Resource-Reservation in Multihop IEEE 802.11e Wireless Mesh Networks

Usman Ashraf and Zainab Malik

Abstract**—**In this paper, we address the problem of resource reservation and admission control for multimedia flows in IEEE 802.11e wireless mesh networks. Previous research on IEEE 802.11e focuses on admission control in single-hop Wireless Local Area Net- works (WLANs) and neglects wireless multihop scenarios which are becoming increasingly popular. This paper proposes the first, com- pletely distributed admission control scheme for IEEE 802.11e-based wireless mesh networks. In this paper, we propose a measurement- based scheme for EDCA mode of IEEE 802.11e. This scheme is based on promiscuous listening capability of wireless radio in which interference measurement on the channel is used to predict the available bandwidth. The proposed scheme is evaluated through extensive simulations against a contemporary solution in the area and results show that the proposed scheme performs significantly better in terms of instantaneous throughput, instantaneous end-to-end delay, routing overhead and admission ratio metrics for several topologies.

Index Terms**—** Bandwidth Estimation Admission Control IEEE 802.11e Wireless Mesh Networks

I. Introduction

Wireless networks have become immensely popular all around the world. The main attraction of wire-

less networks is the flexibility and ease of deployment in comparison to traditional wired networks. Today, we have a diverse range of wireless communication technologies, ranging from low-bandwidth short-range to high-bandwidth long-range wireless technologies. Wireless Local Area Networks (WLANs) are among the most popular flavors of wireless technologies around the world. WLANs are being widely used in homes, offices, universities and cafes, to provide the last-hop wireless Internet access to users. IEEE 802.11 [1] is the most widely used wireless communication technology for WLAN deployments all over the world. The IEEE 802.11 standard, commonly known as ”Wi-Fi” has been extremely popular, but has some significant limitations.

The IEEE 802.11e standard was extensively explored for

single-hop WLAN environments and a large body of research exists on the optimization of various aspects of the standard [2], [3], [4], [5], [6], [7]. However, prior research has neglected optimization and performance of IEEE 802.11e in multihop wireless mesh networks. Wireless mesh networks are a rel- atively new phenomenon, but find applications in a diverse number of areas, ranging from military to health and rescue. Mesh networks come in a range of flavors and use a number of different wireless technologies such as ZigBee and Wi- Fi. Among wireless multihop networks, ad hoc networks and wireless mesh networks based on IEEE 802.11 (Wi-Fi) have become particularly important. Mesh networks are currently being for community networking, video surveillance, rescue and rehabilitation services and most importantly, last-mile Internet connectivity to large number of users spread over wide geographical areas. Wireless multihop networks are therefore an important part of the wireless world and have tremendous applications currently and in the foreseeable future.

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Providing Quality of Service in wireless mesh networks is important because different flows have different requirements and priorities and the underlying network must facilitate flows in achieving their desired goals of bandwidth and delay. Moreover, in the absence of resource-reservation and QoS provisioning, the inherent nature of wireless mesh networks and the unpredictable wireless medium will make any hope of providing a desired level of service to users impossible. Providing QoS in wireless mesh networks is important but difficult to achieve due to a number of reasons including the interference on the wireless medium (intra-flow and inter-flow), collisions, bit-errors, synchronization issues and the dynamic nature of wireless flows. Towards this end, it is important to design mechanisms to provide effective Quality of Service to flows in these networks.

Unfortunately, previous research has mostly neglected IEEE 802.11e as a technology for wireless mesh networks and has considered 802.11e only in the context of WLANs. While there is a large body of research on IEEE 802.11e in single-hop WLANs, it cannot be applied directly to the multihop scenario as multihop mesh networks have several fundamental differ- ences with WLANs. For instance, Intra-Flow Interference and Hidden Station problems are particular to multihop networks. Further, in contrast to a central controlling authority such as the Access Point (AP) in WLANs, multihop networks do not have such flexibility and must rely on completely distributed solutions. In this paper, we explore resource-reservation in IEEE 802.11e based wireless multihop networks. More specif- ically, the paper makes the following contributions:

II. Motivation And Related Work

IEEE 802.11e provides differentiated service to different traffic categories and gives better performance compared to legacy 802.11 in WLANs. However, despite providing a differentiated service, it is unable to provide guaranteed QoS to applications having stringent QoS demands such as bandwidth. Significant efforts have been made in order to improve the QoS mechanism of IEEE 802.11e, in particular

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for its EDCA mode. Many approaches advocate optimal tuning of different features of IEEE 802.11e such as the Contention Window, TxOP, IFS etc. to improve performance[2], [8], [9], [5], [10],[11], [12]. These enhancements bring improved performance overall, but do not solve the problem of guaranteed QoS. In order to provide guaranteed QoS support, different analytical and measurement based models have been proposed. Most of the works on analytical modeling of IEEE 802.11e for bandwidth estimation are based on the original model proposed by Bianchi [13]. In this model, the author uses a two-dimensional Markov chain to model transition from one state to another state and gives the probabilities for these transitions to calculate the throughput in saturated case. In [14], authors provide an analytical model for EDCA based on Bianchi's model. Their model captures the post-collision effect to pro- vide accurate throughput and collision estimation. As each AC within a node behaves as a separate entity, they incorporate the differentiation parameters of EDCA with Bianchi model to es- timate saturated throughput for each AC. The model proposed in [15] uses two-dimensional Markov chain state transitions. It is capable of predicting the throughput in both saturated and unsaturated conditions. Authors in [15], also capture the virtual collision among ACs within a node. In this model, the Access Point is able to calculate the starvation point for each access category. In [3], an admission control mechanism is for IEEE 802.11e in non-saturated conditions. Flows are admitted by estimating its channel occupation time. In order to estimate the collision probability, authors build on the work of [15] as a reference model. In [4], authors provide an admission control by considering the throughput and delay requirement of flows and provide admission control for guaranteed and best effort traffic. The work in [6] provides a model to predict the network throughput under non-saturated conditions by considering the TXOP limit, Contention Window and the Arbitration Inter- Frame Space (AIFS). Authors in [7], provide a more accurate model for IEEE 802.11e, by focusing on standard-specific features, a factor overlooked by existing research.

Among measurement based models, the DAC [16] model, proposed by the IEEE 802.11e task force group is the most popular. In this model, the QAP transmits a "Transmission Budget" for each AC for the next beacon interval. By re- ceiving the budget information, every node can measure its transmission limit and accordingly admit or reject a flow. An improvement of the DAC scheme is proposed in [17], in which authors provide two-level protection. In the first level protection phase, the solution protects existing flows from the newly admitted flow while in second level protection, it protects the flow from best-effort traffic. A measurement based model is presented in [18], which proposes an admission control mechanism by measuring the available bandwidth and estimating the requirement of the new incoming flow. However, to measure the channel status by each Ac, they introduce a priority access mechanism in which every node, sends a busy tone before transmitting every packet in the last slot of AIFS period. This busy tone restricts lower priority traffic from transmitting as long as there is a packet in a higher priority queue, thereby enabling the QAP to estimate the channel status for each AC.

In [19], authors propose a hybrid, model-based admis- sion control. They estimate the available bandwidth in non-saturated network by considering packet size, CW range, packet arrival rate, competing entities and the channel busy probability. The channel busy probability is measured by promiscuously listening to the channel for a specified duration of time. There parameters are input to a Markov chain-based analytical model to estimate the available bandwidth.

All of the above mentioned bandwidth estimation and admission control mechanisms were developed for WLANs. However, to the best of our knowledge, very few works [20], [21], [22], [23], [24], [25] explore IEEE 802.11e in wireless multihop environments. In their pioneering work on 802.11e in multihop networks, Carlos et al. [20] show that in multihop networks, the bandwidth share for a flow decreases significantly as the number of hops increase. This is because multihop networks are exposed to inter and intra-flow interferences imposed by traffic from neighbors. In continuation of this work, recently Torres et al. [21] carried out an experimental investigation of QoS support of 802.11e in indoor multihop environments. Their results suggest that QoS can be maintained to a reasonable level for both voice and video traffic in multihop networks, although the routing protocols can interfere with the performance. However, both works [20][21] do not focus on admission control. In [22], authors propose a QoS solution based on IEEE 802.11e for Vehicular Ad hoc networks. They consider link reliability, end- to-end delay and hop count as the QoS metrics which are optimized during routing. The basic idea is to prefer reliable routes which have longer expected lifetime and less hop count, instead of shortest paths which more likely to break and create a high maintenance overhead. In [23], the basic idea proposed is to provide end-to-end delay guarantees to packets by dynamically adjusting the AC of packets at each node. If the packet is lagging behind the delay budget, then it is moved to a higher priority category at intermediate nodes and vice versa. In [24], authors maintain the bit-rate and keep track of delay at each hop. The queue scheduling mechanism is optimized to ensure that the delayed packets are transmitted faster than other packets. Although this approach can offer improvement, but a guaranteed channel access is not ensured as the collisions and random backoffs still exist.

There are very few works [25] which explore bandwidth estimation and admission control for IEEE 802.11e in wireless multihop networks. In order to capture inter and intra-flow interferences, authors in [25] map conflicting links into a conflict graph and construct maximal cliques for ACs. There is an Access Point in the network which acts as a central scheduler. When a flow request arrives at the AP, via multiple hops, the AP computes clique capacities for the requested AC and takes the admission decision. The clique constraints are calculated for all the maximal cliques that the request has passed through on the multihop path to the AP. If all the relevant maximal cliques can support the required bandwidth, an admission decision is made, otherwise, the AP sends a rejection notification to the source node. There are three problems with this solution. First, this solution works for only flows directed at the AP as opposed to random destinations. Second, it is not a truly distributed multihop solution since all the admission decisions are taken by the central AP. Such a centralized approach may work well for small networks, but will be difficult to handle in a large scale distributed environments. Finally, the route taken by the flow request from the source node to the AP is dictated by the routing protocol, and the clique constraints are derived for this particular route. Such an approach may result in overlooking alternate, higher bandwidth routes or worse, the only feasible routes.

The lack of existence of a comprehensive mechanism for resource-reservation in multihop IEEE 802.11e wireless mesh networks provided the motivation for proposing an efficient bandwidth estimation and admission control solution for 802.11e based networks. The solution must work in a completely distributed multihop setting with each node functioning independently of others and without the assumption of any central authority. We propose a resource-reservation solution which can find the required-bandwidth path through the network and which can reserve the resources on that path. Our solution caters to multiple important factors including intra-flow and inter-flow interference, intricacies of accurate bandwidth estimation in a distributed network, and the protocol-specific features of 802.11e including the virtual collisions and differentiated priorities of different flows.

III. QoS-Aware Routing For 802.11e EDCA

A. Overview of Proposed Solution

Since it has been well established as a popular approach [26], [27], [28] for resource-reservation in wireless multihop networks, we also couple resource-reservation with a reactive routing protocol. In brief, the Route Discovery phase of reactive protocol is used to discover bandwidth-feasible routes as well as perform resource-reservation. More details about route discovery and other components of reactive routing protocol such as AODV can be found in [29]. A source node receives a request from a newly arrived flow with information about the intended destination and the bandwidth required. The node checks if sufficient bandwidth is available locally to accommodate this request. We call our proposed solution as QAr-EDCA(b) which we term as Quality of Service Aware Routing for EDCA for Bandwidth Estimation. We provide more details of this scheme in the next sections. If sufficient bandwidth is not available, the request is dropped. If sufficient bandwidth is available, a partial admission decision is made. The decision is partial because the route request packet may get lost as it traverses the network before reaching the des- tination, or this path may eventually be rejected due to lack of sufficient bandwidth at a later node. After the temporary reservation, the route request is broadcasted again and the next node(s) which receives this packet repeats the same process. A route request packet which makes it to the destination implies that the path it traversed has sufficient bandwidth available. The destination sends back a route reply over the traversed path to the source node. The reservation is made permanent on intermediate nodes as the route reply traverses the path back to the source. The proposed scheme QAR-EDCA(b) is a measurement-based scheme which estimates the available bandwidth based on a promiscuous listening approach.

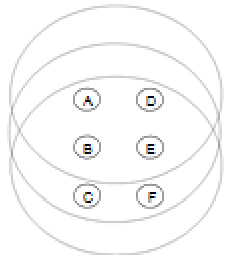

Fig. 1. Topology for promiscuous listening

B. B. Bandwidth Estimation for Measurement-Based Approach (QAR-EDCA(b))

1) Background: Promiscuous listening is also one of the techniques sometimes used for bandwidth estimation. Using promiscuous listening to estimate the available bandwidth is not a new concept and has been widely used [26], [30]. Promiscuous listening is based on the technique that a node can gratuitously monitor medium usage within its carrier sensing range, thereby "sensing" the ratio of time that the medium remains busy (or conversely, free). The listen based approach is very simple to use and does not cause extra message exchange to let a node aware about the bandwidth consumption by its interfering neighbors. However, a limitation of promiscuous listening is that it can result in inaccurate bandwidth estimation. The problem is that promiscuous listening is basically a crude metric for measuring available free air time since it does not guard against situations in which a nearby node is transmitting at a rate lower than that which it reserved for the flow.

To show the problem of inaccurate bandwidth estimation in solutions based on promiscuous listening, we simulate the topology shown in the Figure 1 in ns-2 with the six nodes all within each other's carrier-sensing range. Nodes A, B and C send UDP flows to nodes D, E and F respectively. Figure 3 shows the instantaneous throughput of three flows while Figure 2 shows the evolution of bandwidth estimations at the three nodes with time. When there was no flow in the network, the available throughput was 100% of the total network capacity. Node A starts its flow to node D at t=10s with a rate of 2000 Kbps. The available bandwidth goes to 37% after resources have been reserved for this flow and this flow starts to flow. Node B starts its flow at t=15s to node E with a rate of 1000 Kbps. As the requirement of flow2 can be maintained with the available amount of bandwidth, both flows are admitted and are currently transmitting.

After bandwidth reservation by flow2, the available bandwidth falls to 10% of the network capacity. At t=30s, flow 2 lowers its data rate by 500 Kbps. After t=30s, promiscuous listening estimates the available bandwidth to 23% of total network capacity again, due to reduced data rate of flow2. An additional flow (flow 3) now reserves bandwidth of 1000 kbps at t=60s. At t=70s, flow 2 starts transmitting at its actual reserved rate, i.e. 1000 Kbps. Now the network becomes

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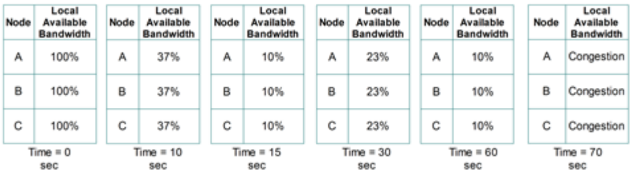

Fig. 2 Status of available bandwidth estimations at nodes

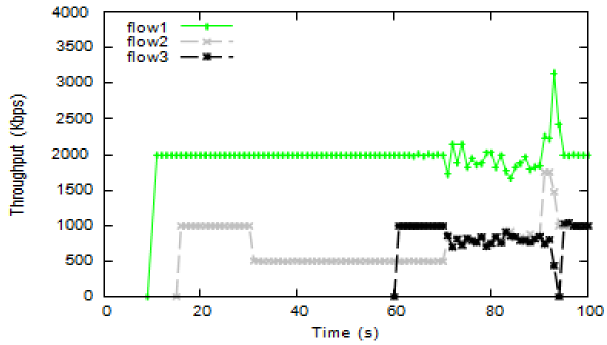

Fig. 3 Bandwidth estimation with promiscuous listening

TABLE I
SIMULATION PARAMETERS

Simulation Paramters	Values
Antenna	Omni Directional
Propagation Model	Two-Ray Ground
Mac Protocol	IEEE 802.11e
Slot Time	20 µs
Short Inter-frame Space (SIFS)	10 µs
ACvo CW	7-15
ACvi CW	7-15
Short Retry Limit	4
Long Retry Limit	7
Simulation Time	100 sec
Simulation Area	1500 * 600 meter
Physical Data Rate	11 Mbps

or too slow response to changing network conditions. Every node can perform promiscuous listening and can estimate the available bandwidth per second by measuring the free air time ratio.

To evaluate the effectiveness of the proposed scheme whichcongested for all the three flows as shown in the Figure 3 as the network capacity has been exceeded.

The proposed approach - QAR-EDCA(b) has negligible routing overhead. Moreover, none of the existing schemes guard against inaccurate bandwidth estimation scenario de- scribed above. To overcome this drawback, this paper provides a mechanism to accurately estimate the bandwidth consump- tion in neighborhood. In our proposed approach, to provide accurate available bandwidth estimation, every node, which starts transmitting a single or multiple flows at a rate lower than its reserved rate, intimates all its carrier-sensing neighbors by broadcasting a high-power message with TTL value of one, named as an ”explicit” message. The message contains the difference between the reserved transmission rate and the actual transmission rate for a single or multiple flows traversing that node. This message will be receive by all carrier sensing neighbors of sender. In this way all neighboring nodes will be able to subtract the specified amount of bandwidth from their estimations based on promiscuous listening. To optimize performance and minimize routing overhead, this explicit message is only transmitted by nodes which start sending data at less than the reserved rate and the message is sent once. To cater the case if the message is not received by some neighbors, the message is repeated but after a long interval (around 10 seconds), causing negligible overhead. In order to measure the free air time present on the wireless medium, in our proposed schemes, each node periodically checks the status of the medium using promiscuous listening.

we term ”Explicit Message”, we conduct a simulation using parameters mentioned in the Table II (section IV) for the topology of Figure 1 and compare it with the techniques used in [26] and [28]. The MARIA scheme in [28] shares the dynamic flow rate information of each node periodically with its carrier sensing neighbors through a high-powered hello message, while [26] sends hello messages via multiple hops containing bandwidth consumption information. Both techniques, in addition to prone to erroneous bandwidth esti- mation, also cause significant routing overhead. Our proposed technique accurately estimates the available bandwidth and minimizes the routing overhead significantly as shown in the Figure 4 because messages are only generated if a node is transmitting at less than the reserved rate.

It is pertinent to mention that the proposed mechanism QAR-EDCA(b) does not, in any way, snoop on the actual data or even the packets of any flow. In fact, we are only interested in finding out the medium occupation percentage around each node. Every node calculates the available bandwidth by measuring the ”Free Air Time” around it periodically.

C. Integrating Virtual Contention

The bandwidth estimation that we have done so far, captures the available bandwidth at a node with respect to external factors, primarily, the bandwidth consumption by flows on nodes within the carrier-sensing range of the node. We have so far, purposely neglected the self-traffic of the node. In IEEE 802.11e, the bandwidth available to a node derived so far is further divided for different flows within the node. In IEEE 802.11e, there are four Access Categories at each node The available bandwidth AB(b) for the QAR-EDCA(b) therefore, the aggregate sum of traffic Fn generated by a node scheme, excluding self-traffic is calculated for every time of window T as:

$$\mathcal{AB}_n^{(b)} = \frac{\text{Free Air Time in } T}{T} \times \mathcal{R} \qquad (1)$$

i can be expressed as:

$$\mathcal{F}_n = \sum_{i=0}^{3} \mathcal{T}_{AC_i}^{n} \qquad \forall n \in \mathcal{V} \qquad (2)$$

We select this window to be 2 seconds, which is a reasonable tradeoff without causing very frequent fluctuations in value where $T^n_{AC_i}$ is the traffic generated by the Access Category i of node n. Let $AB^{(b)}_{n,AC_i}$ be the bandwidth available to the

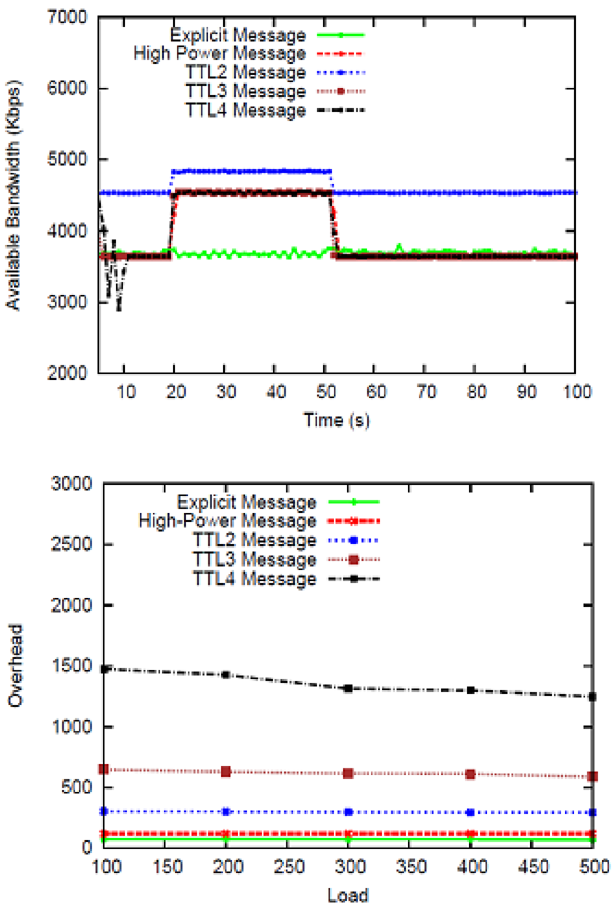

Figure 4

Access Category i, at node n for QAR-EDCA(b) scheme, then we can calculate that:

$$\sum_{i=0}^{3} \mathcal{T}^{n}_{AC_i} \leq \mathcal{AB}_n \qquad \forall n \in \mathcal{V} \tag{3}$$

$$\mathcal{AB}^{(b)}_{n,\,AC_i} = \mathcal{AB}^{(b)}_{n} - \sum_{j=0}^{3} \mathcal{T}^{n}_{AC_j} \qquad \forall n \in \mathcal{V},\; i \in \{0,1,2,3\} \tag{4}$$

Note that the above expression includes the traffic generated by the queue i itself as well. In IEEE 802.11e, each Access Category behaves as a separate entity and contends for medium access independently. If two or more ACs attempt to access the medium at the same time, there is a virtual collision which is different from an actual collision on the wireless medium. The virtual collision occurs, and is handled, within the node. Since the Access Categories mutually interfere, therefore, the effective available bandwidth is reduced by a factor. We carried out a simulation experiment to evaluate the factor by which the effective throughput is reduced for a node under saturated conditions (i.e. all the ACs are backlogged and always have a packet to send). We assumed a simple topology of two nodes within each other's communication range and first admit a single flow. Other flows and nodes are excluded from this simulation as we are not focusing on inter-flow interference. Moreover, we are not considering a multihop topology because we also don't want the impact of intra-flow interference on the results. We aim to study the impact of virtual collision of four ACs in a simple, isolated setting.

We first find out the maximum supportable data rate between

the two nodes for a single UDP flow, which we find out to be equal to be 5500 Kbps. Therefore, when there was no other flow in the network, the considered flow gets its required bandwidth of 5500Kbps. We now replace this single flow with four flows which belong to ACs 0-3 on the same node with the lump-sum required bandwidth of 5500Kbps. However, as we see, the throughput for the four admitted flows is not sufficient if we assume our effective available bandwidth to be still 5500Kbps. We need to reduce the available bandwidth by a factor in order to capture the impact of virtual collisions and the resulting internal back-offs. To Find out the factor by which we must reduce the available bandwidth, we perform five simulations with different reduction factors and results of these simulations are presented in the Figure 5. It can be seen that with a multiplying factor of 0.7, the instantaneous throughput of admitted flows get stable, with the admission control rejecting the 4th flow due to insufficient bandwidth. Based on this experiment and some others, we conclude that a factor of 0.7 provides the upper limit on the effective reduction in the available bandwidth at a node under saturated conditions. The effective bandwidth available at node n to an Access Category i for QAR-EDCA(a) becomes:

$$\mathcal{AB}^{(b)}_{n,AC_i} = \left(\left(\frac{\text{Free Air Time in } T}{T} \times \mathcal{R}\right) \times 0.7\right) - \sum_{j=0}^{3} \mathcal{T}^{n}_{AC_j} \tag{5}$$

D. D. Integrating Intra-Flow Interference

Intra-flow interference also plays an important role in mesh networks. In mesh networks, nodes along a path which lie within the carrier sensing range also interfere with each other for access to the medium for the same flow. This kind of interference is known as intra-flow interference. Since we assume the carrier sensing range to be around 550m, therefore, at least two preceding nodes in the multihop path will interfere with the current node for the same flow. There may be another node, also included in the multihop path, which lies just within the carrier sensing range but outside the two-hop range as shown in the Figure 4. In such cases, the actually required bandwidth will be three times the requested bandwidth. We let the variable *B* be defined as:

$$\beta = \begin{cases} 2: & \text{If 2 nodes in the preceding multihop path} \\ 3: & \text{Otherwise} \end{cases}$$

The actual bandwidth required by a flow at the current node will then be a factor of the product of bandwidth required and the factor *B*.

1) Final Admission Decision Expressions: In this section, we provide the final expressions for admission control for the measurement-based QAR-EDCA(b) scheme. For the measurement-based QAR-EDCA(b), the following inequality is checked:

$$\mathcal{B}_{REQ} \times \beta \leq \mathcal{AB}^{(b)}_{n,\,AC_i} \tag{6}$$

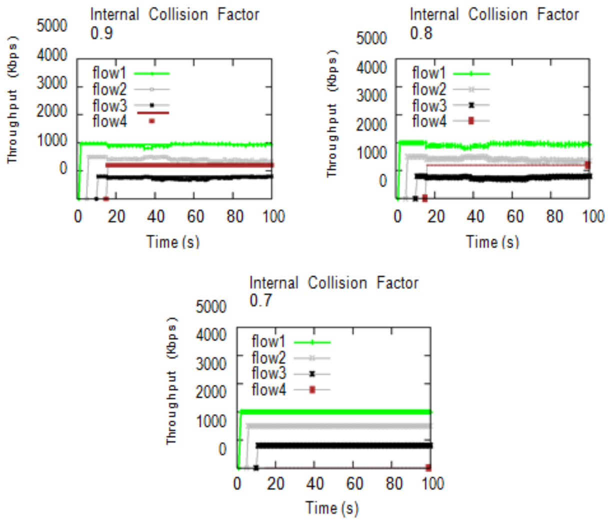

Fig. 5 Multiplying factor to capture virtual collision

TABLE II
SIMULATION PARAMETERS

Simulation Paramters	Values
Antenna	Omni Directional
Propagation Model	Two-Ray Ground
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ACvo CW	7-15
ACvi CW	7-15
Short Retry Limit	4
Long Retry Limit	7
Simulation Time	100 sec
Simulation Area	1500 * 600 meter
Physical Data Rate	11 Mbps

If this equation is satisfied, admission control is done and a temporary reservation is made that has a time limit. The relevant fields in the header of the Route Request packet are updated and the packet is rebroadcasted. Eventually, it is received at the destination if the route which it has followed, has sufficient bandwidth available. The destination sends a unicast route reply message back over the same route. On receipt of this message, the reservation is made permanent

IV. PERFORMANCE EVALUATION

The proposed schemes are evaluated using the ns-2 simulator with TKN Berlin implementation for IEEE 802.11e EDCA model [31]. We evaluate the proposed approach and compare it with the admission control for multi-hop WLAN proposed in [25], which we call "Multihop-WLAN". The performance evaluation is performed for the grid topology and we give the instantaneous throughput, instantaneous end-to-end delay and routing overhead metrics for performance evaluation. Simulation Parameters- Every node is equipped with omni- directional antenna with a single radio and has the same propa- gation model i.e Two-Ray Ground model. The communication range is set to 250m while the carrier-sensing range is set to 550m. Every node transmit packets with the transmission power of 0.281838W and covers an area with a radius of 250m. However, every high-powered message is sent with sufficient to cover all nodes in the carrier sensing range (550m). The simulation parameters are given in the Table II.

Protocol Stack- At MAC layer, we use IEEE 802.11e. The AODV routing protocol is used at the network layer in order to couple the admission control with its Route Discovery process. We have CBR (Constant Bit Rate) traffic generator for traffic generation over UDP. TCP has its own built in mechanism for load balancing and congestion control and in order to avoid these, we used UDP.

Topology and Traffic Settings - We have evaluated our proposed scheme over three different types of topologies. The first topology is a linear topology, shown in the Figure ?? consisting of 8 nodes and 5 flows belonging to different ACs (Voice and Video) with different data rates. Flow details for the linear topology are given in the Table ??. The second topology consists of a 4 × 3 grid topology of 12 nodes with 7 flows. Flow details for the grid topology are given in the Table III. The last topology comprises of 10 UDP flows over 10 random topologies with each topology consisting of 25 nodes, scattered over the simulation area of 700m × 1500m.

Finally, we also carry out the performance evaluation of the three schemes for Variable Bit-Rate (VBR) Traffic in order to study the impact of dynamic flows on the performance of the three schemes.

TABLE III
FLOW SPECIFICATION FOR GRID TOPOLOGY

Flow	AC	Required Rate	Start Time
1	AC-Vo	50 Kbps	10th sec
2	AC-Vi	300 Kbps	20th sec
3	AC-Vo	100 Kbps	30th sec
4	AC-Vi	400 Kbps	40th sec
5	AC-Vo	150 Kbps	50th sec
6	AC-Vi	500 Kbps	60th sec
7	AC-Vo	200 Kbps	70th sec

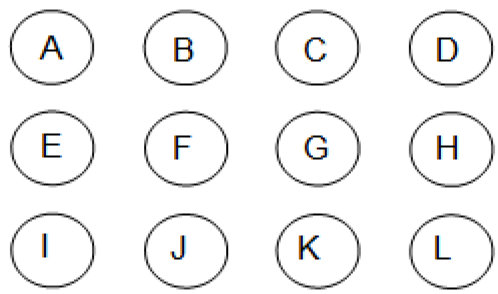

Fig. 6 The 4x3 grid topology

A. *Performance Evaluation over Grid Topology*

The grid topology consists of 12 nodes, placed at a distance of 230 meters from each other, as shown in Figure 6. The flow settings are shown in the Table III. In comparison to the linear topology, the grid topology is denser and generates a greater amount of interference. Figure 7 shows the instantaneous throughput and end-to-end delay results for the three schemes. As the results show, Multihop-WLAN admits four flows and rejects admission to three flows.

For Multihop-WLAN, the reason is due to not considering all possible routes and instead focusing on a single route, pre-selected by the protocol. QAR-EDCA(b) admits the highest number of flows to the network with only a single rejected flow.

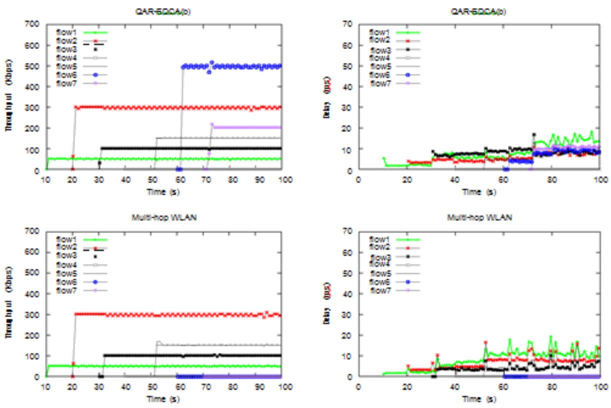

Fig. 7 Instantaneous throughput and instantaneous end-to-end delay over grid topology

The aggregate data rate of the flows admitted by QAR-EDCA(b) is 1300Kbps, a sum far superior to the Multihop-WLAN scheme. QAR-EDCA(b) uses actual measurements of the medium assisted with explicit messages to gauge the precise bandwidth available. The model-based scheme has the disadvantage of stringent clique constraints which are sometimes worse than the actual scenario, resulting in an under-allocation of the medium bandwidth. For Multihop-WLAN, the problem remains that of still being a model-based approach and that the route selection is not appropriate as the route is not discovered but an existing route is just verified to see if it offers enough bandwidth.

In terms of the end-to-end delay, the delay offered by both schemes remains within 20ms for all the considered flows. The delays observed should be noted keeping in view that Multihop-WLAN admits fewer flows than the other schemes and hence the flows have less interference between them. Overall, for the given flows, all three schemes provide delays within reasonable bounds and are comparable to each other, hence no scheme outperforms the other in terms of end-to-end delay.

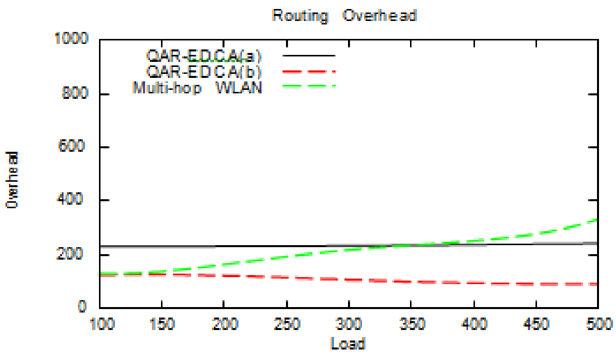

Fig. 8. Routing overhead for grid topology

The last metric for the grid topology is the routing overhead. Figure 8 shows the routing overhead for the two schemes. The results indicate that for the considered loads, the routing over- head is more or less similar. However, for larger topologies, the routing overhead increases for Multihop-WLAN since it needs to exchange data packets for computing the clique constraints. For QAR-EDCA(b) the routing overhead packets are gen- erated for exchanging traffic details between nodes within the maximal cliques. However, we use the optimization in which nodes only inform each other if they admit a new flow. Otherwise, the flow bandwidth reservations remain the same and are not exchanged repeatedly unless a new flow is admitted or an existing one finishes. Due to these optimizations for both the schemes, the number of routing packets remain constant regardless of the load.

V. Conclusion

Traditionally, IEEE 802.11e has been popular for Wire-less Local Area Network scenarios in which the service differentiation offered by 802.11e is used to provide QoS to different flows. However, with the recent popularity of wireless mesh networks, it is pertinent to explore resource-reservation based solutions for 802.11e in mesh networks. Few existing works in the area propose a distributed solution for resource-reservation in 802.11e mesh networks. Moreover, important issues such as intra-flow and inter-flow interference and collisions (both actual and virtual) are neglected by existing works for bandwidth estimation and flow admission. We propose a bandwidth-reservation solution for 802.11e mesh networks in which promiscuous listening is used along with the use of explicit messages by nodes which are transmitting at less than the reserved rate to avoid incorrect bandwidth estimation by neighbors. We then capture the impact of virtual collision between different Access Categories of 802.11e on the available bandwidth. We also integrate the impact of intra- flow interference on the bandwidth of the incoming flow.

Based on the performance evaluation carried out over a range of topologies and traffic settings, we conclude that listen- based QAR-EDCA(b) is not only simple to implement, but also gives decent results over a wide range of topologies. More generally, we can conclude that 802.11e can be used effectively in wireless multihop environments for providing service differentiation and bandwidth guarantees to multihop flows. However, in order to provide QoS to flows in these networks, well-designed QoS solutions must be implemented. The tradeoff for schemes such as QAR-EDCA (b) is that while they ensure relatively precise bandwidth estimation and admission control, due to their approach of fixing of bandwidth reservation to the maximum bandwidth required, some bandwidth can remain unutilized, but this mechanism on the other hand ensures that a varying flow will never violate the bandwidth contract of neighboring flows. Overall, we conclude that 802.11e can be used effectively in wireless mesh networks provided resource-reservation and admission control mechanisms are in place

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