interface between the wired Internet and the mesh network, thereby serving to collect the packets of each flow passing through several gateways. Although the gateways can be located at disjoint positions in the network, the gateways and supergateway are connected by wired links. This enables us to consider the wireless links as the bottleneck of the mesh network. Thus the characteristics of paths between the gateway to the supergateway are assumed not to cause bottlenecks unlike the path characteristics on the wireless mesh links. Further, the super-gateway collects the packets entering the wired section through different gateways and routes them to the appropriate destination nodes after performing reassmebly. Thus packets destined to each wired node travel on a single connection originating at the super-gateway. Thus, intelligent scheduling at the client and algorithms implemented at the super-gateway together ensure FIFO delivery and present the abstraction of a single connection between source and destination. For the downstream direction, the reassembly process should be implemented at the client device, while the scheduling algorithm should be implemented at the super-gateway.

B. Design Considerations

Having discussed the architectural component of the solution, we proceed to describe the algorithmic components. The algorithms that comprise our solution are designed to perform the following four key functionalities: (i) gateway characterization, (ii) gateway selection, (iii) gateway rate proportioning, and (iv) scheduling.

- Stage 1: Gateway Characterization
  At the beginning of a flow, every client identifies the relevant characteristics of paths to different gateways. The specific parameters to be estimated in this component include the available bandwidth AB, delay d, loss rate lr and the number of hops of the end-to-end path to each of the gateways. This four tuple for each gateway will be used in the decision making processes in the sections to follow. Achieving this in a distributed manner presents several challenges and will be part of future work. For the centralized solution, we focus only on the parameters to be estimated and not on how they would be estimated.
- Stage 2: Gateway Selection
  The gateway selection process at each active node is the process of identifying the number of gateways to associate with and the actual gateways from the set of available gateways. This decision is based on the characteristics of the end-to-end paths to different gateways (which are obtained from stage one of the algorithm).
- Stage 3: Gateway Rate Proportioning

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Variables:
    $g$: Number of gateways,$c$:Current Node id,$f$:Flow id,
    $W$: Channel Bandwidth, $F$ : Number of existing flows
    $P_i$: Path from node c to gateway $i$,$l_c$:Load of flow c
    $BL(P_i)$: Bottleneck Load of path $P_i$,
    $FS_i$ Flow Set of Path $P_i$, $OFS$: Overall Flow Set
    $Rate(f,g)$: Sending Rate of flow $f$ to gateway $g$,
    $Rate(f)$:Aggregate Sending rate of flow $f$,
    $FR(f,n)$: Rate of flow f passing through node $n$,
    $AB(i)$ : Available Bandwidth on the path to gateway $i$
Given:
    Gateways,nodes,routers,2-hop contention regions,
    Shortest Paths,Bandwidths, Existing flows and loads
ComputeBL($P_i$)
    INPUT:$P_i$
    OUTPUT:$BL(P_i)$
    For each node j in Path $P_i$
        $AL(j) = \sum_{k:k\epsilon \text{interference region of node j}} FR(f_k,j)$
    $BL(P_i) = max(AL(j))$

MAIN
    INPUT:New flow $f_c$ with load $l_c$
    OUTPUT:$Rate(i,j) : i = 1$ to $F + 1$ , $j = 1$ to $g$
    For $i$ = 1 to $g$
        $P_i$ = ComputeShortestpath($i$)
        $BL(P_i)$ = ComputeBL($P_i$)
        $AB(i) = W - BL(P_i)$
    IF $l_c < \sum_{i=1}^{g} AB(i)$
        do while ($l_c$ has been alloted)
            Sort in descending order $AB(i) : i = 1$ to $g$
            Allocate load from the gateway with largest $AB(i)$
            Update $AB(i)$
    ELSE
        Identify all bottlenecks for the paths $P_1$ to $P_g$
        $FS_i = \bigcap$ Flow sets of maximum bottleneck on path $i$
        $OFS = \bigcup FS_i$
        Do
            Sort $OFS$ in descending order of $Rate(f)$
            Choose Flow $f_k$ in $OFS$ with maximum $Rate(f)$
            Decrease $Rate(f_k,i)$  $i : f_k \epsilon BL(P_i)$
                and $Rate(f_k)$ by 1 unit
            Increase $Rate(f_c,m)$ [ $m : P_m$ contains the maximum
                bottleneck of $f_k$] and $Rate(f_c)$ by 1 unit
        Until ($Rate(f_c) = l_c$ or $Rate(f_c) = Rate(f_k)$)
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Fig. 5. Gateway Association Algorithm

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Variables:
    $g$: Number of gateways,$c$:Current Node id,$P$: Packet Size,
    $d_i$ : End-to-end propagation and queuing delay on path 'i'
    $r_i$: sending rate on path 'i' ,$Td_i$:Total delay to gateway i
    $P_i$: Path between current node and gateway 'i',
    $a(i)$ Normalized delay for path i,$b(i)$:Integral scaling of $a(i)$
    $RT(i,j)$: Receive Time of the $i^th$ packet destined to gateway j,
    $ID$ : Vector of gateway Identifiers

INPUT:
    Delays and rates to each gateway
OUTPUT:
    Number of packets to each gateway

Window
    For each gateway
        $Td_i = d_i + \frac{P}{r_i}$
    $a(i) = \frac{Td_i}{max(Td_i)}$
    $b(i)$ = Integer($a(i)$)
    $NP = \sum_{i=1}^{g} b(i)$

SCHEDULE
    INPUT: Number of packets $b(i)$
    OUTPUT: Destination IDs for each pkt and Tx sequence
    For j = 1 to g
        For k=1 to $b(i)$
            $RT(i,j) = (\frac{1}{r_j} + d_j) * k$
    $ID$=SortID($RT(i,j)$)
```

Fig. 6. Scheduling Algorithm

In this stage, the sending rate of each client to the 'associated gateways' is determined. In particular, this decision is affected by the load of the client and the characteristics of the paths to different gateways. This decision is made in a manner that balances the disparities in the available bandwidths of the paths to different gateways due to the heterogeneities in loss, delay, number of hops and available bandwidth.

- Stage 4: Scheduling
  This stage determines the order of packet transmission at the client which ensures the "in-sequence delivery" of packets at the super-gateway and also maximizes the utilization.

C. Algorithm overview

In this section we present our algorithm which performs the functionalities identified in the subsection V-B. We assume knowledge of network characteristics and thus gateway characterization is assumed to be complete. Stages 2 and 3 are accomplished by the following algorithm shown in the figure 5. The algorithm attempts to identify the associations and rates for the flows in the network in a greedy manner. It is designed to maximize the aggregate throughput of the network subject to a fairness constraint following the Max-Min Fairness model. It also takes into account the 'non-gateway bottlenecks' and presents an allocation vector that produces the maximum aggregate throughput for the given network conditions. The algorithm takes as input a flow and its load (demand). The output is the final rate allocation vector between each (flow, gateway) pair.

1) Algorithm Details: Referring to figure 5, the algorithm first computes the shortest paths from the current node (where the flow originates) to each gateway. After this, the effects of contention on the flow throughput is obtained by finding the sum of flow rates of flows within the contention region of each node in the path. The maximum of these sums over all nodes in the paths is taken as the bottleneck load for the path i, denoted by $BL(i)$. From this, the available bandwidth on the path to each gateway is computed as $AB(i)$. Thereafter, the load requirement of the new flow l_c is checked against the total available bandwidth at all the gateways. If this load is sustainable, the available bandwidth at the gateways is distributed to the flow in a greedy manner (the IF section in the algorithm). The flow procures bandwidth from the gateways in the descending order of available bandwidths. If the load is not supportable (ELSE section of the pseudo-code), the rate allocation vector is modified to ensure a max-min fair allocation and hence the rates of flows are changed as follows. The first step is the identification of maximum degree bottlenecks in the paths P_1 to P_g. The intersection symbol in the pseudo-code is used to account for the existence of multiple maximum degree bottlenecks in the path. The flowset for the path i, namely FS_i, is the set of flows that are part of the maximum bottleneck. This is repeated for the paths to all the gateways and the overall flow set OFS is obtained as the union of the flowsets of paths to each gateway. After obtaining the OFS, the OFS is sorted in the descending order of the rates of flows contained in it. The flow with the maximum rate is chosen (denoted by f_k in the code). The sending rate of this flow is decremented by one unit, on the path which contributes to the maximum bottleneck among P_1 to P_g. Correspondingly, the rate of flow f_c is also incremented on the path, in which the other flow has given up one unit of bandwidth. In this manner, the algorithm continues, until the new flow has met its load requirement or the rate of the new flow converges to the maximum flow rate in the network.

2) Scheduling: The aim of the scheduling algorithm is to determine the actual schedule of packets to different gateways by striving for FIFO delivery without relying on reassembly. This is done in a two step process at the sending nodes as shown in figure 6.

- *Step 1:* In the first step, the window of packets to be considered for scheduling is determined based on the rates and delays of the paths to the different gateways. The window size represents the number of packets to each gateway that must be scheduled in the current epoch. This value is calculated as follows. For each gateway, the parameter $d_i = p_i + \frac{P}{r_i}$ is calculated as the total delay from that client to each gateway i. These values are normalized by dividing by the maximum delay over all gateways (denoted by d_i^n). The obtained values may not be integral. To account for this, the nearest integral solution that preserves the relative ratios gives the number of packets to be considered for each gateway.
- *Step 2:* After identifying the number of packets that must be directed to each gateway, the packet schedule is obtained as follows. For each packet to a gateway, the reception times are calculated as the sum of the transmission instant and the delay on the path. Referring to figure 6,the transmission delays are indicated as $\frac{P}{r_i}$ where P is the packet size and r_i is the rate achievable on the path to gateway i and the remaining component of the end-to-end delay to gateway i as p_i. After this, the packets are arranged in ascending order of their receiving times and scheduled for transmission. It is straight forward to note that the scheme ensures in-sequence delivery of packets as long as the delays do not vary significantly at very short time scales.

VI. PERFORMANCE EVALUATION

In this section we evaluate the performance of the algorithm proposed in the previous section. Specifically, we show how the algorithm maximizes each of capacity,security and diversity benefits.

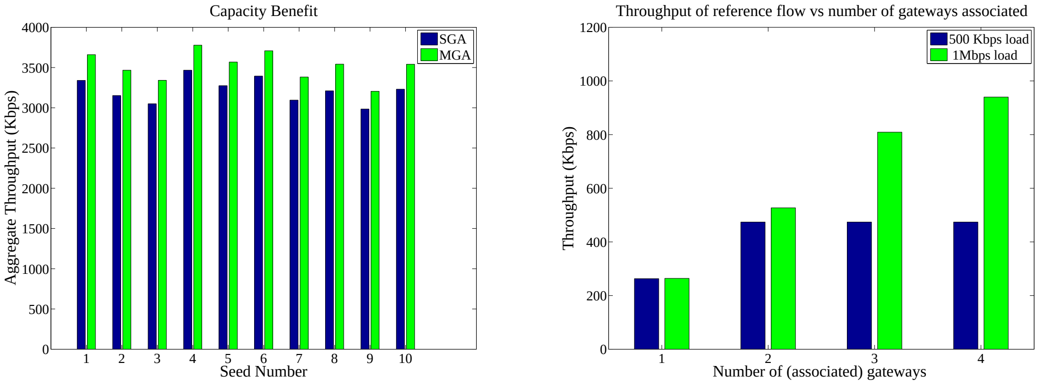
A. Simulation Environment

The network simulator ns2 [3] is used for the experiments. CBR(Constant Bit Rate) is used as the data generating application. For preliminary evaluation, UDP (User Datagram Protocol) is used as the transport protocol. The routes are computed using a shortest path algorithm in a centralized manner. In order to avoid the impact of distributed inefficiencies and other limitations of the IEEE 802.11 MAC protocol, a centralized scheduling MAC protocol is used. The details of this protocol namely,IFS (Ideal Flow Scheduling) is available in [17]. The total number of nodes is 70 which includes 4 gateways, 61 routers and 5 clients. The topology considered is a 1000m X 1000m grid. The position of the gateways is fixed at the coordinates (200,200),(200,900),(900,200) and (900,900). The position of the routers is uniformly distributed within the grid. The position of the clients is also uniformly distributed within the grid. A bandwidth of 2Mbps is used and all nodes operate on the same channel. The transmission range is set to 250m. Unless otherwise stated, the number of users is 5 and the loads of the users are 100Kbps,100Kbps,100Kbps,100Kbps,2Mbps.

B. Evaluation of achievable benefits

The aim of this section is to quantify the achievable benefits of the MGA-centralized algorithm for each of the following four aspects.

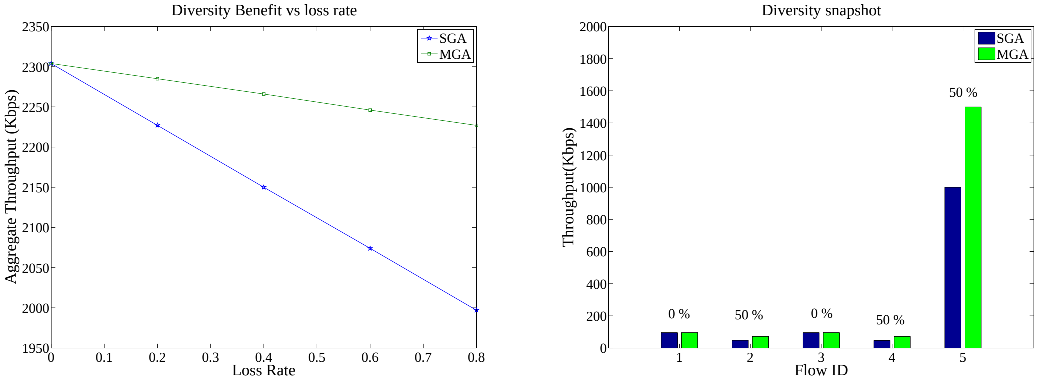
1) Capacity: The capacity impacts of the proposed principle are evaluated by determining the aggregate throughput of all the flows. First, we evaluate the benefit of multi-gateway association and the performance of our algorithm by simulations in a random setting. All parameters are as stated in the beginning of the section except that there are 10 users with a load of 500Kbps each. Figure 7(a) shows the aggregate throughput of SGA and MGA for 10 best seeds out of 40 seeds. It can be observed that MGA gives an improvement of around 10 percent in this random setting. This is essentially limited by the average hop length of a client to a gateway and



(a) Throughput improvement for random topologies

(b) Throughput of reference flow

Fig. 7. Performance Evaluation-Throughput



(a) Diversity benefit vs loss rate

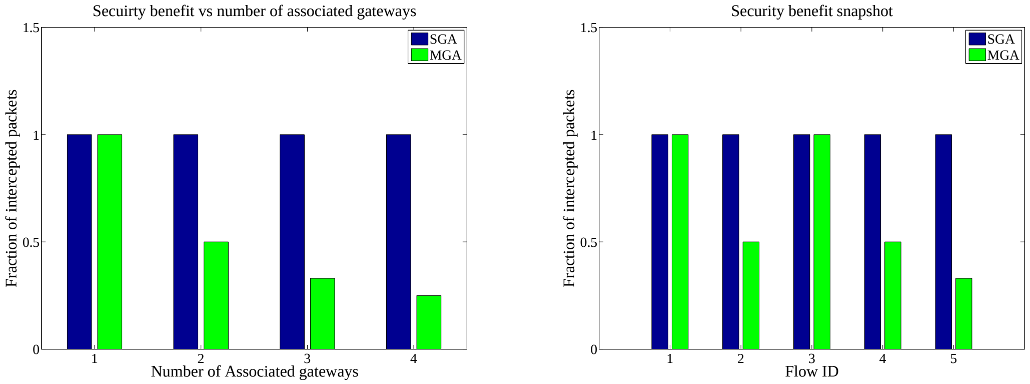
(b) Diversity snapshot for 4 gateways

Fig. 8. Performance Evaluation-Diversity

the total spatial reuse available in the network. The next part of the evaluation is to identify how individual user's throughput changes as a function of the number of associations. For this part, the client positions are as follows. One (reference)client is located at the center of the grid. The remaining clients are distributed uniformly on the periphery of the network, outside the grid formed by the gateways. In this setting, the throughput of the client at the center as a function of the number of associations is shown in figure 7(b) for two values of the load, namely 500 kbps per client and 1Mbps per client. It can be observed that the curve for 500Kbps saturates because, the flow achieves close to its load requirement. However, we can observe that the room for benefit is more with 1Mbps flows.

2) Diversity: The diversity benefit is evaluated by introducing packet losses at the gateways. Since we are interested in the end-to-end packet success probabilities the effect of losses is simulated by probabilistic packet dropping at the routing/transport layer of the gateways. Figure 8(a) relates to the scenario where there is one lossy gateway (gateway at (200,200)). The aggregate throughput as a function of the loss probability at this gateway is shown in the figure 8(a). The values are averaged over 10 random seeds for each value of loss probability. As can be observed, the throughput in general decreases with increasing loss rate. However, the throughput of MGA is always higher than the throughput of SGA. Further, the rate of degradation of aggregate throughput is also lesser for MGA than SGA. Also, the algorithm achieves near ideal throughput. The effect on different flows can be observed in the next figure. It can be seen that flows which are not associated with the lossy gateway achieve maximum capacity whereas the flows associated with the lossy gateway experience losses equally. Figure 8(b) shows the throughput for a gateway loss rate of 0.5 for each of the five flows. Since the load of the 5th flow is larger, the benefit is also larger.

3) Security: The security aspect considered here is privacy. Here the number of packets of each flow that can be intercepted by an intruder located at one of the gateways is the metric considered. In figure 9(a) the security benefit ratio as a function of the number of associated gateways is shown. The use of the ideal medium access control and routing algorithms , enables a $\frac{1}{g}$ security benefit. This occurs when security is the main metric of our algorithm. To observe a more practical case, we maximize the security benefit subject to less than 10 percent degradation in aggregate throughput. In this case, the



(a) Security vs number of gateways

(b) Security for different flows

Fig. 9. Performance Evaluation-Security

security benefit for different users is different depending on the number of associations performed by that user. For this case, the number of associations for the different flows are 1,2,1,2 and 3. This is illustrated in figure 9(b).

VII. RELATED WORK

We now briefly present an overview of literature in two distinct yet related areas.

A. *Mesh Networks*

While, reference [10] presents a survey of wireless mesh networks, [15] discusses some challenges that need to be overcome before the actual benefits of this technology can be leveraged [15]. There are several other works that consider the capacity [11] or capacity improvements with the use of multiple channels and one or more radios [12] but none considering the MGA model. In [13], the authors consider the problem of a user associating with more than one access point or router. Thus, their notion of association is different from that of ours.

B. *Multiple Transport Connections*

There are a few other works in the same spirit of the present work [8], [9]. While [8],is a transport layer solution which seats the intelligence at the last hop wireless link in order to improve performance.Both are not intended for multihop wireless mesh networks, [9] is a transport protocol that allows aggregation of bandwidths whenever, a source and destination are connected by multiple paths.

VIII. CONCLUSIONS AND FUTURE WORK

In this work, we have presented an alternate model for the association of mobile devices to gateways, referred to as the *Multi-Gateway Association* (MGA) model. We have presented arguments for why such a model can result in better capacity, fairness, diversity and security when compared to the default single-association model. We have also identified the key challenges that need to be addressed when using multiple-gateway association, and proposed a layer 3.5 MGA protocol plane to handle the challenges. We have evaluated the proposed model and protocol solutions through ns2 based simulations.As part of future work, we intend evaluating the performance of the association algorithm for TCP flows.Further, we have not described the optimality of our algorithm nor a distributed version of the algorithm.Further, preliminary evaluation has mostly considered equal associations for the users concerned and the splitting is also equal.The granularity of association and the splitting ratios are interesting problems left for future work.

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