Delay Analysis of IEEE 802.11 PCF MAC based Wireless Networks

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***Abstract*— In this paper, we present an analytic model for evaluating the queueing delays at nodes using the IEEE 802.11 Point Coordination Function (PCF) MAC for real time, delay sensitive traffic. Our work extends existing models by accounting for the power management mode where nodes may switch to the power save mode in order to conserve energy. We develop a queueing model for each node to obtain closed form expressions for the expected delay which accounts for arbitrary packet sizes, polling rates, channel rates and the order in which the nodes are polled. Our analytical results are verified through simulations.**

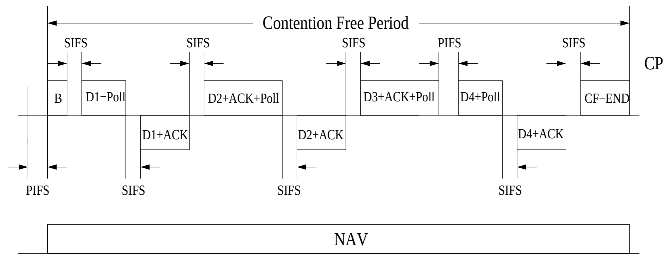

Fig. 1. PC to station frame transmissions in PCF.

I. Introduction

The IEEE 802.11 MAC [3] has become ubiquitous and gained widespread popularity as a layer-2 protocol for wireless local area and in-home networks. With increasing deployment, the services supported by such networks have started to migrate from the traditional data applications to various forms of interactive multimedia involving voice and video transmissions as well as multiplayer network gaming, specially in home environments. Supporting these real-time applications requires that the MAC layer provide sufficient delay guarantees and the Point Coordination Function has been included in 802.11 to achieve this objective. This paper analytically characterizes the delays experienced with the 802.11 PCF where nodes may employ the power management modes specified in the standards in order to conserve energy.

The delay characteristics of the 802.11 PCF has been extensively studied using simulations [2], [9]. The effect of different polling strategies on PCF performance is presented in [10] while the performance of video transmission with PCF has been investigated in [6], [8]. However, these are all simulation studies, and to the best of our knowledge, no detailed queueing or analytic models for 802.11 PCF exists in literature. This paper addresses this issue by proposing a queueing model and closed form expressions for the expected delay at each node. In [7] an analytic model has been proposed to evaluate the delays in nodes with 802.11 PCF as the MAC protocol. However, it does not account for the power management modes which the nodes may employ.

This paper extends the queueing model for nodes using 802.11 PCF as the MAC protocol proposed in [7] to account for the delays when the nodes employ power management strategies. In the power management mode, the node may stay in the active mode (AM) or switch to the power save (PS) or doze mode in order to save energy. Our model allows for arbitrary number of users in the network, their packet arrival rates and packet lengths and both unidirectional and bidirectional data transfers. The model evaluates the delays as a function of various 802.11 specific parameters like the superframe and beacon lengths facilitating the estimation of the tradeoffs involving the values of these parameters and the system performance. Our analysis has been validated using simulations.

The rest of the paper is organized as follows. In Section II we give a brief overview of the 802.11 PCF. Section III presents our delay model, Section IV presents the validation results and Section V presents the concluding remarks.

II. Background

In addition to the physical layer specifications, the IEEE 802.11 standard [3] specifies two methods for medium access: Distributed Coordination Function (DCF) and the PCF. While DCF uses a distributed, backoff based mechanism for channel access and is not the focus of the paper, in PCF the nodes are polled by a "master" residing within the base station. The channel access mechanism alternates between the DCF and PCF modes when PCF is implemented. The duration of time the DCF is used for channel access is termed the contention period (CP) and the polled duration is called the contention-free period (CFP). The lengths of the CP and the CFP is controlled explicitly by the contention free period repetition interval (CFPri) and we call a CFPri duration where the PCF and DCF alternate a "superframe".

Each CFP begins with a beacon frame and the CFPs occur at a defined repetition rate as determined by the CFPrate parameter. With PCF, the access to the channel is determined centrally by the base station, usually referred to as the Point Coordinator (PC) and provides a contention free transfer service. The PC gains control of the medium at the beginning of the CFP and maintains control for the entire CFP by waiting for a shorter time between transmissions than the stations using the DCF access mode. All stations other than the PC

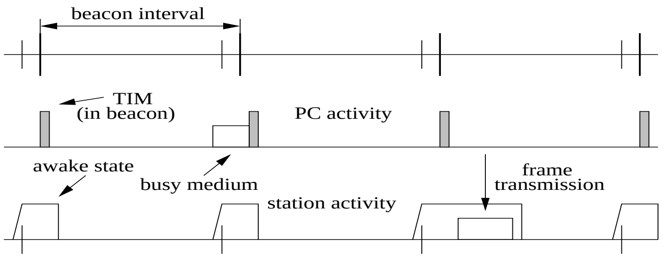

Fig. 2. Power management operation in IEEE 802.11 PCF.

set their NAVs to the CFPMaxDuration at the start of each CFP. The PC transmits a CF-End or CF-End+ACK frame at the end of each CFP and on receiving either of these frames a station resets its NAV. During the CFP, the base station polls the nodes for a *single* pending frame transmission according to a list ordering of their association with the base station, known as the polling list. The PC starts CF transmissions a SIFS interval after the beacon frame by sending a CF-Poll (no data), Data or Data+CF-Poll frame. If a station receives a CF-Poll (no data) frame from the PC, the station can respond to the PC after a SIFS interval with a CF-ACK (no data) or a Data+CF-ACK frame. If the PC receives a Data+CF-ACK frame from a station, it can send a Data+CF-ACK+CF-Poll frame to a different station where the CF-ACK part is used to acknowledge receipt of the previous data frame. If the PC transmits a CF-Poll (no data) frame and the destination station does not have any data to transmit, the station sends a Null Function (no data) frame back to the PC. If the PC fails to receive an ACK for a transmitted data frame, it waits for a PIFS interval and moves on to the next station in the polling list. Figure 1 shows the transmission of frames between the PC and stations.

The IEEE 802.11 also specifies a power management strategy wherein a station may either be in the active mode where it is full powered and may receive frames at any time or be in the power save mode. In the PS mode, the station stays in the doze state where it is unale to transmit or receive and consumes very low power. Also, the station enters the awake state to receive selected beacons and transmit and receive frames. Stations inform the PC about their state using the Power Management bits within the Frame Control field of transmitted frames. The PC buffers frames destined for stations in the PS mode and stations with buffered frames are identified in a traffic indication map (TIM) which is included in each beacon generated by the PC. On receiving a TIM indicating buffered frames for it, a station stays awake until the buffered frame is received. If the More Data field in the Frame Control field of the last frame from the AP indicates more traffic is buffered, the node may enter to doze state during the contention period and wake again at the start of the next CFP. Figure 2 illustrates PC and station activity with power management.

III. Analysis

In this section we present our model to evaluate the delays experienced by stations using the PCF mode and power management to transmit their data. We assume that an arbitrary number of nodes, M, use the PCF mode to transmit their packets. The packet inter-arrival times at the i^{th} node are assumed to be exponentially distributed with rate λ_i, $1 \leq i \leq M$. We denote the duration of the superframe by T_S and the length of a polling duration by V and the expected length of a packet from the i^{th} polled node by L_i, $1 \leq i \leq M$. Note that we include the lengths of the SIFS and CF-Poll in V and SIFS and CF-ACK in L_i. The utilization of the i^{th} station is denoted by ρ_i. Note that since each polled stations gets to transmit once in every superframe, the service rate of the i^{th} station is $\mu_i = 1/T_S$, $1 \leq i \leq M$. The utilizations are thus given by $\rho_i = \lambda_i/\mu_i = \lambda_i T_S$. In the derivations presented in this paper, we assume that the arrival rates and packet lengths are the same at each node, i.e., $\lambda_i = \lambda$, $\forall i$ and $L_i = L$, $\forall i$ and thus $\rho_i = \rho = \lambda T_S$, $\forall i$. We also assume that once a station enters the doze mode, the next time it wakes up is for the S^{th} beacon following the current frame.

We now evaluate the expected delay experienced by an arbitrary packet arriving at the i^{th} polled node. We break the analysis into two parts: (1) the delay experienced when the packet arrived while the station is in the PS mode and (2) when the arrival occurred while the station is in the active mode. A station may go into the sleep mode if there are no packets queued up for it at the PC or in its own queue. Also, even if there are packets queued up, the station may go into the sleep mode at the end of the CFP and wake up again for the next beacon. In the latter case, the station gets served in every superframe and while there are energy savings, the delay stays the same as in the active mode. We thus include the analysis for this case the analysis for the active mode. Thus in the rest of the paper, in the *sleep* mode, we only consider the scenario where the station goes into sleep because it has no outstanding packets queued up and the station goes into the doze mode for $ST_S - B$ seconds.

The probability that an arbitrary arrival finds the queue empty, $P[\text{EQ}]$, is given by

$$P[\text{EQ}] = 1 - \rho = 1 - \lambda T_S \tag{1}$$

and the probability that an arbitrary arrival finds the queue busy, $P[\text{NEQ}]$, is thus

$$P[\text{NEQ}] = 1 - P[\text{EQ}] = \rho = \lambda T_S. \tag{2}$$

Since the arrivals at each queue are independent and the probability that a queue is busy is given by ρ, the number of active stations, j, at any instant of time, out of M queues follows a Binomial distribution and is given by

$$P[j \text{ active}] = \binom{M}{j} \rho^j (1-\rho)^{M-j} \qquad j = 0, 1, \cdots, M \tag{3}$$

If at the end of the beacon (and the TIM) a station does not have any packets to transmit and the PC PC does not have any packet queued up for it, the station goes in the sleep mode for a duration of $ST_S - B$ seconds. If either queue is non empty, the node stays awake for the CFP and also for the next

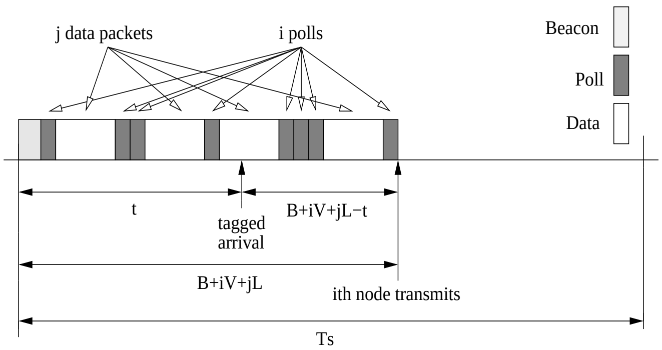

Fig. 3. Packet delays when arriving packet finds an empty queue.

beacon. The probability that a station is in the *sleep* mode at any arbitrary instant of time is then given by

$$P[\text{PS}] = \frac{(1-\rho)^2(ST_S - B)}{(1-\rho)^2 ST_S + (1-(1-\rho)^2)T_S} \tag{4}$$

and the probability that a station is in the acitve mode, $P[\text{AM}]$, is thus $P[\text{AM}] = 1 - P[\text{PS}]$. Note that a station may enter the sleep mode in the middle of a CFP after it and the PC transmit packets to each other and their queues becmoe empty. The equation above approximates this case by considering it equivalent to the sleep state entered just after the beacon transmission.

A. Arrivals in the Active Mode

We now evaluate the expected delay experienced by an arbitrary packet arriving at the i^{th} polled node in the active mode. We break the analysis into two parts: (1) the delay experienced when the packet arrived at an empty queue and (2) when the arrival occurred at a non empty queue.

1) Arrivals at an Empty Queue: Consider an arrival at the i^{th} polled station whose queue is currently empty and we call this arrival the “tagged arrival”. If this station has not yet been polled in the current superframe when the packet arrives, the packet gets served in the current superframe. Otherwise, the packet gets served in the following superframe. Now, it is well known that with exponential arrivals in a slotted departure system (for example a classical M/D/1 queue), an arrival is equally likely to occur anywhere in a slot or frame [5], [1]. In our case, *given* that an arrival occurs in a given superframe, the arrival instance is thus uniformly distributed random variable over $[0, T_s]$ *relative* to the start of the superframe. Consider the case where j of the $2i-1$ nodes (where we have also included the downstream queues at the PC for each station as a node) polled before the i^{th} node in a given superframe have data to send. In this case, a period of $B + (i-1)V + jL$ seconds elapse in the superframe before the i^{th} node is polled and $B + iV + jL$ seconds elapse before it has to reply to the poll. Thus if the tagged arrival occurs in this duration, it gets served in this superframe. Otherwise it waits for the next superframe. We now evaluate the probabilities of the associated events and the expected waiting time of the packet.

Since the arrival instant, t, of any packet relative to the start of its superframe is uniformly distributed ($U[0, T_S]$), the probability that the tagged packet arrived at node i in the first $B + iV + jL$ seconds is given by

$$P[t \le B + iV + jL] = \frac{B + iV + jL}{T_S}. \tag{5}$$

In this case (which we call case C1), the packet waits till the i^{th} node is polled and is then transmitted, as shown in Figure 3. The time the packet waits before it begins service, $X_{i,j,C1}$, is thus $X_{i,j,C1} = B+iV+jL-t$ after which it receives service for another L seconds before departing the system. We will now characterize the distribution of $X_{i,j,C1}$. The probability distribution function (PDF) of t given that the arrival occurred in the first $B + iV + jL$ seconds of the superframe is given by

$$\begin{aligned} P[t \le \tau \mid t \le B+iV+jL] &= \frac{P[t \le \tau, t \le B+iV+jL]}{P[t \le B + iV + jL]} \\ &= \frac{\tau}{B + iV + jL} \end{aligned} \tag{6}$$

which is an Uniform distribution in the range 0 to $B+iV+jL$. Now, note that if a random variable Y is uniformly distributed in the range 0 to a, then the random variable $a - Y$ is also uniformly distributed in the range 0 to a. Following this observation, since the conditional PDF of t is uniformly distributed in the range 0 to $B+iV+jL$, the conditional PDF of $X_{i,j,C1} = B + iV + jL - t$ is also an Uniform distribution in the range 0 to $B + iV + jL$, i.e., $U[0, B + iV + jL]$. The expected value of $X_{i,j,C1}$ is thus

$$E[X_{i,j,C1}] = E[U[0, B + iV + jL]] = \frac{B + iV + jL}{2}. \tag{7}$$

In the case where the packet does not arrive in the first $B + iV + jL$ seconds of the superframe (which we call case C2), i.e. $t > B + iV + jL$, the packet has to wait till the remaining part of the superframe ($T_S - t$) is over and node i is polled in the following round. The PDF of t given that the arrival occurred after the first $B + iV + jL$ seconds of the superframe is then an Uniform distribution in the range $B + iV + jL$ to T_S, i.e., $U[B + iV + jL, T_S]$. Thus the duration of the remaining part of the superframe, $T_S - t$, is also uniformly distributed and is $U[0, T_S - B - iV - jL]$.

In the following superframe, if there are k nodes with data to send among the $2i-1$ nodes polled before the i^{th} node, the tagged packet has to wait for $B + iV + kL$ seconds before its service begins. Since the probability that there are k nodes with data among $2i-1$ nodes follows a Binomial distribution as given in Eqn. (3), the probability mass function (pmf) of this waiting time, X_{NR} is given by

$$P[X_{NR} = x] = \begin{cases} \binom{2i-1}{k} \rho^k (1-\rho)^{2i-k-1} & x = B+iV+kL \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

with $0 \le k \le 2i-1$ and the expected value of X_{NR} is given by

$$E[X_{NR}] = B + iV + (2i-1)\rho L. \tag{9}$$

Thus the amount of time, $X_{i,j,C2}$, before the packet begins its service is $X_{i,j,C2} = T_S - t + X_{NR}$. The expected value of $X_{i,j,C2}$ is thus

$$\begin{aligned} E[X_{i,j,C2}] &= E[U[0, T_S - B - iV - jL]] + E[X_{NR}] \\ &= \frac{T_S - B - iV - jL}{2} + B + iV + (2i-1)\rho L \end{aligned} \quad (10)$$

To find the expected waiting time in the systems when an arrival occurs at an empty queue given that j of the $2i-1$ nodes before the i^{th} node send data in the current superframe, we combine the waiting times of the above two cases. This expected waiting time, $D_{i,j,EQ}$, is given by

$$D_{i,j,EQ} = E[X_{i,j}] + L \quad (11)$$

with

$$E[X_{i,j}] = E[X_{i,j,C1}]P[C1] + E[X_{i,j,C2}]P[C2] \quad (12)$$

where $E[X_{i,j,C1}]$ and $E[X_{i,j,C2}]$ are given in Eqns. (7) and (10) respectively and $P[C1]$ and $P[C2]$ are the probabilities that the arrival occurs in the first $B + iV + jL$ seconds of the superframe or not, respectively. As discussed earlier in this section, these are given by

$$\begin{aligned} P[C1] &= \frac{B + iV + jL}{T_S} \\ P[C2] &= 1 - \frac{B + iV + jL}{T_S} \end{aligned} \quad (13)$$

Putting these values in Eqn. (12), $E[X_{i,j}]$ can be simplified to

$$\begin{aligned} E[X_{i,j}] &= \frac{T}{2} + \frac{(B + iV + jL)^2}{T_S} - (B + iV + jL) \\ &\quad + E[X_{NR}]\frac{T_S - B - iV - jL}{T_S} \end{aligned} \quad (14)$$

which can now be used in Eqn. (11) to obtain $D_{i,j,EQ}$. The expected delay at the i^{th} node, $D_{i,EQ}$ is then obtained by unconditioning Eqn. (11) on j. Recall that j denotes the number of nodes among the $2i-1$ polled ahead of node i had packets to send in an arbitrary superframe and has a Binomial pmf given in Eqn. (3). Thus $D_{i,EQ}$ is given by

$$\begin{aligned} D_{i,EQ} &= \sum_{j=0}^{2i-1} (E[X_{i,j}] + L) \binom{2i-1}{j} \rho^j (1-\rho)^{2i-j-1} \\ &= \frac{T_S}{2} + \frac{\rho L^2 (2i-1)(1-\rho)}{T_S} + L \end{aligned} \quad (15)$$

2) Arrivals at a Non-Empty Queue: We now consider the case when an arbitrary arrival to the i^{th} polled node finds the queue non-empty and we denote the number of packets in the queue found by this packet by N_{NQ}. In this case, this tagged arrival has to wait till all preceding arrivals have been served. To calculate the packet's waiting time, we again consider two possible cases: whether the i^{th} node has already been served in the current superframe when the tagged arrival occurs (case C2) or not (case C1). Consider again the case where j of the $2i-1$ nodes polled before node i have packets to send in the current superframe. Then the probabilities of the events C1 and C2 are given by

$$\begin{aligned} P[C1] &= \frac{B + iV + (j+1)L}{T_S} \\ P[C2] &= 1 - \frac{B + iV + (j+1)L}{T_S} \end{aligned} \quad (16)$$

where the $j+1$ terms comes from the fact that in addition to the j nodes, node i is also transmitting.

In case the i^{th} node has not yet been served when the tagged packet arrives (case C1), one of the N_{NQ} packets currently waiting in the queue at node i gets served during this superframe. If we denote the instant of the tagged packet's arrival in the superframe by t, it has to wait for $T_S - t$ seconds before the current superframe ends. The tagged packet then has to wait for another $N_{NQ} - 1$ packets to depart, with one departure in one superframe or $(N_{NQ} - 1)T_S$ seconds before the start of the superframe where it receives service. We denote the wait in the final superframe by X_{FR}. Thus the total time before the packet begins service in this case, $X_{i,j,C1}$, is given by $X_{i,j,C1} = T_S - t + (N_{NQ} - 1)T_S + X_{FR}$.

Following the derivation in Eqn. (6), the PDF of t given that the arrival occurred in the first $B + iV + (j+1)L$ seconds is the Uniform distribution $U[0, B + iV + (j+1)L]$. Thus $T_S - t$ follows the Uniform distribution $U[T_S - B - iV - (j+1)L, T_S]$. To evaluate the distribution of X_{FR}, we note that if there are k nodes with data to send among the $2i-1$ nodes polled before node i, the packet has to wait for $B + iV + kL$ seconds before its service begins. Since k follows the Binomial distribution of Eqn. (3), the pmf of X_{FR} is given by

$$P[X_{FR} = x] = \begin{cases} \binom{2i-1}{k} \rho^k (1-\rho)^{2i-k-1} & x = B + iV + kL \\ 0 & \text{otherwise} \end{cases} \quad (17)$$

with $0 \le k \le 2i-1$ and the expected value of X_{FR} is

$$E[X_{FR}] = B + iV + (2i-1)\rho L. \quad (18)$$

The expected value of $X_{i,j,C1}$ is thus

$$\begin{aligned} E[X_{i,j,C1}] &= E[T_S - t] + E[(N_{NQ} - 1)T_S] + E[X_{FR}] \\ &= \frac{B + iV + (j+1)L}{2} + (E[N_{NQ}] - 1)T_S \\ &\quad + B + iV + (2i-1)\rho L \end{aligned} \quad (19)$$

In the case where the tagged arrival occurs after the i^{th} node has been served in the current round (case C2), at the end of the current superframe, there are still N_{NQ} packets ahead of the tagged packet. Thus at the end of a further $N_{NQ}T_S$ seconds, the superframe in which the tagged packet gets served starts. The amount of time the tagged packet has to wait in this final round is again denoted by X_{FR} and its pmf and expected values are given in Eqns. (17) and (18) respectively. Thus the total time before the packet begins service in this case, $X_{i,j,C2}$, is given by $X_{i,j,C2} = T_S - t + N_{NQ}T_S + X_{FR}$. Now, the PDF of t given that the arrival occurred after the first $B+iV+(j+1)L$ seconds of the superframe is

$$P[t \le \tau \mid t > B+iV+(j+1)L] = \frac{\tau}{T_S - B - iV - (j+1)L}$$

the Uniform distribution $U[B+iV+(j+1)L, T_S]$. Thus $T_S - t$ is also uniformly distributed and is $U[0, T_S - B - iV - (j+1)L]$. The expected value of $X_{i,j,C2}$ is thus

$$\begin{aligned} E[X_{i,j,C2}] &= E[T_S - t] + E[N_{NQ} T_S] + E[X_{FR}] \\ &= \frac{T_S - B - iV - (j+1)L}{2} + E[N_{NQ}] T_S \\ &\quad + B + iV + (2i-1)\rho L \end{aligned} \tag{20}$$

Combining the two cases above, the expected waiting time at the i^{th} node, $D_{i,j,NEQ}$, is then given by

$$\begin{aligned} D_{i,j,NEQ} &= E[X_{i,j}] + L \\ &= E[X_{i,j,C1}]P[C1] + E[X_{i,j,C2}]P[C2] + L \\ &= \frac{T_S}{2} + E[N_{NQ}]T_S + E[X_{FR}] - B - iV - jL \end{aligned}$$

Unconditioning the above equation on j and recalling that j follows the Binomial distribution of Eqn. (3), the expected delay at the i^{th} node, $D_{i,NEQ}$ is given by

$$\begin{aligned} D_{i,NEQ} &= \sum_{j=0}^{2i-1} D_{i,j,NEQ} \binom{2i-1}{j} \rho^j (1-\rho)^{2i-j-1} \\ &= \frac{T_S}{2} + E[N_{NQ}] T_S \end{aligned} \tag{21}$$

3) Overall Delay in the Active Mode: The expressions for the delays of the previous two sections can now be combined to obtain the expression for the delay experienced by an arbitrary arrival in the active mode, $D_{i,AM}$.

$$\begin{aligned} D_{i,AM} &= D_{i,EQ} P[\text{EQ}] + D_{i,NEQ} P[\text{NEQ}] \\ &= \frac{T_S}{2} + \rho E[N_{NQ}] T_S + \left[\frac{\rho L^2 (2i-1)(1-\rho)}{T_S} + L\right](1-\rho) \end{aligned} \tag{22}$$

where $P[\text{EQ}]$, $P[\text{NEQ}]$, $D_{i,EQ}$ and $D_{i,NEQ}$ are given in Eqns. (1), (2), (15) and (21) respectively. Note however, that the expression $E[N_{NQ}]$ is the expected number of packets seen an arrival *given* that the queue is non-empty. The expected number in the queue seen by an arbitrary arrival, $E[N] = \sum_{i=1}^{\infty} iP[N=i]$ is related to $E[N_{NQ}]$ by

$$E[N_{NQ}] = \sum_{i=0}^{\infty} \frac{iP[N{=}i, \text{NEQ}]}{P[\text{NEQ}]} = \sum_{i=1}^{\infty} \frac{iP[N{=}i]}{\rho} = \frac{E[N]}{\rho} \tag{23}$$

where $P[N = i, \text{NEQ}]$ represents the joint probability that there are i packets in the queue and the queue is non-empty. Also from Little's Law $E[N] = \lambda D_i$. We thus have $E[N_{NQ}] = \lambda D_i / \rho$ and substituting this in Eqn. (23) we have the final expression for D_i

$$D_{i,AM} = \frac{1}{1 - \lambda T_S}\left[\frac{T_S}{2} + \left(\frac{\rho L^2 (2i-1)(1-\rho)}{T_S} + L\right)(1-\rho)\right] \tag{24}$$

B. Arrivals in the Power Save Mode

When an arrival occurs while the station is in the PS mode, it has to wait to till the end of the sleep period before its service starts. The sleep period corresponding to each node is of duration $ST_S - B$ seconds. If we denote the instant of the tagged packet's arrival relative to the start of the sleep period by t, it has to wait for $ST_S - B - t$ seconds before the sleep period ends. In addition, it must wait for the other arrivals before it in the current sleep period to be served and if there are κ such packets, a waiting time of κT_S seconds is introduced bfore the start of the superframe where the tagged packet receives service. We denote the wait in the final superframe by X_{FR}. Thus the total time before the packet begins service in this case, $X_{i,PS}$, is given by $X_{i,PS} = ST_S - B - t + \kappa T_S + X_{FR}$.

Since arrivals are independent of the service process and following the arguments in the pervious sub-section, the arrival instant t of the tagged arrival relative to the start of the sleep period is uniformly distributed and is $U[0, ST_S - B]$. Thus $ST_S - B - t$ also follows the same uniform distribution and is $U[0, ST_S - B]$. Now, given that packet inter-arrival times are exponentially distributed, the pmf of the number of arrivals κ before the tagged packet is given by

$$P[\kappa = k \mid t] = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{25}$$

and thus $E[\kappa \mid t] = \lambda t$. Finally, the pmf and expected value of X_{FR} are given in Eqns. (17) and (18) respectively. The total time before the tagged packet receives service is then

$$\begin{aligned} E[X_{i,PS}] &= E[ST_S - B - t] + E\left[E[\kappa \mid t]\right] T_S + E[X_{FR}] \\ &= \frac{ST_S - B}{2} + \lambda T_S \frac{ST_S - B}{2} + B + iV + (2i-1)\rho L \end{aligned}$$

The expected delay at the i^{th} node is given by

$$D_{i,PS} = E[X_{i,PS}] + L \tag{26}$$

C. Overall Delay

The expressions for the delays of the previous two sections can now be combined to obtain the expression for the delay experienced by an arbitrary arrival. The expected packet delay at node i is given by

$$\begin{aligned} D_i &= D_{i,AM} P[\text{AM}] + D_{i,PS} P[\text{PS}] \\ &= \left[\frac{T_S}{2} + \left(\frac{\rho L^2 (2i-1)(1-\rho)}{T_S} + L\right)(1-\rho)\right] \frac{1 - P[\text{PS}]}{1 - \lambda T_S} + \\ &\quad \left[(1+\lambda T_S)\frac{ST_S - B}{2} + B + iV + (2i-1)\rho L + L\right] P[\text{PS}] \end{aligned} \tag{27}$$

where $P[\text{PS}]$ is given in Eqn. (4).

IV. Simulation Results

In this section we validate the analytic models proposed in the previous sections by comparing them with simulation results. These simulations were carried out using the network simulator *ns* as well as our own simulation code. The simulations were carried out for different network sizes

Parameter	Value
Transmission power	281.8 mW
Transmission range	250 meters
Slot time	20 μsec
SIFS	10 μsec
DIFS	50 μsec
PIFS	30 μsec
CFPriMax	30 msec
Channel bandwidth	2 Mbps
Beacon	209 μsec
CF-Poll	209 μsec
CF-End	209 μsec
CF-ACK	153 μsec
Packet size	520 B

TABLE I
SIMULATION SETTINGS

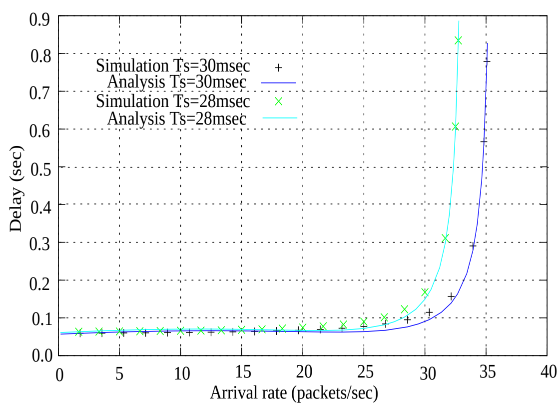

Fig. 4. Simulation and analytic results for CFPri values of 28 msec and 30 msec.

and parameter settings as indicated in in Table IV. In the simulations, we considered a circular region of radius 240 meters with the base station at the center and all other nodes within its range.

In Figure 4 we compare the simulation and analytic results (from Eqn. (28)) when there are 5 nodes in the network. We show two cases corresponding to CFPri values of 28 msec and 30 msec and in both cases we note the close match between the simulation and analytic results. We also note that having a shorter CFPri supports higher arrival rates for a given delay requirement. In Figure 5 we compare the analytic model of Eqn. (28) for two different lengths of the sleep period, $S = 2$ and $S = 4$. We again note the close match. Similar results were obtained for other network sizes, CFPri lengths and packet sizes and are not shown here due to space limitations.

V. CONCLUSIONS

In this paper, we presented an analytic model to evaluate the delays is wireless networks using the IEEE 802.11 PCF as the MAC layer protocol. Our model accounts for the behavior of stations using the power management mechanism and the associated awake and power save modes. We obtained closed form expressions for the delays at each node as a function of various systems parameters. The model allows for arbitrary packet sizes, polling frequencies, channel rates and the order in which a node is polled. The accuracy of these expressions was verified using simulations.

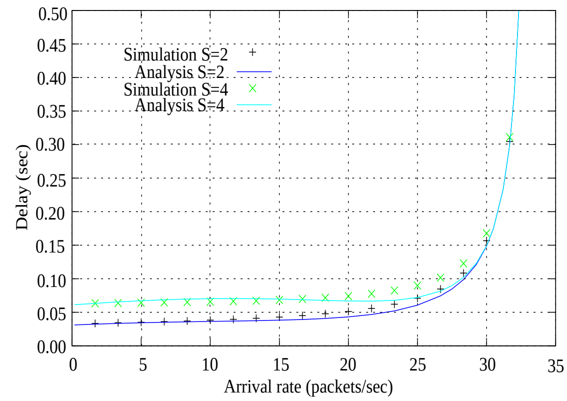

Fig. 5. Simulation and analytic results for $S = 2$ and $S = 4$.

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