Abstract—We consider the problem of supporting VoIP calls over a wireless mesh network. We particularly consider the call admission control (CAC) decision problem for VoIP calls on a mesh network. The goal of the call admission decision is to maintain the quality of VoIP calls as given by the R-score measure. In this work, we define a notion of interference capacity model that can be efficiently used to design a CAC algorithm. We show through extensive simulation of 802.11 mesh using ns-2, that our CAC performs well in multi-hop scenarios. Specifically, the proposed CAC provides less than 20% incorrect decisions for different sizes of a multihop linear topology.

I. INTRODUCTION

A. Background

Voice over IP (VoIP) such as skype [1] is an emerging application in the Internet. The cost savings achieved by VoIP by using existing data infrastructures along with easy deployment benefits are the main reasons driving the steady growth of VoIP. At the same time, VoIP over wireless LAN (WLAN) has the potential of becoming an important application due to the ubiquity of the WLAN in homes and offices. With the advent of dual cell phone handset with WiFi capabilities and softphones over PDAs, carrying voice over the WLAN is gaining a significant importance. Once VoIP over WLAN becomes widespread, most cell phone or WiFi handset owners will migrate to using VoIP over WLAN inside the administrative boundaries of the enterprise buildings, campuses, public places such as airports or even in WLAN equipped homes.

Providing VoIP users with true mobile phone services having the freedom of roaming requires wide area wireless coverage, and IEEE 802.11-based multihop wireless mesh networks have been considered a practical solution for wide area coverage. The benefits of mesh network compared to wired LAN connecting WiFi access points are: i) ease of deployment and expansion; ii) better coverage; iii) resilience to node failure; iv) reduced cost of maintenance. Such a mesh network has the potential of creating an enterprise-scale or community-scale wireless backbone supporting multiple users while driving these users from using fixed phones to wireless VoIP phones. However, supporting delay sensitive realtime applications such as VoIP over wireless mesh network is a challenge.

B. Motivation and contribution

In this paper, we investigate the VoIP call admission control with a model-based approach. Interference is one of the major factors that limits the performance of wireless mesh networks. An accurate network capacity model should consider the interference factor in a wireless mesh network. To support call admission control for VoIP in wireless mesh, we first build an interference-aware capacity model and then admit arriving calls based on this mesh network call capacity model. Compared to a measurement-based call admission control approach, this model-based approach could provide guidelines for network deployment and provisioning in addition to providing call admission control mechanism as calls arrive. The model based approach also avoid fluctuating call admission results due to short-term wireless channel quality variation.

An analytical VoIP call capacity model could not be easily derived due to non-linear behaviors resulting from multiple interactions between multihop relay routing, 802.11 random access control, and the complicated non-linear R-score call quality measure. Therefore, we apply the estimation technique to derive the capacity model. The estimated capacity model is first created by topology-specific call capacity and then validated through generic scenarios.

In the first part of the paper, we explain the interference-aware call capacity model. We also estimate the call capacity based on VoIP simulation results in chain-topologies.

In the second part of this paper, we consider generic CAC application scenarios with random mesh node locations and random traffic source-destination traffic pattern. The ns-2 simulations of random topology with random traffic pattern are applied to verify the effectiveness of CAC algorithm.

C. Related work

Initial study on the performance of real-time applications over 802.11 was presented by authors in [3], [4]. Study focussing specifically on VoIP over 802.11 in [5], [6] considered the delay and loss characteristics under PCF and DCF mode. Another recent work on VoIP over WLAN in [7] presents analytical studies on the number of calls that can be supported in a single hop WLAN. The study reports that increasing the payload per frame increases the number of supported calls.

Several performance optimization schemes were proposed for WLAN in improving the VoIP quality such as in [8], [9]. Authors in [8] propose the use of dual queue of 802.11 MAC to provide priority to VoIP while [10] proposed packet aggregation to increase capacity.
Recently, a significant research has been conducted in the area of 802.11 based wireless multihop mesh network. Study was conducted to understand the capacity of multihop network as presented in [2].

II. VOICE QUALITY MEASURES

To measure the quality of a call, we used a metric proposed in [11], which takes into account mouth to ear delay, loss rate, and the type of the encoder. Quality is defined by the $R$-score, which should provide a value above 70, for medium quality:

$$R = 94.2 - 0.024d - 0.11(d - 177.3)H(d - 177.3) - 11 - 40\log(1 + 10e)$$

where:
- $d = 25 + d_{jitter,buffer} + d_{network}$ is the total ear to mouth delay comprising 25 ms vocoder delay, delay in the de-jitter buffer, and network delay
- $e = e_{network} + (1 - e_{network})e_{jitter}$ is the total loss including network and jitter losses
- $H(x) = 1$ if $x > 0$; otherwise is the Heaviside function
- the parameters used are specific to the G.729a encoder with uniformly distributed loss

Unlike circuit-based networks which has call admission control, determining whether a packet network has the resources to carry a voice call is not a simple undertaking. Without admission control mechanisms, new traffic may keep entering the network even beyond the network capacity limitation; consequently making both the existing and the new flows suffer packet delay and loss. To prevent these occurrences, admission control mechanisms should be at place. Figure 1 shows how introducing one more call beyond the network capacity despairs the quality of the existing calls. In chain topology with 6 hops, of which maximum capacity is two calls, adding one more call at 50 seconds over the capacity of the network makes packet drops increased, jitter larger, network delay longer of the calls, which degrade the quality of the existing calls as well as the new call to 0.

A. Impact of additional call over link capacity

Figures 2 and 3 show the network statistics when a call is added beyond the capacity. In this example, we consider a single 802.11 link supporting VoIP with R score greater than 70. The figures show the queueing delay and the average throughput over time. With 8 calls, the capacity is still met as shown in Figure 2. In this case, the queue delay is almost zero and the throughput is stable as well. When the 9th call is added to the link, the behavior is shown in Figure 3. The queueing delay increases to 430 msec from 2 msec, the queue length increases to 196, which increases average end-to-end delay of all calls from 3 msec to 300 msec, making quality (R score) of the existing calls as well as the new call to 0, the throughput increased to 320 KBps though.

III. INTERFERENCE MODEL IN WIRELESS MESH NETWORKS

An interference model is built for the creation of VoIP call capacity model. When a node is transmitting, all nodes within this node’s interference range is said to be interfered. In IEEE 802.11 based network, we consider the maximum range that
an RTS or a CTS message could be correctly received as the interference range.

Now we construct the interference model for a multihop VoIP call. The interference model in mesh networks includes interference state variable \( s_j \) for each node \( n_j \). As a node transmits the packet on the multihop route, all nodes within the interference range of the active node increase their interference state by 1.

In a wireless mesh network, initially, when no VoIP calls are admitted to the network, \( s_j \) is set to 0 for all nodes. When a VoIP call is established through a multihop route, there will be several active transmissions \( t_k \), in which node \( n_k \) is the transmitter. If \( n_j \) is within the interference range of \( n_k \), which implies node \( n_j \) is under the interference of this active transmission, then we add 1 to \( s_j \). An interference state example is illustrated in Figure 4.

![Fig. 4. A 6-hop VoIP interference state example](image)

Numbers within the nodes are the interference state of a bi-directional call. The nodes are placed just within the transmission range. Interference range and transmission range are shown with the IEEE 802.11 default values in NS-2 simulator, which we use for evaluation.

Now we determine the interference state of VoIP call in chain topologies. VoIP calls are placed between two end nodes of the chain topology. Number of packet loss and call delay are simulated with NS-2 simulator. The R-score [11] is computed to evaluate the call quality (R-score greater than 70 is considered as acceptable quality). The IEEE 802.11b MAC is used with the default 250-meter transmission range, and the 550-meter interference range. The WLAN link rate is 11 Mb/s. Mesh nodes are placed 250 away from each other. G.729a codec is assumed for VoIP traffic model.

In the table I, we illustrate the maximum number of calls that can be placed in linear topologies with different number of hops. The interference states of nodes are computed for these scenarios. We define the maximum \( s_j \) as the interference factor \( f_{int}(m) \) of an m-hop call. In this interference-aware capacity model, the interference capacity, \( c_{int} \), of an m-hop linear multihop network is defined as the product of \( f_{int}(m) \) and the maximum number of calls along the m-hop route. The \( f_{int}(m) \) is proportional to the maximum radio resource a VoIP call is expected to consume at the bottleneck. The interference capacity \( c_{int} \) represents the maximum total amount of radio resource that the network bottleneck consumes when the maximum number of VoIP calls are simultaneously admitted to this network.

<table>
<thead>
<tr>
<th>hop</th>
<th>( f_{int} )</th>
<th>max call</th>
<th>( c_{int} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>6</td>
<td>24</td>
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</tr>
<tr>
<td>9</td>
<td>9</td>
<td>2</td>
<td>18</td>
</tr>
</tbody>
</table>

![TABLE I
INTERFERENCE CAPACITY FOR A LINEAR TOPOLOGY](table)

Based on the information obtained from chain-topology simulation, we estimate the interference capacity for generic random topology. We consider two types of call capacity model: (1) call capacity is independent of the number of hops (2) call capacity depends on the maximum number of hops. We built two call admission control policies based on these two different assumptions. The first model is termed constant capacity model while the second model is termed linear capacity model.

As shown in Figure 5, the notation CAC1 is the constant estimation model and CAC2 is the linear estimation model. First, based on a constant model \( c_{int} = k \), we could estimate parameter \( k \) to build a constant \( (c_{int}) \) capacity model termed CAC1. Based on the minimum mean square error principle (MMSE), the derived result is actually equivalent to the mean of all data points in this case. In the second case, a linear regression model, \( c_{int} = k \cdot m \), is applied to estimate capacity values that are dependent on the number of hops of a VoIP call. The CAC2 algorithm adopts the estimated hop-dependent capacity bound for call admission control.

![Fig. 5. Call admission control with 11Mb/s WLAN](graph)

IV. CALL ADMISSION CONTROL WITH INTERFERENCE CAPACITY

After we estimated the maximum interference capacity, we could conduct call admission control based on this model. When a VoIP call arrives in the mesh network, the interference
state is computed. If all the interference state values are under the maximum capacity, this call is admitted; otherwise, the call is rejected.

We evaluate the proposed model and the corresponding CAC validity with randomly generated node location and randomly selected VoIP node pairs. An example random mesh topology is shown in Figure 6. We examine the two call admission control policies with random VoIP node pairs. NS-2 simulations are conducted for the admitted VoIP call pairs and the R-score is computed to evaluate the call quality. R-scores of the 2 CAC algorithms for three random scenarios are given in Table II.

In addition, we also want to find out whether the two capacity models give tight upperbounds. A good call admission control policy makes sure that quality of all admitted calls is good. Nevertheless, a call admission control might admit a limited number of calls and under utilizes the network resource. We examine the two policies with relaxed interference capacity bounds. We admit VoIP calls based on \((100 + x)\%)\) of the interference capacity \(c_{int}\). The value of \(x\) is gradually increased until the R-score becomes extreme low.

In Figure 7, we show the R-score with capacity bound from tight to loose in the 3 random examples in the respective subplots. We found that CAC1 policy performs well. All calls that are admitted by CAC1 have a good R-score. In addition, the capacity bound of CAC1 is a tight upperbound. The actual allowable interference capacity is 110\%, 130\%, and 110\% of the estimated bound respectively. Meanwhile, CAC2 is not adequate for the call admission control for wireless mesh VoIP. In one case, the R-score of CAC2 admitted VoIP calls is 0, which is caused by severe packet loss and extensive packet delay. As readily observed, the CAC2 actual allowable interference capacity is looser compared to the bound in CAC1. Therefore, the hop-count independent interference capacity model fits better, and the corresponding admission control policy is more suitable for VoIP call in wireless mesh.

### A. Call Admission Control in 802.11 mesh with 2Mb/s rate

In addition to the call capacity model and call admission algorithms for IEEE 802.11b 11Mb/s WLAN mesh networks, we also investigate the 2Mb/s IEEE 802.11 WLAN mesh. The interference capacity for 2Mb/s for linear topology is given in Table III. As we expected, the VoIP call admission control with 2Mb/s WLAN has similar performance results as the previous 11Mb/s case except the number of allowed VoIP calls reduces. The maximum number of VoIP calls in chain topologies with variable length is given in Table III. The maximum number of VoIP calls in 2Mb/s chain topology, interference factor and interference capacity is given in the table below. The interference capacity and the two capacity estimations based on the simulation results are shown in Figure 8.

Some 2Mb/s R-score results on the random topology are shown in Table IV. In the simulated scenarios, all calls with call admission control algorithm have good R-score. Similar to the 11Mb/s case, CAC1 policy, which has a tight upperbound, performs better than CAC2 policy. As a result, we could conclude the CAC1 algorithm is a better choice for admission control.
TABLE IV
COMPARISON OF CAC1 AND CAC2 FOR 2MB/s

<table>
<thead>
<tr>
<th>scenario</th>
<th># of calls</th>
<th>max hops</th>
<th>ave hops</th>
<th>R-Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)CAC1</td>
<td>4</td>
<td>4</td>
<td>2.25</td>
<td>80.53</td>
</tr>
<tr>
<td>CAC2</td>
<td>4</td>
<td>4</td>
<td>2.25</td>
<td>80.53</td>
</tr>
<tr>
<td>(b)CAC1</td>
<td>2</td>
<td>7</td>
<td>4.00</td>
<td>81.27</td>
</tr>
<tr>
<td>CAC2</td>
<td>5</td>
<td>3</td>
<td>1.80</td>
<td>73.51</td>
</tr>
<tr>
<td>(c)CAC1</td>
<td>4</td>
<td>3</td>
<td>1.50</td>
<td>81.32</td>
</tr>
<tr>
<td>CAC2</td>
<td>5</td>
<td>3</td>
<td>1.40</td>
<td>81.34</td>
</tr>
</tbody>
</table>

B. Percentage of incorrect decisions

We now compare for both rates 2Mb/s and 11Mb/s the percentage of incorrect decision for CAC1 policy. We define as incorrect decision when the following two conditions are not satisfied: condition 1 (false positive): addition of a call that does not satisfy the R-score requirement or capacity constraint is not met; condition 2 (false negative): rejection of a call where there exist available capacity to admit the call.

Figure 9 shows the percentage of incorrect decision for different number of hops for flows with random source and destination pairs. We note that the percentage is almost below 20%. With increase in hops for more than five, the percentage increase slightly. There is no noticeable difference between the two rate (2Mb/s and 11Mb/s) cases.

Figure 10 shows how the percentage of incorrect decision varies with load. In order to demonstrate this behavior, we plot the percentage of incorrect decision for different callid. A callid i arrives before callid i+1 in the graph. We note that after some point (say 10 for 11Mb/s), the percentage is zero as at this point, the capacity is already met. Therefore, the major part of incorrect decision is at medium load (2 to 7 callids). However, the percentage remains on average below 30.

C. Observations in call quality related statistics

In this section, we further examine packet delay, packet loss rate, jitter, and R-score of the calls in a wireless mesh network. In Figures 11 and 12, we show several call statistics measured in the same 11Mb/s mesh topology with the different number of VoIP call pairs. The number of calls are 11, 10, and 11 in each of the configuration. In these scenarios, 9 admitted VoIP calls are the same. One or two different admitted calls make the VoIP quality varies significantly. We plot statistics of all the simultaneous (10 or 11) VoIP calls in the same subgraph.

In Figure 11, the call quality is excellent. The VoIP calls are admitted based on the CAC1 algorithm. There are two small periods with some packet losses. Packet delay typically is less than 10 ms, and delay jitter occurs occasionally.

In Figure 12, the call quality is poor. The VoIP calls are admitted based on the CAC1 algorithm with 120% capacity bound. In 22 R-score values (i.e. 11 bi-directional calls), only 17 of them are greater than 70, which is the threshold for acceptable call quality. Some calls have 0 R-score due to severe packet loss and extreme delay. Packet delay could easily go up to 600 ms and could be as high as 900 ms. Burst packet loss and strong variation in delay jitter are also observed. Ten out of the 11 calls in this case and the excellent quality case are the same. The only difference is one 4-hop call is used for instead of 2-hop call in the first case. Although, it is only a small difference in call admission control, the QoS of the whole VoIP mesh network could be adversely affected.

As we observe, the VoIP call quality degrades dramatically when admitting more calls beyond the supportable capacity of the mesh network. Call admission control based on simply counting the number of calls does not work in wireless mesh...
environment. In addition, the variation in call quality related statistics could be observed. Call admission control based on short-term delay or packet loss statistics may result in unstable system performance.

V. CONCLUSION

In this work, we consider the call admission decision for VoIP calls for wireless mesh network. The goal of CAC decision is to maintain the R-score of the existing calls while maximizing the number of admitted calls. We propose an Interference capacity model for a mesh network, based on which, we define two CAC schemes. We find our proposed CAC provides a tight upper bound and attains less than 20% incorrect decision for various size of the topology and different rate (2Mb/s and 11Mb/s).

REFERENCES