An Analytical Model for the Capacity Estimation of Combined VoIP and TCP File Transfers over EDCA in an IEEE 802.11e WLAN

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***Abstract*— In this paper we develop and numerically explore the modeling heuristic of using saturation attempt probabilities as *state dependent attempt probabilities* in an IEEE 802.11e infrastructure network carrying packet telephone calls and TCP controlled file downloads, using Enhanced Distributed Channel Access (EDCA). We build upon the fixed point analysis and performance insights in [1]. When there are a certain number of nodes of each class contending for the channel (i.e., have nonempty queues), then their attempt probabilities are taken to be those obtained from saturation analysis for that number of nodes. Then we model the system queue dynamics at the network nodes. With the proposed heuristic, the system evolution at channel slot boundaries becomes a Markov renewal process, and regenerative analysis yields the desired performance measures.**

The results obtained from this approach match well with ns2 simulations. We find that, with the default IEEE 802.11e EDCA parameters for AC 1 and AC 3, the voice call capacity decreases if even one file download is initiated by some station. Subsequently, reducing the voice calls increases the file download capacity almost linearly (by 1/3 Mbps per voice call for the 11 Mbps PHY).

I. Introduction

In order to guarantee the QoS requirements in IEEE 802.11 WLANs, the IEEE 802.11e group has developed MAC enhancements to support QoS sensitive applications and has proposed the IEEE 802.11e standard [2]. This standard introduces an enhanced, distributed, contention-based access scheme, called Enhanced Distributed Channel Access (EDCA), that offers the possibility to define four different classes of service at the MAC layer so that QoS requirements of the multimedia traffic can be supported in addition to data traffic. At the MAC layer, each service class is called an *access category* (AC), and service between classes is differentiated by different set of parameters to contend for the channel.

Performance analysis of IEEE 802.11e WLANs has become an active research area. While many simulation studies have been reported [3], [4], [5], [6], it is important to develop analytical models. An analytical modeling exercise provides insights into the working of the system and leads to a more general understanding of the effects of various parameters, and design choices, than many simulation runs. Further, these models may provide general guidelines for admission control and MAC parameter optimization, and may lead to ideas for novel adaptive MAC algorithms. The availability of good analytical models is also useful for developing fast simulations [7], [8], [9].

Model based performance analysis of EDCA 802.11e WLANs have been proposed in [10], [11], [12], [13], [1]. Robinson and Randhawa [11] and Zhu and Chlamtac [12] consider a WLAN with saturated nodes (nodes that always have packets to transmit). Ramaiyan et al. [1] extend the fixed point analysis of Kumar et al. [14] for a single cell IEEE 802.11e WLAN with saturated nodes and propose a general fixed point analysis that captures the differentiation by minimum contention window (CW), maximum CW and arbitrary interframe space (AIFS).

With real traffic, however, the nodes are not always saturated. Shankar et al. [13] evaluate the VoIP capacity in 802.11e WLAN, but in a scenario where other classes of traffic are not coexistent in the WLAN. Clifford et al. [15] have proposed a model for 802.11e for different classes of traffic when the nodes are nonsaturated. This model yields throughputs of various flows. The authors do not model the buffer dynamics for different traffic types.

Our Contribution: We provide a model that can predict the performance of a single cell infrastructure IEEE 802.11e WLAN, under a scenario where VoIP and TCP controlled data traffic are carried over EDCA. We model the queue dynamics at different nodes as per the considered application traffic. Using the model, we find the maximum number of voice calls that can be carried with and without file downloads and the aggregate file download throughput for each number of admissible voice calls.

We take advantage of the fact that the 802.11e MAC layer works on system slot boundaries. A system slot is the time unit employed for discrete-time backoff countdown. We replace the real WLAN with a system where each station transmits its head-of-line packet (if it has one) in a slot with a probability that depends only on the set of stations contending for the channel at that time, i.e., the set of stations that have packets to send. These attempt probabilities are approximated using the saturation analysis in [1]. The intervals between the instants at which our Markov chain is embedded are random, but together these constitute a Markov renewal process. We will show by simulations that such an approach is valid and provides good insights into the performance of 802.11e WLANs. ■

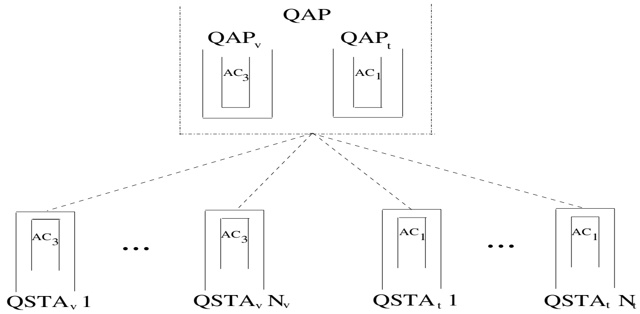

Fig. 1. An IEEE 802.11e WLAN model scenario where VoIP calls and TCP traffic are serviced on EDCA

Paper Outline: In Sec II we discuss the approach for modeling along with the observations and assumptions of the network and the traffic. In Sec III we formulate a Markov renewal framework, by using the state dependent attempt probabilities of [1]. In Sec IV we derive the performance measures, namely, the VoIP call capacity and the TCP throughput. In Sec V we derive three more measures namely, the attempt rate of nodes with access category 1 (AC 1), the attempt rate of nodes with AC 3 and the system collision rate, in order to validate the model. This is followed by numerical and simulation results for all the measures so derived. Lastly, in Sec VI we conclude with the listing of useful modeling and performance insights obtained in this analysis. ■

II. The Modeling Approach

We study the performance of a single cell infrastructure 802.11e WLAN that uses EDCA, when both AC 3 and AC 1 are used. While IEEE 802.11e also defines TXOPs as an optional feature, for simplicity, we do not use TXOP in our model. We follow the modeling approach of Kuriakose [16] and Harsha et al. [17], where only the IEEE 802.11 WLAN is analyzed for voice traffic and for TCP traffic separately. The approach of [16] and [17] can be briefly explained as follows:

1) Embed the number of active nodes at *channel slot boundaries*. The *channel slot boundaries* are those instants of time when an activity ends. The activity could be a successful transmission or a collision or no transmission (an idle slot).
2) If n nodes are active (i.e., have non empty queues) at a channel slot boundary, then the attempt probability of a node is taken to be β_n. This is the approximation from Bianchi [18] and Kumar et al. [14] where if there are n saturated nodes, the attempt probability of each node is β_n.
3) Use these attempt probabilities to model the evolution of the number of contending nodes at channel slot boundaries. This yields a Markov renewal process.
4) Obtain the stationary probability vector $\boldsymbol{\pi}$ of this Markov chain.
5) Use Markov regenerative argument to obtain the performance measures.

In case of 802.11e WLANs, due to different parameters, each AC has a different attempt probability, that further depends on the number of nodes in other ACs. The attempt probabilities obtainable from [14] do not consider the differentiation in the parameters and hence cannot be used. We approach this problem by incorporating the attempt probability values obtained from the fixed point analysis in [1]. We build a model that can use the results of [1].

A. The Network Scenario and Modeling Observations

Consider an infrastructure IEEE 802.11e WLAN, which has VoIP and TCP traffic, both serviced on EDCA. The VoIP traffic and TCP traffic could be handled at the same node. Then we have multiple queues per node. It has been shown in the journal version of [1] that with increase in the number of nodes, the performance of the *multiple queues per node* case coincides with the performance of the *single queue per node* case, each node with one queue of the original system; basically the probability of virtual collision within a node is small. This observation leads to substantial reduction in complexity of our analysis. We make use of this observation and consider the VoIP traffic and TCP traffic as originating from different nodes. Thus, let N_v be the number of full duplex CBR VoIP calls in the WLAN, involving N_v number of 802.11e complaint wireless stations (QSTAs), each carrying one VoIP call. Similarly let N_t be the number of QSTAs downloading TCP traffic in the WLAN, each having one session. The 802.11e complaint access point (QAP) can be viewed as two nodes: QAP_v having a queue for AC 3 VoIP traffic for all VoIP calls, and the other, QAP_t, having a queue for AC 1 TCP traffic to serve all TCP downloads. This model is illustrated in Fig. 1. Note that at any time the WLAN in Fig. 1 can be seen to consist of $N_v + N_t + 2$ nodes. Lets call the QSTAs with AC 3 as $QSTA_v$ and QSTAs with AC 1 as $QSTA_t$.

We assume that there are no bit errors, and packets in the channel are lost only due to collisions.

B. VoIP Traffic

Each VoIP call results in two RTP/UDP streams, one from a remote client to a wireless QSTA, and another in the reverse direction. We consider that each call uses the ITU G711 codec. Packets are generated every 20 ms. Including the IP, UDP and RTP headers, the size of the packet emitted in each call in each direction is 200 bytes every 20 ms.

As a QoS requirement we demand that the probability that a packet is transmitted successfully within 20 ms is close to 1. While a more relaxed delay QoS may seem appropriate, we have observed through simulations that even 'an objective of $Prob(delay \geq 100ms)$ is small', yields no increase in the call capacity. Since the packets will experience delays in the rest of the network also, this seems like a reasonable delay target to achieve. This QoS objective also simplifies the modeling since, if the QoS objective is met, the probability of more than one packet of a call in a queue is small. Thus, if the QoS target is met, whenever a new packet arrives at a $QSTA_v$, it

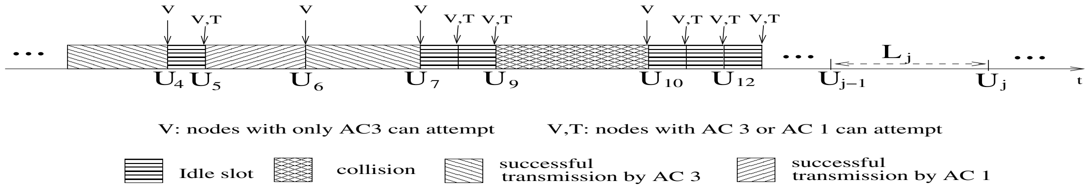

Fig. 2. An evolution of the channel activity with two ACs in 802.11e WLANs.

will find the queue empty with a high probability. Hence, the following three assumptions will be acceptable in the region where we want to operate: (1) the buffer of every $QSTA_v$ has a queue length of at most one packet, and (2) new packets arriving to the $QSTA_v$s arrive only at empty queues. The latter assumption implies that if there are k $QSTA_v$s with voice packets then, a new voice packet arrival comes to a $(k+1)^{th}$ $QSTA_v$. (3) Since the QAP_v handles packets from N_v streams, there can be up to N_v packets of different calls in the QAP_v. Thus we expect that QAP_v is the bottleneck for voice traffic, and we assume that it will contend at all times (at least when N_v is large). This is a realistic assumption near system capacity.

As mentioned earlier, packets arrive every 20 ms in every stream. We use this model in our simulations. However, since our analytical approach is via Markov chains, we assume that the probability that a voice call generates a packet in an interval of length l slots is $p_l = 1 - (1 - \lambda)^l$, where λ is obtained as follows. Each system slot in 802.11b is of $20\mu s$ duration (hereafter denoted as δ). Thus in 1000 system slots there is one arrival. Therefore, for the 802.11b PHY we take $\lambda = 0.001$. This simplification turns out to yield a good approximation.

C. TCP Controlled File Downloads

Each $QSTA_t$ has a single TCP connection to download a large file from a local file server. Hence, the QAP_t delivers TCP data packets towards the $QSTA_t$s, while the $QSTA_t$s return TCP ACKs. Here we assume that when a $QSTA_t$ receives data from the QAP_t, it immediately sends an ACK, i.e., we do not model delayed ACKs here, though the delayed ACKs case can also be done (see [16]). We assume that the QAP_t and the $QSTA_t$s have buffers large enough so that TCP data packets or ACKS are not lost due to buffer overflows. Since, by assumption, there are no bit errors, packets in the channel are lost only due to collisions. Also, we assume that these collisions are recovered by the MAC before TCP time-outs occur. As a result of these assumptions, for large file transfers, the TCP window will grow to its maximum value and stay there. As N_t is increased this assumption is close to what happens in reality. We then adopt an observation made by Bruno et al. [19]. Since all nodes with AC 1 (including the QAP_t) will contend for the channel and no preference is given to the QAP_t, most of the packets in the TCP window will get backlogged at the QAP_t. The QAP_t's buffer is served FIFO, and we can assume that the probability that a packet transmitted by the QAP_t to a particular $QSTA_t$ is $\frac{1}{N_t}$. Thus it is apparent that the larger the N_t, the lower is the probability that the QAP_t sends to the same $QSTA_t$ before receiving the ACK for the last packet sent. Then it is assumed that the probability that any $QSTA_t$ has more than one ACK is negligible. We can thus simply keep track of the *number* of $QSTA_t$ with ACKs. If there are several $QSTA_t$s with ACKs then the chance that QAP_t succeeds in sending a packet is small. Thus the system has a tendency to keep most of the packets in the QAP_t with a few $QSTA_t$s having ACK to send back. This results in a closed system, wherein each time the QAP_t succeeds, it activates a $QSTA_t$ having an ACK packet and each time a $QSTA_t$ succeeds, the number of non-empty $QSTA_t$s reduces by one.

Thus for the $QSTA_t$s that are downloading files, our modeling assumptions are: (1) A $QSTA_t$ has either 0 or 1 ACK packet wanting to be sent to the QAP_t. (2) When the QAP_t sends a data packet it is assumed to be destined to a $QSTA_t$ that has no ACK queued.

III. The Analytical Model

A. An Embedded Chain

The evolution of the channel activity in the network is as in Fig. 2. $U_j,\ j \in 0, 1, 2, 3, \dots,$ are the random instants where either an idle slot, or a successful transmission, or a collision ends. Let us define the time between two such successive instants as a *channel slot*. Thus the interval $[U_{j-1}, U_j)$ is called the j^{th} channel slot. Let the time length of the j^{th} channel slot be L_j (see Fig. 2).

Let $Y_j^{(v)}$ be the number of non-empty $QSTA_v$s and $Y_j^{(t)}$ be the number of non-empty $QSTA_t$s at the instant U_j. Thus $0 \le Y_j^{(v)} \le N_v$ and $0 \le Y_j^{(t)} \le N_t$. Let $B_j^{(v)}$ be the number of new VoIP packet arrivals at all the $QSTA_v$s, in the channel slot j. Let $V_j^{(v)}$ be the number of departures from $QSTA_v$s, $V_j^{(tAP)}$ be the number of departures from QAP_t and $V_j^{(tSTA)}$ be the number of departures from $QSTA_t$s, in the j^{th} channel slot. We know that at most one departure can happen in any channel slot.

The implication of access differentiation through AIFS is that the ACs with larger AIFS values cannot contend in those slots that were preceded by some activity (i.e., successful transmission or collision). After every activity (successful transmission or collision) on the channel, AC 1 nodes wait for an additional system slot before contending for the channel. Fig. 2 shows the evolution of the channel activity when AC 3 and AC 1 queues are active. Note that at the instants U_4, U_6, U_7 and U_{10}, only AC 3 nodes can contend for the channel,

$$\text{Prob}\ \left(B_{j+1}^{(v)} = b/(Y_j^{(v)}) = n_v; L_{j+1} = l)\right) = \binom{N_v - n_v}{b}\ (p_l)^b\ (1-p_l)^{N_v - n_v - b} \tag{1}$$

whereas AC 1 nodes have still to wait for one more system slot to be able to contend. At other instants, U_5, U_8, U_{11} and U_{13}, nodes with AC 3 or AC 1 can attempt.

The AC attempt probabilities obtained from [1] are conditioned on when an AC can attempt. We use the variable $Y_j^{(s)}$ to keep track of which ACs are permitted to attempt in a channel slot. Let $Y_j^{(s)} = 1$ denote that the preceding channel slot had an activity and so in the beginning of the j^{th} channel slot, only nodes with AC 3 can attempt. Let $Y_j^{(s)} = 0$ denote that the preceding channel slot remained idle and hence, at the beginning of the j^{th} channel slot any node can attempt. Thus $Y_j^{(s)} \in \{0, 1\}$.

Then we have the following dynamics.

$$\begin{aligned} Y_{j+1}^{(v)} &= Y_j^{(v)} - V_{j+1}^{(v)} + B_{j+1}^{(v)} \\ Y_{j+1}^{(t)} &= Y_j^{(t)} - V_{j+1}^{(tSTA)} + V_{j+1}^{(tAP)} \end{aligned}$$

with the condition that $V_{j+1}^{(v)} + V_{j+1}^{(tSTA)} + V_{j+1}^{(tAP)} \in \{0, 1\}$.

Since the probability with which a packet arrives at a node in a channel slot of length l is p_l and we assume that packets arrive at only empty $QSTA_v$s, $B_j^{(v)}$ can be modeled as having a binomial distribution and the conditioned probability $Prob(B_{j+1}^{(v)}/(Y_j^{(v)}, L_{j+1}) = (n_v, l))$ is given by Equation 1.

B. Markov Property via State Dependent Attempt Probabilities

For determining the expressions of $V_{j+1}^{(v)}$, $V_{j+1}^{(tSTA)}$ and $V_{j+1}^{(tAP)}$, we use the attempt probabilities of [1]. Let $\beta_{n_v+1,n_t+1}^{(v)}$ be the attempt probability of a node with AC 3 and $\beta_{n_v+1,n_t+1}^{(t)}$ be the attempt probability of a node with AC 1, when there are n_v VoIP calls and n_t TCP sessions in the network. These attempt probabilities are conditioned on the event that the ACs can attempt. Note that the addition of one in the subscripts is so as to include the QAP_v and QAP_t, which by assumption, always contend. The values, $\beta_{n_v+1,n_t+1}^{(v)}$ for AC 3 and $\beta_{n_v+1,n_t+1}^{(t)}$ for AC 1 are obtained from saturation fixed point analysis of [1] for all combinations of n_v, n_t. Our approximation is that the state dependent values of attempt probabilities from the saturated nodes case can be used for a WLAN where the nodes are not saturated, by keeping track of the number of nonempty nodes in the WLAN and taking the state dependent attempt probabilities corresponding to this number of nonempty nodes.

For convenience, let us define the following probability functions depicting the activities in the channel slot $j+1$: $\eta_t(Y_j^{(v)}, Y_j^{(t)})$ be the probability that all nodes with AC 1 remain idle; $\alpha_v(Y_j^{(v)}, Y_j^{(t)})$ be the probability that any one $QSTA_v$ attempts while QAP_v is idle; $\alpha_t(Y_j^{(v)}, Y_j^{(t)})$ be the probability that any one $QSTA_t$ attempts while QAP_t is idle; $\sigma_v(Y_j^{(v)}, Y_j^{(t)})$ be the probability that the QAP_v attempts and all $QSTA_v$s are idle; $\sigma_t(Y_j^{(v)}, Y_j^{(t)})$ be the probability that the QAP_t attempts and all $QSTA_t$s are idle; $\zeta_v(Y_j^{(v)}, Y_j^{(t)})$ be the probability that there is a collision amongst nodes with AC 3; $\zeta_t(Y_j^{(v)}, Y_j^{(t)})$ be the probability that there is a collision amongst $QSTA_t$s; $\psi_1(Y_j^{(v)}, Y_j^{(t)})$ be the probability that there is a hybrid collision involving nodes with AC 3 (including QAP_v) and $QSTA_t$s (excluding QAP_t); $\psi_{tAP}(Y_j^{(v)}, Y_j^{(t)})$ be the probability that there is a hybrid collision between QAP_t and any other node. The expressions for these functions are given in Appendix. We can express the conditional distributions $V_{j+1}^{(v)}$, $V_{j+1}^{(tSTA)}$ and $V_{j+1}^{(tAP)}$ using these functions. $V_j^{(v)}$ is 1 if a $QSTA_v$ wins the contention for the channel and 0 otherwise. Then,

$$V_{j+1}^{(v)} = \begin{cases} 1 & \text{w.p. } \alpha_v(Y_j^{(v)}, Y_j^{(t)})\ \eta_t(Y_j^{(v)}, Y_j^{(t)}) & \text{if } Y_j^{(s)} = 0 \\ 1 & \text{w.p. } \alpha_v(Y_j^{(v)}, Y_j^{(t)}) & \text{if } Y_j^{(s)} = 1 \\ 0 & \text{otherwise} \end{cases}$$

Similarly, $V_j^{(tSTA)}$ and $V_j^{(tAP)}$ are expressed as follows:

$$V_{j+1}^{(tSTA)} = \begin{cases} 1 & \text{w.p. } \alpha_t(Y_j^{(v)}, Y_j^{(t)})\ \eta_v(Y_j^{(v)}, Y_j^{(t)}) & \text{if } Y_j^{(s)} = 0 \\ 0 & \text{otherwise} \end{cases}$$

$$V_{j+1}^{(tAP)} = \begin{cases} 1 & \text{w.p. } \sigma_t(Y_j^{(v)}, Y_j^{(t)})\ \eta_v(Y_j^{(v)}, Y_j^{(t)}) & \text{if } Y_j^{(s)} = 0 \\ 0 & \text{otherwise} \end{cases}$$

$Y_{j+1}^{(s)}$ takes the values in $\{0, 1\}$ with the following probabilities:

$$Y_{j+1}^{(s)} = \begin{cases} 0 & \text{w.p. } \eta_v(Y_j^{(v)}, Y_j^{(t)})\ \eta_t(Y_j^{(v)}, Y_j^{(t)}) \\ 1 & \text{otherwise} \end{cases}$$

with the initial state, $Y_0^{(s)} = 0$.

With the binomial distribution for voice packet arrivals assumed above and the state dependent probabilities of attempt, it is easily seen that $\{Y_j^{(v)}, Y_j^{(t)}, Y_j^{(s)}; j \geq 0\}$ forms a finite irreducible three dimensional discrete time Markov chain on the channel slot boundaries and hence is positive recurrent. The stationary probabilities π_{n_v,n_t,n_s} of the Markov Chain $\{Y_j^{(v)}, Y_j^{(t)}, Y_j^{(s)}; j \geq 0\}$ can then be numerically determined using expressions for distributions of $B_j^{(v)}$, $V_j^{(v)}$, $V_j^{(tAP)}$ and $V_j^{(tSTA)}$ and the functions in the Appendix.

C. The Markov Renewal Process

In this subsection we use the state dependent attempt probabilities to obtain the distribution of the channel slot duration. On combining this with the Markov chain in Sec III-B, we finally conclude that $\{\ (Y_j^{(v)}, Y_j^{(t)}, Y_j^{(s)}; U_j), j = 0, 1, 2, \ldots\}$ is a Markov renewal process.

We use the basic access mechanism for the TCP traffic. This shall facilitate the validation of analytical results

$$
\begin{aligned}
EL_{j+1}/(Y_j^{(s)}=0) &= \eta_v(Y_j^{(v)},Y_j^{(t)})\eta_t(Y_j^{(v)},Y_j^{(t)}) + T_{s-v}\ \eta_t(Y_j^{(v)},Y_j^{(t)})(\alpha_v(Y_j^{(v)},Y_j^{(t)}) + \sigma_v(Y_j^{(v)},Y_j^{(t)})) \\
&+ T_{s-tSTA}\ \eta_v(Y_j^{(v)},Y_j^{(t)})\ \alpha_t(Y_j^{(v)},Y_j^{(t)}) + T_{s-tAP}\ \eta_v(Y_j^{(v)},Y_j^{(t)})\ \sigma_t(Y_j^{(v)},Y_j^{(t)}) \\
&+ T_{c-short}\ \eta_v(Y_j^{(v)},Y_j^{(t)})\ \zeta_t(Y_j^{(v)},Y_j^{(t)}) \\
&+ T_{c-voice}\ (\eta_t(Y_j^{(v)},Y_j^{(t)})\ \zeta_v(Y_j^{(v)},Y_j^{(t)}) + \psi_1(Y_j^{(v)},Y_j^{(t)})) + T_{c-long}\phi_{tAP}(Y_j^{(v)},Y_j^{(t)}) \\
EL_{j+1}/(Y_j^{(s)}=1) &= \eta_v(Y_j^{(v)},Y_j^{(t)}) + T_{s-v}\ (\alpha_v(Y_j^{(v)},Y_j^{(t)}) + \sigma_v(Y_j^{(v)},Y_j^{(t)})) + T_{c-voice}\zeta_v(Y_j^{(v)},Y_j^{(t)}) \qquad (2)
\end{aligned}
$$

$$
\begin{aligned}
P\left(\underline{Y}_{j+1}=\underline{y},(U_{j+1}-U_j)\le l/((\underline{Y}_0=\underline{y}_0,\underline{U}_0=\underline{u}_0),(\underline{Y}_1=\underline{y}_1,\underline{U}_1=\underline{u}_1),...,(\underline{Y}_j=\underline{y}_j,\underline{U}_j=\underline{u}_j)\right) \\
= P\left(\underline{Y}_{j+1}=\underline{y},(U_{j+1}-U_j)\le l/(\underline{Y}_j=\underline{y}_j,\underline{U}_j=\underline{u}_j)\right) \qquad (3)
\end{aligned}
$$

through simulations by the *ns-2* with EDCA implementation [20], that supports only basic access mechanism and not RTS/CTS mechanism. However, our analysis can be worked out for RTS/CTS mechanism as well. When basic access mechanism is used, there shall be collisions between three kinds of packets. The longest collision time is seen when QAP_t packet collides with a packet of any other node. A smaller collision time is seen when VoIP packet collides with a packet of any other node except with packet of QAP_t. The shortest collision time is seen when only packets of $QSTA_t$s collide. Then L_j (in system slots) takes one of the seven values: 1 if it is an idle slot, T_{s-v} if it corresponds to a successful transmission of a AC 3 node, T_{s-tAP} if it corresponds to a successful transmission of QAP_t, T_{s-tSTA} if it corresponds to a successful transmission of $QSTA_t$, $T_{c-short}$ if it corresponds to a collision between $QSTA_t$s, $T_{c-voice}$ if it corresponds to a collision amongst nodes with AC 3 or between AC 3 nodes and any $QSTA_t$ and T_{c-long} if it corresponds to a collision between QAP_t and any other $QSTA$. The conditional expectation of L_{j+1} is given by Equation 2 that uses the following notations:

- $T_{s-v} = T_P + T_{PHY} + \frac{L_{MAC}+L_{voice}}{C_d} + T_{SIFS} + T_P + T_{PHY} + \frac{L_{ACK}}{C_c} + T_{AIFS(3)}$;
- $T_{s-tSTA} = T_P + T_{PHY} + \frac{L_{MAC}+L_{TCPACK}}{C_d} + T_{SIFS} + T_P + T_{PHY} + \frac{L_{ACK}}{C_c} + T_{AIFS(1)}$;
- $T_{s-tAP} = T_P + T_{PHY} + \frac{L_{MAC}+L_{IPH}+L_{data}}{C_d} + T_{SIFS} + T_P + T_{PHY} + \frac{L_{ACK}}{C_c} + T_{AIFS(1)}$;
- $T_{c-voice} = T_P + T_{PHY} + \frac{L_{MAC}+L_{voice}}{C_d} + T'_{EIFS} + T_{AIFS(3)}$;
- $T_{c-short} = T_P + T_{PHY} + \frac{L_{MAC}+L_{TCPACK}}{C_d} + T'_{EIFS} + T_{AIFS(1)}$;
- $T_{c-long} = T_P + T_{PHY} + \frac{L_{MAC}+L_{IPH}+L_{data}}{C_d} + T'_{EIFS} + T_{AIFS(1)}$;
- $T'_{EIFS} = T_P + T_{PHY} + \frac{L_{ACK}}{C_c} + T_{SIFS}$.

See Table I for meaning and values of various parameters.

We thus observe Equation 3 and so conclude that $\{(Y_j^{(v)}, Y_j^{(t)}, Y_j^{(s)}; U_j), j = 0, 1, 2, \ldots\}$ is a Markov renewal process with $L_j = U_j - U_{j-1}$ being the renewal cycle time.

Parameter	Symbol	Value
PHY data rate	C_d	11 Mbps
Control rate	C_c	2 Mbps
PLCP preamble time	T_P	$144\mu s$
PHY Header time	T_{PHY}	$48\mu s$
SIFS Time	T_{SIFS}	$10\mu s$
AIFS(3) Time	$T_{AIFS(3)}$	$50\mu s$
AIFS(1) Time	$T_{AIFS(1)}$	$70\mu s$
G711 packet size	L_{voice}	200 Bytes
Data packet size	L_{data}	1500 Bytes
MAC ACK Packet Size	L_{ACK}	112 bits
MAC Header size	L_{MAC}	288 bits
TCP ACK size	L_{TCPACK}	320 bits
AC(3) Min. CW	$CW_{min}(AC(3)$	7
AC(3) Max. CW	$CW_{max}(AC(3)$	15
AC(1) Min. CW	$CW_{min}(AC(1)$	31
AC(1)Max. CW	$CW_{max}(AC(1)$	1023

TABLE I
PARAMETERS USED IN ANALYSIS AND SIMULATION FOR EDCA 802.11E WLAN

IV. VoIP Capacity and TCP Throughput

A. Call Capacity

Let A_j be the "reward" when the QAP_v wins the channel contention in j^{th} channel slot. If we have $Y_{j-1}^{(v)} = n_v$, $Y_{j-1}^{(t)} = n_t$ and $Y_{j-1}^{(s)} = n_s$ at the $(j-1)^{th}$ channel slot boundary, then,

$$
A_j = \begin{cases} 1 \text{ w.p. } \sigma_v(n_v,n_t)\ \eta_t(n_v,n_t) & \text{if } n_s = 0 \\ 1 \text{ w.p. } \sigma_v(n_v,n_t) & \text{if } n_s = 1 \\ 0 \text{ otherwise} & \end{cases}
$$

Let $A(t)$ denote the cumulative reward of the QAP_v until time t. Applying Markov regenerative analysis [21], we obtain the service rate of the QAP_v, $\Theta_{AP-VoIP}(N_v, N_t)$, as given by Equation 4.

Since the rate at which a single call sends data to the QAP_v is λ, and the QAP_v serves N_v such calls the total arrival rate to the QAP_v is $N_v\lambda$. This rate should be less than $\Theta_{AP-VoIP}(N_v, N_t)$ for stability. Thus, a permissible combination of N_v VoIP calls and N_t TCP sessions, while meeting the delay QoS of VoIP calls, must satisfy

$$\Theta_{AP-VoIP}(N_v, N_t) > N_v\lambda \qquad (5)$$

$$\Theta_{AP-VoIP}(N_v, N_t) = \lim_{t\to\infty} \frac{A(t)}{t} \overset{a.s.}{=} \frac{\sum_{n_v=0}^{N_v}\sum_{n_t=0}^{N_t}\sum_{n_s=0}^{1}\pi_{n_v,n_t,n_s}\ E_{n_v,n_t,n_s}A}{\sum_{n_v=0}^{N_v}\sum_{n_t=0}^{N_t}\sum_{n_s=0}^{1}\pi_{n_v,n_t,n_s}\ E_{n_v,n_t,n_s}L} \quad (4)$$

where, $E_{n_v,n_t,n_s}A = E\left(A_j/(Y_{j-1}^{(v)}, Y_{j-1}^{(t)}, Y_{j-1}^{(s)}) = (n_v, n_t, n_s)\right)$, $E_{n_v,n_t,n_s}L = E\left(L_j/(Y_{j-1}^{(v)}, Y_{j-1}^{(t)}, Y_{j-1}^{(s)}) = (n_v, n_t, n_s)\right)$.

$$\text{Prob}\ \left(B_{j+1}^{(vAP)} = b/X_j^{(vAP)} = x; L_{j+1} = l\right) = \binom{N_v - x}{b} (p_l)^b\ (1-p_l)^{N_v - x - b} \quad (6)$$

$$\lim_{t\to\infty} \frac{R(t)}{t} \overset{a.s.}{=} \frac{\sum_{n_v=0}^{N_v}\sum_{n_t=0}^{N_t}\sum_{n_s=0}^{1}\sum_{n_{vAP}=0}^{N_v}\pi_{n_v,n_t,n_s,n_{vAP}}\ E_{n_v,n_t,n_s,n_{vAP}}R}{\sum_{n_v=0}^{N_v}\sum_{n_t=0}^{N_t}\sum_{n_s=0}^{1}\sum_{n_{vAP}=0}^{N_v}\pi_{n_v,n_t,n_s,n_{vAP}}\ E_{n_v,n_t,n_s,n_{vAP}}L} \quad (7)$$

The above inequality defines the admission region for VoIP. Note that we are asserting that the N_v that satisfies inequality 5 also ensures the delay QoS. This is based on the observation in earlier research [22] that when the arrival rate is less than the saturation throughput then the delay is very small.

Remark: The model discussed above does not give the TCP download throughput. This is due to the fact that we assume that the voice queue of the AP is saturated all the time. But actually, the VoIP queue of AP saturates only at system capacity [16]. Thus if we follow the above method to obtain analytical TCP download throughput, we obtain an underestimated throughput. This problem can be solved by considering that QAP_v is not saturated and we consider this case in the following subsection. ■

B. TCP Throughput

Depending on whether the QAP_v queue contains a packet, the total number of nonempty nodes with AC 3 will be $Y_j^{(v)}$ (in case no packet is there in QAP_v queue) or $Y_j^{(v)} + 1$ (if QAP_v queue has at least one packet). We then need to know the state of the QAP_v queue so as to know the number of nonempty nodes with AC 3, at the channel slot boundaries. Therefore, we introduce another variable to track the number of packets in the QAP_v queue.

Let $X_j^{(v)}$ be the number of packets in the QAP_v queue, $B_j^{(vAP)}$ be the number of new packets arriving at the QAP_v queue and $V_j^{(vAP)}$ be the number of departures from QAP_v at the end of j^{th} channel slot. Then, the set of evolution equations are:

$$\begin{aligned} Y_{j+1}^{(v)} &= Y_j^{(v)} - V_{j+1}^{(v)} + B_{j+1}^{(v)} \\ Y_{j+1}^{(t)} &= Y_j^{(t)} - V_{j+1}^{(tSTA)} + V_{j+1}^{(tAP)} \\ X_{j+1}^{(v)} &= X_j^{(v)} - V_{j+1}^{(vAP)} + B_{j+1}^{(vAP)} \end{aligned}$$

with the condition that $V_{j+1}^{(v)} + V_{j+1}^{(tSTA)} + V_{j+1}^{(tAP)} + V_{j+1}^{(vAP)} \in \{0, 1\}$.

On similar lines as $B_j^{(v)}$, $B_j^{(vAP)}$ can be modeled as having a binomial distribution. Observe that if x packets are already there in QAP_v queue, at most $N_v - x$ packets can arrive before the QoS delay bound of the earliest arrived packet gets exceeded. Using the earlier definition of p_l, the conditional probability $prob(B_{j+1}^{(vAP)}/X_j^{(vAP)}, L_{j+1})$ is given by Equation 6.

In order to take into account the fact that QAP_v may or may not be active at any channel slot boundary, define $Z_j^{(v)} := Y_j^{(v)} + 1$, if $X_j^{(vAP)} \neq 0$ and $Z_j^{(v)} := Y_j^{(v)}$ if $X_j^{(vAP)} = 0$. Then the functions in the Appendix need a modification. Instead of $\beta_{Y_j^{(v)}+1, Y_j^{(t)}+1}$, we now have to use $\beta_{Z_j^{(v)}, Y_j^{(t)}+1}$. With the above change incorporated, $V_{j+1}^{(vAP)}$ is given as:

$$V_{j+1}^{(vAP)} = \begin{cases} 1 & \text{w.p. } \sigma_v(Z_j^{(v)}, Y_j^{(t)})\ \eta_t(Z_j^{(v)}, Y_j^{(t)}) & \text{if } Y_j^{(s)} = 0 \\ 1 & \text{w.p. } \sigma_v(Z_j^{(v)}, Y_j^{(t)}) & \text{if } Y_j^{(s)} = 1 \\ 0 & \text{otherwise} & \end{cases}$$

We again see that, under our model for the attempt probabilities, $\{Y_j^{(v)}, Y_j^{(t)}, Y_j^{(s)}, X_j^{(vAP)}; j \geq 0\}$ forms a finite irreducible four dimensional discrete time Markov chain on the channel slot boundaries and hence is positive recurrent. The stationary probabilities $\pi_{n_v,n_t,n_s,n_{vAP}}$ can be numerically obtained. If R_j be the reward and L_j be the cycle time in j^{th} channel slot, in this context, applying Markov regenerative analysis [21], mean reward rate is given by Equation 7, where $R(t)$ is the cumulative reward until time t. We use this equation to obtain various measures of interest.

Let us define T_j to be the reward when the QAP_t wins the channel contention in j^{th} channel slot and $T(t)$ denote the cumulative reward of the QAP_t until time t. If there are $Z_{j-1}^{(v)} = n_v$ AC 3 nodes active, $Y_{j-1}^{(t)} = n_t$ $QSTA_t$s active and $Y_{j-1}^{(s)} = n_s$, then,

$$T_j = \begin{cases} 1 \text{ w.p. } \sigma_t(n_v, n_t)\ \eta_v(n_v, n_t) & \text{if } n_s = 0 \\ 0 \text{ otherwise} & \end{cases}$$

$\Theta_{AP-data}(N_v, N_t)$ in Mbps, is then given as:

$$\Theta_{AP-data}(N_v, N_t) = \frac{L_{data}}{\delta} \lim_{t\to\infty} \frac{T(t)}{t} \quad (8)$$

where we use Equation 7 to evaluate $\lim_{t\to\infty} \frac{T(t)}{t}$, with $R = T$.

V. Model Validation and Numerical Results

A. Attempt and Collision Rates

In order to validate and show the accuracy of the model, we now analytically derive three other measures: the attempt rate of AC 3 nodes, the attempt rate of AC 1 nodes, and the total collision rate in the WLAN. We compare the numerical results with that obtained from the simulations.

1) Attempt Rate: Let $S_j^{(v)}$ be the number of attempts process of AC 3 nodes, i.e., $S_j^{(v)}$ counts the number of AC 3 nodes that attempt in the channel slot, j. Let, as before, $Z_{j-1}^{(v)} = n_v$ and $Y_{j-1}^{(t)} = n_t$. Then

$$S_j^{(v)} = i \text{ w.p. } \binom{n_v}{i} (\beta_{n_v, n_t+1}^{(v)})^i (1 - \beta_{n_v, n_t+1}^{(v)})^{n_v - i}$$

Let $S^{(v)}(t)$ denote the cumulative reward of number of attempts of AC 3 nodes until time t. Then the total attempt rate of AC 3 nodes, $\Phi_v(N_v, N_t)$ is

$$\Phi_v(N_v, N_t) = \frac{1}{\delta} \lim_{t \to \infty} \frac{S^{(v)}(t)}{t} \tag{9}$$

and we use Equation 7 to evaluate $\lim_{t\to\infty} \frac{S^{(v)}(t)}{t}$, with $R = S^{(v)}$.

Similarly, let $S_j^{(t)}$ be the number of attempts process of AC 1 nodes, i.e., $S_j^{(t)}$ counts the number of AC 1 nodes that attempt in the channel slot, j. Then

$$S_j^{(t)} = \begin{cases} i \text{ w.p. } \binom{n_t+1}{i} (\beta_{n_v, n_t+1}^{(t)})^i (1 - \beta_{n_v, n_t+1}^{(t)})^{n_t - i} & \text{if } Y_j^{(s)} = 0 \\ 0 \text{ otherwise} & \end{cases}$$

The total attempt rate of AC 1 nodes, $\Phi_t(N_v, N_t)$ is then

$$\Phi_t(N_v, N_t) = \frac{1}{\delta} \lim_{t \to \infty} \frac{S^{(t)}(t)}{t} \tag{10}$$

and we again use Equation 7 to evaluate $\lim_{t\to\infty} \frac{S^{(t)}(t)}{t}$, with $R = S^{(t)}$.

2) Collision Rate: Let C_j be the number of collisions process in the WLAN, i.e., C_j counts the total number collisions in the WLAN in the channel slot, j. For instance, if five nodes are involved in a collision in the j^{th} channel slot, then $C_j = 5$. If $E_{n_v, n_t, n_s, n_{vAP}} C$ is the state dependent mean number of collisions,

$$\begin{aligned} E_{n_v, n_t, n_s, n_{vAP}} C &= E(S^{(v)} + S^{(t)}) \\ &- 1 * Prob(S^{(v)} = 1; S^{(t)} = 0) \\ &- 1 * Prob(S^{(v)} = 0; S^{(t)} = 1) \end{aligned}$$

Let $C(t)$ denote the cumulative reward of number of collisions in the WLAN, until time t. Then, if $\Gamma(N_v, N_t)$ is the system collision rate in the WLAN,

$$\Gamma(N_v, N_t) = \lim_{t \to \infty} \frac{C(t)}{t} \tag{11}$$

and again we use Equation 7 to evaluate $\lim_{t\to\infty} \frac{C(t)}{t}$, with $R = C$.

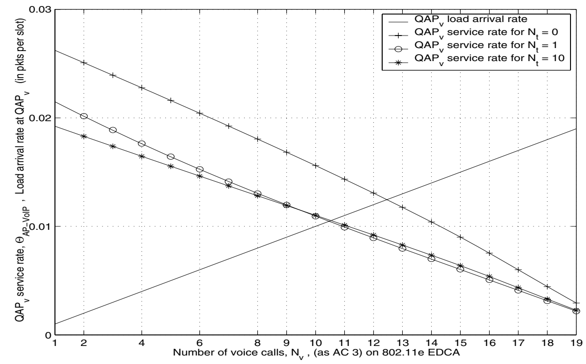

Fig. 3. The service rate $\Theta_{AP-VoIP}$ applied to the QAP_v is plotted vs the number of voice calls, N_v for different number of TCP sessions N_t. Also shown is the line $N_v\lambda$. The point where the line $N_v\lambda$ crosses the curves gives the maximum number of calls supported. VoIP packet size is 200B (G711 Codec); data packet size is 1500 Bytes; PHY data rate is 11Mbps and basic rate is 2Mbps.

B. Numerical Results

We present the results obtained from the analysis and simulation. The simulations were obtained using *ns-2* with EDCA implementation [20]. The VoIP traffic was considered on AC 3 and the TCP traffic was considered on AC 1. The PHY parameters confirm to the 802.11b standard. See Table I for the values used in simulation.

1) VoIP Capacity: In Fig. 3, we show the analytical plot of QAP_v service rate vs. the number of calls, N_v for three different values of $N_t \in \{0, 1, 10\}$. From Fig. 3, we note that the QAP_v service rate crosses the QAP_v load rate, after 12 calls for $N_t = 0$. This implies that a maximum of 12 calls are possible while meeting the delay QoS, on a 802.11e WLAN when no TCP traffic is present on AC 1. When one TCP session is added to the WLAN (i.e., $N_t = 1$), the QAP_v service rate crosses below the QAP_v load rate, after 10 calls. This implies that only 10 calls are possible when any TCP session is added to the WLAN. The same is the case even when 10 TCP sessions are added to the WLAN.

Remark: The analysis represented by Fig. 3, assumes that the QAP_v is saturated. It is for this reason that the QAP_v service rate exceeds the load arrival rate for small N_v. The crossover point would however correctly model the value of N_v beyond which voice QoS will be violated.

From Fig. 3, we observe that for each value N_v, with increase in the value of N_t from zero to a non-zero value, the service rate available to the QAP_v decreases. This is, of course, because the QAP needs to service the TCP traffic also. However, the curves of $N_t = 1$ and $N_t = 10$ are very close. The effect of one TCP transfer is the same as that of 10 TCP transfers. Partly, the reason is that QAP_t queue is already saturated with 1 TCP. By adding more TCP transfers a few more QSTAs begin to contend, but this number will not change much with increasing N_t (see also Kuriakose [16]). ■

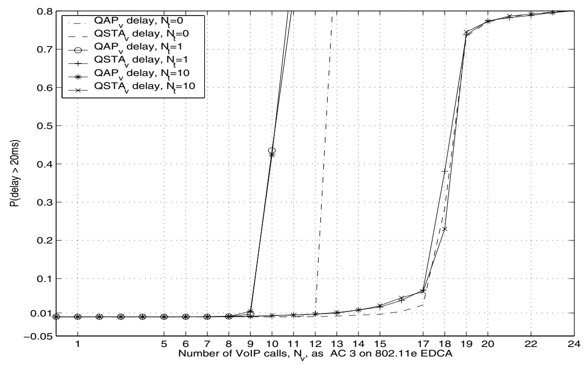

Fig. 4. Simulation results showing probability of delay of QAP_v and QSTA with AC 3, being greater than 20ms vs the number of calls (N_v) for different values of N_t. Analysis and simulation use VoIP packet size = 200B (G711 Codec); TCP download packet size = 1500B (Basic access mechanism); PHY data rate = 11Mbps and basic rate = 2Mbps.

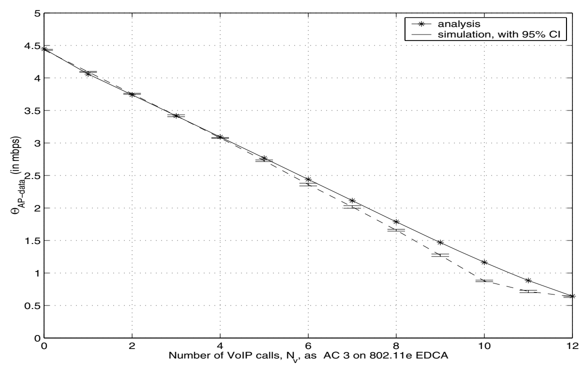

Fig. 5. Analysis and simulation results showing total download throughput obtained by $QSTA_t$s for different values of N_v and $N_t = 10$. VoIP packet size is 200B (G711 Codec); data packet size is 1500 Bytes; PHY data rate is 11Mbps and basic rate is 2Mbps.

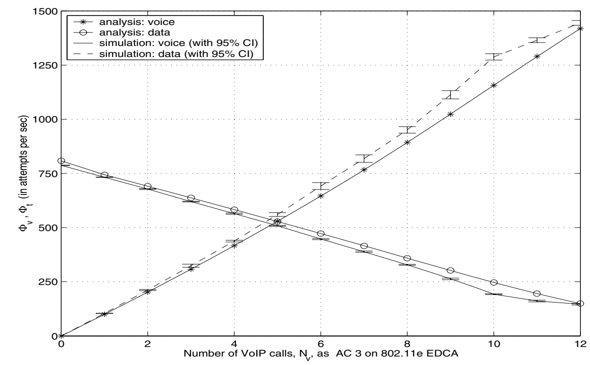

Fig. 6. Analysis and simulation results showing attempt rates of AC 3 nodes and AC 1 nodes, for different values of N_v and $N_t = 10$. PHY data rate is 11Mbps and basic rate is 2Mbps.

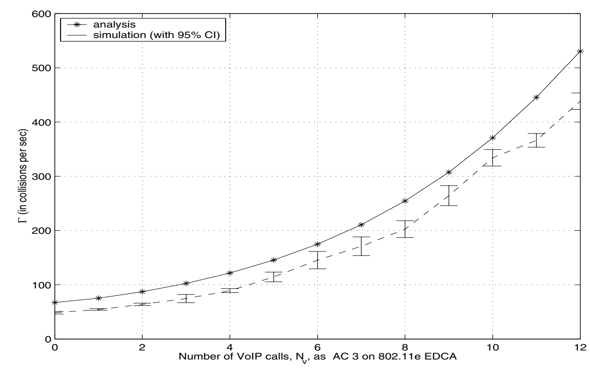

Fig. 7. Analysis and simulation results showing collision rate in the WLAN, for different values of N_v and $N_t = 10$. PHY data rate is 11Mbps and basic rate is 2Mbps.

Simulation results for the QoS objective of $Prob(delay \geq 20ms)$ for the QAP_v and the $QSTA_v$s are shown in Fig. 4. Note that the $Prob(delay : QAP_v \geq 20ms)$ is greater than $Prob(delay : QSTA_v \geq 20ms)$ for given N_v and that the QAP_v delay shoots up before the $QSTA_v$ delay, *confirming that the QAP_v is the bottleneck*, as per our assumptions. It can be seen that with and without TCP traffic, there is a value of N_v at which the $Prob(delay \geq 20ms)$ sharply increases from a value below 0.01. This can be taken to be the voice capacity. In case of no data traffic, we obtain 12 calls, matching the analysis result and when there is data traffic, we get 9 calls, one less than the analysis result.

2) TCP Throughput: For the data packet length of 1500 bytes, using IEEE 802.11b PHY parameters, with PHY data rate of 11Mbps, we numerically calculate the total download throughput for TCP traffic (fixed at $N_t = 10$) using Equation 8, for varying number of voice calls. The analytical plot has been given in Fig. 5 and the figure also shows the simulated TCP download throughput with 95% confidence intervals.

Fig. 5 shows that the reduction of TCP throughput with increasing N_v is almost linear at the rate of $\frac{1}{3}$ Mbps per VoIP call.

Remark: Fig. 5 can also be used for admission control of VoIP calls in order to guarantee a net minimal throughput to the data traffic. For instance if at least 2 Mbps of aggregate TCP throughput is to be allotted to data traffic then Fig. 5 says that only 7 VoIP calls should be admitted. ■

3) Attempt and Collision Rates: In order to validate the model, we numerically calculate the attempt rates of AC 3 nodes and AC 1 nodes using Equation 9 and Equation 10 respectively and compare them with the simulations. Fig. 6 shows the attempt rates obtained from analysis and simulations for AC 3 and AC 1 nodes for different values of N_v and $N_t = 10$.

We further calculate the system collision rates for different values of N_v and $N_t = 10$, using Equation 11. Fig. 7 shows the collision rates obtained from analysis and simulations.

Remark: From Fig. 6 and 7 we conclude that the analytical model not only predicts the performance measures well but certain other measures such as attempt rate and collision rate are also captured well. This shows that the model captures the behaviour of the system quite well.

It can be observed from Fig. 4 that the $Prob(delay :$

$QSTA_v \geq 20ms$) begins to rise from $N_v = 9$ onwards. This implies that the model assumption that the $QSTA_v$s have at most one packet fails over $N_v = 9$ calls. Over the operating point, the $QSTA_v$s will start buffering more than one packet. This is getting reflected in the attempt rates and system collision rate, after $N_v = 9$, where the error between the analytical value and stimulation value increases. ■

VI. CONCLUSION

In this paper we provided an analytical model for obtaining the capacity of VoIP calls and the TCP controlled download throughput in EDCA 802.11e WLAN, when both VoIP and data traffic are present. The analysis proceeds by modeling the evolution of the number of contending QSTAs at channel slot boundaries. This yields a Markov renewal process. A regenerative analysis then yields the required performance measures. In case of VoIP capacity, the analytical results match with those obtained from simulations, while overestimating the number of VoIP calls by just 1 call, when TCP sessions are added to the WLAN. In case of TCP download traffic, the error in download throughput is within 5% in the region of operation, i.e. up to 9 VoIP calls.

Our work provides the following modeling insights:

- The idea of using saturation attempt probabilities as state dependent attempt rates yields an accurate model in the unsaturated case.
- Using this approximation, an IEEE 802.11e infrastructure WLAN can be well modeled by a multidimensional Markov renewal process embedded at channel slot boundaries.

We also obtain the following performance insights:

- Unlike the original DCF, the EDCA mechanism supports the coexistence of VoIP connections and TCP file transfers; but even 1 TCP transfer reduces the VoIP capacity from 12 calls to 9 calls. Subsequently the VoIP capacity is independent of the number of TCP transfers (see Fig. 4).
- For an 11 Mbps PHY, the file download throughput reduces linearly with the number of voice calls at the rate of $\frac{1}{3}$ Mbps per additional voice call from 0 to 9 calls.

Our ongoing work will extend the analysis in this paper to the case when data traffic is both ways instead of just download traffic. We also are working on finding the capacities of 802.11e WLANs for real time and streaming video sessions in the EDCA framework. In related work, we have also provided an analytical model for IEEE 802.11e infrastructure WLANs using HCCA, with voice being carried in contention free period and TCP data in the remaining time using EDCA.

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Appendix

The expressions for various probabilities defined in III-B are as follows:

$$\eta_v(Y_j^{(v)}, Y_j^{(t)}) = (1-\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{Y_j^{(v)}+1}$$

$$\eta_t(Y_j^{(v)}, Y_j^{(t)}) = (1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{Y_j^{(t)}+1}$$

$$\alpha_v(Y_j^{(v)}, Y_j^{(t)}) = Y_j^{(v)}\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1}(1-\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{Y_j^{(v)}}$$

$$\alpha_t(Y_j^{(v)}, Y_j^{(t)}) = Y_j^{(t)}\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1}(1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{Y_j^{(t)}}$$

$$\sigma_v(Y_j^{(v)}, Y_j^{(t)}) = \beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1}(1-\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{Y_j^{(v)}}$$

$$\sigma_t(Y_j^{(v)}, Y_j^{(t)}) = \beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1}(1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{Y_j^{(t)}}$$

$$\zeta_v(Y_j^{(v)}, Y_j^{(t)}) = \sum_{i=2}^{Y_j^{(v)}+1} \binom{Y_j^{(v)}+1}{i} (\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(v)}+1-i)}$$

$$\zeta_t(Y_j^{(v)}, Y_j^{(t)}) = \sum_{i=2}^{Y_j^{(t)}} \binom{Y_j^{(t)}}{i} (\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(t)}+1-i)}$$

$$\psi_1(Y_j^{(v)}, Y_j^{(t)}) = \sum_{i=1}^{Y_j^{(v)}+1} \binom{Y_j^{(v)}+1}{i} (\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(v)}+1-i)}$$
$$\sum_{i=1}^{Y_j^{(t)}} \binom{Y_j^{(t)}}{i} (\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(t)}+1-i)}$$

$$\begin{aligned}\psi_{tAP}(Y_j^{(v)}, Y_j^{(t)}) &= \beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1} \\ &\Bigg[\frac{\eta_t(Y_j^{(v)}, Y_j^{(t)})}{(1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})} \sum_{i=1}^{Y_j^{(v)}+1} \binom{Y_j^{(v)}+1}{i} (\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(v)}+1-i)} \\ &+ \eta_v(Y_j^{(v)}, Y_j^{(t)}) \sum_{i=1}^{Y_j^{(t)}} \binom{Y_j^{(t)}}{i} (\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(t)}-i)} \\ &+ \sum_{i=1}^{Y_j^{(v)}+1} \binom{Y_j^{(v)}+1}{i} (\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(v)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(v)}+1-i)} \\ &\sum_{i=1}^{Y_j^{(t)}} \binom{Y_j^{(t)}}{i} (\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^i \; (1-\beta^{(t)}_{Y_j^{(v)}+1, Y_j^{(t)}+1})^{(Y_j^{(t)}-i)}\Bigg]\end{aligned}$$