Modeling and Analysis of Traffic Characteristics in IEEE 802.11 MAC Based Networks

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Abstract—**This paper presents an analytic model for characterizing the traffic in wireless networks using *IEEE 802.11 as the MAC protocol.* The results of this paper are aimed at filling the existing void created by the absence of any accurate models or understanding of wireless traffic, critical for effective performance evaluation. Our results show that the behavior of wireless traffic can vary significantly from the characteristics of traffic in wired networks. We show that the operating mechanism of 802.11 MAC leads to "pacing" in the wireless traffic. Additionally, the interarrival times are best characterized by a multimodal distribution, in sharp contrast to the models used for for wired networks. The analytic model has been verified through extensive simulations and is applicable to both ad hoc and infrastructure based wireless networks.**

I. INTRODUCTION

Inspite of a lot of research efforts in the area of wireless networking, very little or nothing has been done about modeling of the wireless traffic. Authors till date have proposed improvements to connectivity, mobility, energy (battery power), signal strength and contention. Most of the results reported for wireless networks have been obtained with IEEE 802.11 serving as the MAC specification primarily due to its popularity and greater acceptance over other protocols. Existing work on characterizing the behavior of 802.11 MAC has concentrated around modeling its performance and capacity [2], [9]. Work has also been conducted on improving the 802.11 MAC as reported in [1], [10] and the references therein. A trace based study of traffic self-similarity in wireless networks is presented in [5]. We strongly believe that a good traffic model is an essential building block for advanced research in networking, wired or wireless. It is with this goal in mind that we present a comprehensive analytic traffic model for wireless networks in this paper. The choice of IEEE 802.11 as the underlying MAC for our analysis was motivated by the facts mentioned earlier about its widespread deployment and popularity.

Our analysis shows that the mechanism of operation of 802.11 MAC leads to pacing in the TCP traffic making the interarrival times at a busy station (a station acting as a router or a destination for many flows) distributed in discrete slots. We present our analysis for both the infrastructure and the ad-hoc networks and show that the model stays valid in both the cases. The analytic model is cross verified with the simulation results obtained with *ns-2* simulator. Our results show that in contrast to wired networks, the interarrival time distribution in wireless networks shows evidence of pacing induced by the MAC protocol and the interarrival times have a multimodal distribution.

The rest of the paper is organized as follows: in Section II we give a brief introduction of concepts used in this paper. An analytic model of the 802.11 MAC behavior for the TCP traffic is presented in SectionIII. We extend our analytical results to adhoc systems in Section III-B. We present the simulation results used in Section IV. Section V summarizes the paper's contributions.

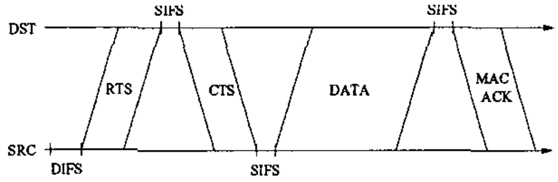

Fig. 1. Basic operation of the CSMA/CA protocol.

II. INTRODUCTION TO IEEE 802.11 MAC

The IEEE 802.11 standard [4] covers both the physical (PHY) and the medium access control (MAC) layer of wireless networks. The standard specifies that a network can be configured in two different ways: infrastructure and ad-hoc. The IEEE 802.11 MAC layer is responsible for a structured channel access scheme and is implemented using a Distributed Coordination Function (DCF) based on the Carrier Sense Medium Access with Collision Avoidance (CSMA/CA) protocol.

In a network with a CSMA/CA MAC protocol, each node with a packet to transmit first senses the channel to ascertain whether it is in use. If the channel is sensed to be idle for an interval greater than the Distributed Inter-Frame Space (DIFS), the node proceeds with its transmission. If the channel is sensed as busy, the node defers transmission till the end of the ongoing transmission. The node then initializes its *backoff timer*, which has the granularity of a *backoff slot*, with a randomly selected *backoff interval* and decrements this timer everytime it senses the channel to be idle. Along with the Collision Avoidance, 802.11 uses a positive acknowledgment (ACK) scheme. For every packet received correctly, the receiver waits for a brief period, called the Short Inter-Frame Space (SIFS), before it transmits the ACK.

In addition, to account for the "hidden node" problem in wireless LANs [4], 802.11 MAC uses a reservation based scheme. A station with a packet to transmit sends an Ready To Send (RTS) packet to the receiver and the receiver responds with a Clear To Send (CTS) packet if it is willing to accept the packet and is currently not busy. This RTS/CTS exchange is detected by all the nodes within hearing distance of either the sender or receiver or both and they defer their transmissions till the current transmission is complete. The basic operation of the CSMA/CA based MAC protocol of IEEE 802.11 is shown in Figure 1.

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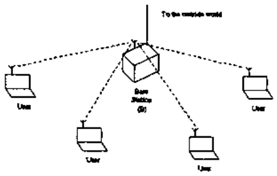
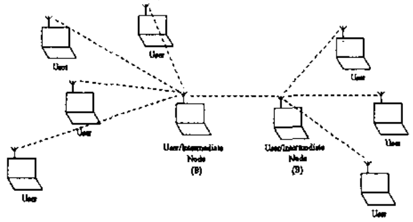


(a) Infrastructure



(b) Ad hoc network

Fig. 2. The network models assumed in this paper: (a) BSS with fixed base station and (b) an ad hoc network.

III. MODELING INTER-ARRIVAL TIMES

In this section we develop the analytic model to characterize the inter-arrival times of packets arriving at the base station or an intermediate point ("router") in an ad hoc network. We denote the transmission rate of the wireless links by C bits/sec. Also, we are not concerned with issues of mobility here since we are interested in the traffic dynamics at a node which is being used by a set of other nodes.

The set of nodes n can send packets of different lengths and in the following derivation we restrict the possible packet lengths to two values: L_1 and L_2 bits to correspond to data and acknowledgment (ACK) packets respectively. However, this model can be easily extended to account for arbitrary packet size distributions. We consider that all nodes have packets to send at all points in time and the throughput is limited by other network related factors.

In order to model the interarrival times, we first analyze the back-off mechanism associated with the exponential back-off mechanism of the 802.11 MAC protocol's Collision Avoidance mechanism. The full details of the back-off scheme are given in [4]. With multiple nodes contending for the channel, once the channel is sensed idle for a DIFS, each node with a packet to transmits decrements its backoff timer. The node whose timer expires first begins transmission and the remaining nodes stop their timer and defer their transmission. Once a node goes into collision avoidance or the exponential back-off phase, we denote the number of slots that it waits beyond a DIFS period before initiating transmission by BC. This back-off counter is calculated from

$$BC = \mathrm{int}\left(\mathrm{rnd}() \cdot CW(k)\right) \tag{1}$$

where the function `rnd()` returns a pseudo-random number uniformly distributed in $[0, 1]$ and $CW(k)$ represents the contention window after k unsuccessful transmission attempts. At the end of k unsuccessful attempts, $CW(k)$ is given by

$$CW(k) = \min\left(CW_{max}, 2^{k-1}CW_{min}\right) \tag{2}$$

Also, let the probability that a transmission attempt is unsuccessful, i.e., the probability of a collision be denoted by p. Then, the probability that $CW = W$ is given by

$$\Pr\{CW = W\} = \begin{cases} p^{k-1}(1-p) & \text{for } W = 2^{k-1}CW_{min} \\ p^n & \text{for } W = CW_{max} \end{cases} \tag{3}$$

where $n = \log_2(CW_{max}/CW_{min})$ and $k \leq n$. The probability that back-off counter $BC = i$, $1 \leq i \leq CW_{max}$, is then given by

$$\Pr\{BC = i\} = \begin{cases} \left[\sum_{k=0}^{n-1} \frac{p^k(1-p)}{2^k CW_{min}} \right. & 1 \leq i \leq CW_{min} \\ \left. + \frac{p^n}{CW_{max}}\right] & \\ \left[\sum_{k=j}^{n-1} \frac{p^k(1-p)}{2^k CW_{min}} \right. & 2^{j-1}CW_{min} + 1 \leq \\ \left. + \frac{p^n}{CW_{max}}\right] & i \leq 2^j CW_{min} \\ \frac{p^n}{CW_{max}} & 2^{n-1}CW_{min} + 1 \leq \\ & i \leq CW_{max} \end{cases} \tag{4}$$

The expected value of the back-off counter is then given by

$$E[BC] = \frac{1 - p - p(2p)^n}{1 - 2p} \frac{CW_{min}}{2} \tag{5}$$

Once the back-off counter value is selected after each unsuccessful transmission attempt, this value is decremented everytime the node senses an idle DIFS in the channel. However, if some other node transmits before the BC value of the tagged node is decremented to 0, the counter is stopped. At the end of the next idle DIFS interval, this node only has to wait till the *residual* value of BC is decremented to 0. Note that the generation of values for the BC at every unsuccessful transmission constitute a discrete renewal process. Using the results for the residual time distribution for discrete time processes [8], the residual time distribution for the back-off counter is given by

$$\Pr\{R = k\} = \frac{\Pr\{BC > k\}}{E[BC]} \tag{6}$$

where R represents the residual time and $1 \leq k \leq CW_{max}$. Note that while this is the residual time distribution only after the first idle DIFS, we use the above expression to approximate the residual time of the back-off counter at the end of the subsequent idle DIFSs.

With N nodes contending for the channel and decrementing their back-off counters simultaneously, the number of back-off slots from the end of the first idle DIFS period till the next packet transmission is the minimum of the residual times of the contending nodes. This distribution is given by

$$\Pr\{M \leq k\} = 1 - \prod_{i=1}^{N} \left(1 - \Pr\{R \leq k\}\right) \tag{7}$$

where $R_i, 1 \leq i \leq N$ represents the residual time at node i and in the final expression, we assume that all the R_i's are independent and identically distributed. We add here that from the results of [9], the probability of collision p can be obtained by solving the following equation:

$$p\frac{1 - p - p(2p)^n}{1 - 2p} = \frac{2}{CW_{min}}\left(1 + \frac{2}{3}N\right)\frac{N-1}{N} \tag{8}$$

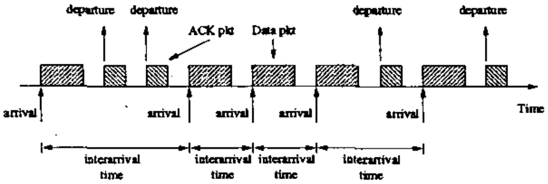


Fig. 3. Packet arrivals and departures at node B with uni-directional data flow.

A. *Wireless Networks with Infrastructure*

We now consider the network depicted in Figure 2 (a) where a number of wireless stations, which may be either fixed or mobile, use the central base station (B) to communicate with the outside world. To derive the distribution of the inter-arrival times at B, we first start with the simple case where all nodes send *only* data packets and receive *only* ACK packets. In other words, we assume uni-directional data transfer. The duration for which the channel is busy when a data packet is successfully transmitted can be calculated as

$$T_1 = DIFS + 3SIFS + \tau_{RTS} + \tau_{CTS} + \tau_{L_1} + \tau_{ack} \quad (9)$$

where τ_{RTS}, τ_{CTS}, τ_{L_1} and τ_{ack} correspond to the transmission times of RTS, CTS, data packet of length L_1 bits and the MAC layer acknowledgment packet. Note that τ_{L_1} is given by $\tau_{L_1} = \frac{L_1}{C}$. Similarly, the time to successfully transmit an ACK packet is given by

$$T_2 = DIFS + 3SIFS + \tau_{RTS} + \tau_{CTS} + \tau_{L_2} + \tau_{ack} \quad (10)$$

with $\tau_{L_1} = \frac{L_2}{C}$. Additionally, in the case of a collision, the channel stays busy for a duration of T_C before contending nodes start decrementing their backoff counters again. This duration corresponds to a DIFS period and τ_{RTS} when the RTS messages from the colliding nodes overlap. Thus

$$T_C = DIFS + \tau_{RTS} \quad (11)$$

The arrival of data packets and the departure of ACK packets at node B from the wireless medium form a sequence of events as shown in Figure 3. The inter-arrival times at B correspond to the difference of the arrival instants of two successive data packets which can vary depending on the number of ACK packets which arrive between them. Now, since we have N_1 and N_2 data and ACK packets respectively, the probabilities p_1 and p_2 that any arbitrary arrival at node B is a data or ACK packet respectively are given by

$$p_1 = \frac{N_1}{N_1 + N_2} \qquad p_2 = \frac{N_2}{N_1 + N_2} \quad (12)$$

The presence of each ACK packet adds a time of T_2 seconds to the interarrival time while the first of the two data packets under consideration adds T_1 seconds. The expected value of the contribution due to the back-off slots associated with each ACK packet is given by $E[M]$ obtained using Eqn. (7). Then, the probability that we wait for T seconds between two successive arrivals at node B is given by

$$\Pr\{T = t\} = p^i(1-p)^{j+1} p_1 p_2^j \Pr\{M = k\} \quad (13)$$

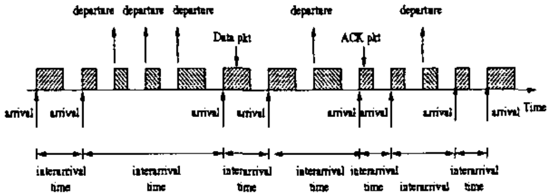


Fig. 4. Packet arrivals and departures at node B with bi-directional data flow.

where

$$t = T_1 + jT_2 + iT_C + (i+j)E[M] + k\Delta, \quad (14)$$

Δ represents the width of a back-off slot in seconds and $i \geq 0$, $j \geq 0$ and $1 \geq k \geq CW_{max}$. The term p^i in the expression accounts for the increase in the interarrival times by $i(T_C + E[M])$ in the case of i consecutive collisions. The term $p_1 p_2^j$ denotes the probability of j ACK packets being forwarded by B before receiving a data packet. Each of these j ACKs adds $(T_2 + E[M])$ seconds to the interarrival time. The final term $\Pr\{M = k\}$ denotes the probability of having k back-off slots before the data packet transmission begins once the sender senses that the channel is idle for a DIFS. Note that the same value of t can be obtained through a number of possible choices of i, j and k and the probability corresponding to each of these cases should be summed up obtain the probability of an interval having a length of t.

The generalization of the above model to consider the case when the user nodes are allowed to transmit as well as receive data can be done through the derivations in the next sub-section which considers the intermediate nodes in an ad hoc network.

B. *Ad Hoc Networks*

We now consider the ad hoc network of Figure 2 (b) and relax the unidirectional data flow assumption to allow bidirectional traffic at the user nodes. With bi-directional traffic, a possible sequence of packet arrivals and departures from node B is shown in Figure 4. In this case, inter-arrivals can correspond to successive arrivals of the following possible order of packets: (1) data, data (2) data, ACK (3) ACK, data and (4) ACK, ACK.

Let N_1 and N_2 be the number of data and ACK packets be successfully forwarded by the users and other intermediate nodes to node B. Assuming no buffer overflows, the probability that any point of time, node B is receiving data or ACK packets, p_1 and p_2 respectively, and the probability that it is forwarding data or ACK packets, p_3 and p_4 respectively, is then given by

$$p_1 = p_3 = \frac{N_1}{2(N_1 + N_2)} \qquad p_2 = p_4 = \frac{N_2}{2(N_1 + N_2)} \quad (15)$$

Now, if the first of the two arrivals constituting an interarrival is a data packet, it adds T_1 seconds to the interarrival time while an ACK packet adds T_2 seconds. Each data or ACK packet forwarded by node B between the two arrivals constituting the interarrival adds another $T_1 + E[M]$ or $T_2 + E[M]$ seconds respectively while any collision adds $T_C + E[M]$ seconds. Then, the probability that we wait for T seconds between two successive arrivals at node B is given by

$$\Pr\{T=t\} = \begin{cases} \Big[(1-p)^{i+j+1}\frac{p_1}{p_1+p_2}\cdot & \text{first arrival:} \\ p^l p_3^i p_4^j \Pr\{M=k\}\Big] & \text{data packet} \\ \Big[(1-p)^{i+j+1}\frac{p_2}{p_1+p_2}\cdot & \text{first arrival:} \\ p^l p_3^i p_4^j \Pr\{M=k\}\Big] & \text{ACK packet} \end{cases} \quad (16)$$

where

$$t = \begin{cases} [(i+1)T_1 + jT_2 + lT_C + & \text{first arrival:} \\ (i+j+l)E[M] + k\Delta] & \text{data packet} \\ [(j+1)T_2 + iT_1 + lT_C + & \text{first arrival:} \\ (i+j+l)E[M] + k\Delta] & \text{ACK packet} \end{cases} \quad (17)$$

where $i \geq 0$, $j \geq 0$, $l \geq 0$ and $1 \geq k \geq CW_{max}$. The term p^l in Eqn. (16) represents l successive data or ACK packet transmissions attempted unsuccessfully before a second packet is correctly received at node B. These add $l(T_C + E[M]$ seconds to the interarrival time. The terms $\frac{p_1}{p_1+p_2}$ and $\frac{p_2}{p_1+p_2}$ represent the probability that the first of the two arrivals constituting the interarrival is a data or ACK packet respectively. This adds T_1 or T_2 seconds to the interarrival time. The term $p_3^i p_4^j$ corresponds to cases where i data and j ACK packets are forwarded by node N between the two arrival contributing $iT_1 + jT_2 + (i+j)E[M]$ seconds. Finally, the term $\Pr\{M=k\}$ denotes the probability of having k back-off slots before the data or ACK packet transmission corresponding to the second arrival begins.

The model can also be extended to find the interarrival times considering the arrivals from only the data or ACK packets in the stream. For the case when we consider *only* the data packets arrivals to constitute the arrival process, the probability mass function for the interarrival time can be expressed as

$$\Pr\{T=t\} = p^i(1-p)^{j+l+m+1} p_1 p_2^j p_3^l p_4^m \Pr\{M=k\} \quad (18)$$

where

$$t = (l+1)T_1 + (j+m)T_2 + iT_C + (i+j+l+m)E[M] + k\Delta \quad (19)$$

where $i \geq 0$, $j \geq 0$, $1 \geq k \geq CW_{max}$, $l \geq 0$ and $m \geq 0$. A simple modification to Eqn. (18) allows us to model the case when we consider *only* the ACK arrivals at B to constitute our arrival process. The interarrival time mass function is given by

$$\Pr\{T=t\} = p^{j-1}(1-p) p_1^i p_2^j p_3^l p_4^m \Pr\{M=k\} \quad (20)$$

where

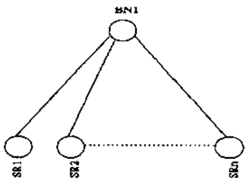
$$t = (i+l)T_1 + (j+m)T_2 + (i+j+l+m-1)E[M] + k\Delta \quad (21)$$

where $j \geq 1, i \geq 0, 1 \geq k \geq CW_{max}, l \geq 0$ and $m \geq 0$.

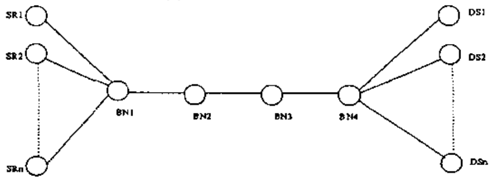
IV. SIMULATION RESULTS

To verify our analytic models we conducted extensive simulations using the *ns-2* simulator for the topologies shown in Figure 5. Node BN1 can be considered as the base station B of Section III-A and the intermediate node B in Section III-B. The results presented in this section correspond to the traces and statistics collected at node BN1. For both topologies, we consider the following scenarios: (1) 40 sources and (2) 10 sources. In our simulations models, the nodes have no mobility. The sources use TCP as the transport protocol and the data packet size was 1000 bytes while the ACK packets were 40 bytes long. Each simulation was run for 3600 seconds of simulated time. The interface queues used a Droptail policy with a queue length of 50 packets. All the simulation results reported use DSDV [7] as the routing protocol. However, we have also verified our results with another routing protocol, DSR [6], and the results we got match the ones reported in this paper for DSDV. All sources and receivers have an OmniAntenna of height 1.5m and transmitter and receiver gains of 1. All other parameter settings for these simulations are given in Table 1.

Figure 6(a) shows the interarrival time distribution at node BN1 when the interarrival process corresponds to just the the data packet arrivals. These results correspond to the topology shown in Figure 5(b). The figure also shows the analytic results as given by Eqn. (18) and we note the close match with the simulation results. The first peak corresponds to two TCP packets coming next to each other while the next two peaks signify cases where we have one or two ACK packets between the TCP packet, respectively. Figure 6(b) shows the interarrival times when we consider both TCP and ACK packets to constitute the arrival process. The analytic model, which again shows a close match to the simulation results is expressed in Eqn. (16). Note that in this case the first peaks appear much earlier and correspond to back to back ACK packets. The smaller peaks correspond to the increase in interarrival times due to the ACK and TCP packets being for-



(a) Fixed base station

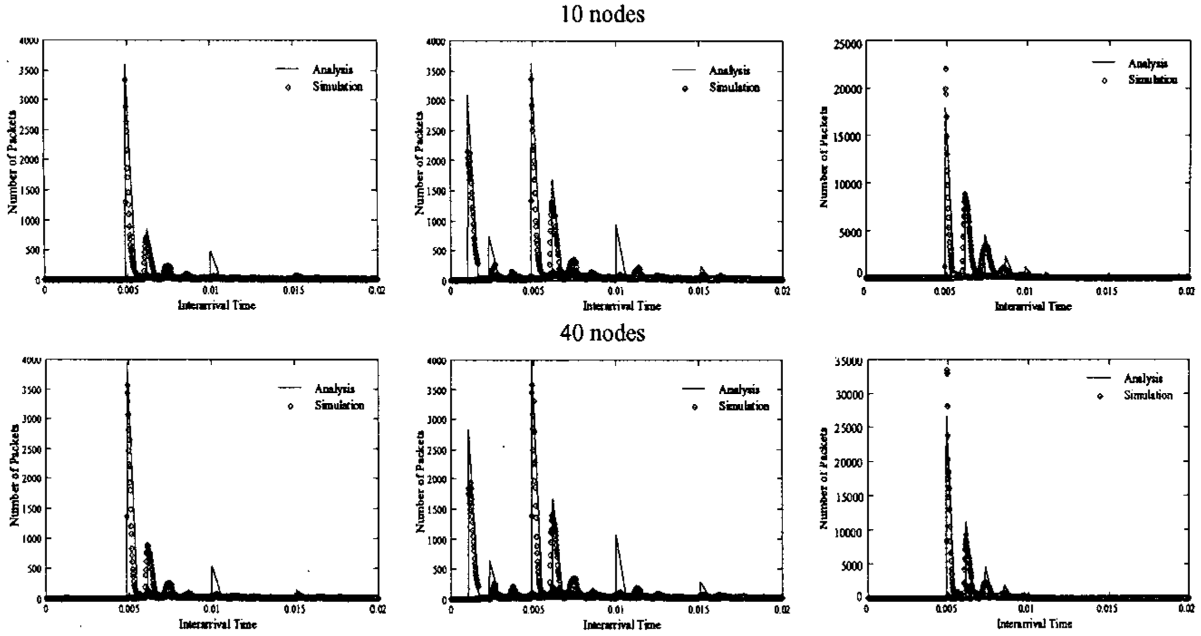


(b) Ad hoc network

Fig. 5. Simulation topologies: (a) BSS with infrastructure (b) ad hoc network.

Physical Layer		802.11 MAC	
Propagation	2 ray gnd	RTS size	44 bytes
Channel	Wireless	CTS size	38 bytes
Rx Threshold	3.652e-10	DIFS	50 μsec
Bandwidth	2 Mbps	SIFS	10 μsec
Frequency	914 MHz	Slot size	20 μsec
Loss Factor	1.0		

TABLE I
SIMULATION SETTINGS


10 nodes

40 nodes

(a) TCP packets, ad hoc network (b) TCP and ACK packets, ad hoc network (c) TCP packets, infrastructure network

Fig. 6. Interarrival times for ad hoc and infrastructure based wireless networks.

warded by the node.

In Figure 6(c) we show the interarrival time distribution at the base station BS1 of the topology shown in Figure 5(a). The analytic model corresponds to Eqn. (13) and the arrival process at BN1 corresponds to the TCP packets being received. We note that there are more peaks in this case with the first peak corresponding to two TCP packets being received back to back. The subsequent 4 discernible peaks correspond to 1, 2, 3 or 4 ACK packets arriving between two data packets.

The most significant observation from these figures is the pacing or clustering of the interarrival times around various modes in the distribution. The times T_1 and T_2 associated with the transmission times and the inter-mingling of the reception and forwarding events at the base station or intermediate node leads to the formation of these peaks.

V. CONCLUSIONS

In this paper we studied the implications of IEEE 802.11 MAC protocol on the traffic characteristics of a wireless network. We developed an analytic model to characterize the interarrival time distribution of packets arriving at the base station of a wireless BSS or the intermediate nodes acting as routers in ad hoc networks. Our model was validated using extensive *ns-2* simulations.

The main result of our analytic model and the simulation results in its support is to show the pacing of traffic induced by the 802.11 MAC protocol. The resulting interarrival times have a multimodal distribution with the position of the peaks determined by the transmission times associated with packets of different sizes. This has serious implications for designing interface buffers at wireless nodes and traditional traffic models can no longer be used to evaluate performance. Our model provides a basis for further performance studies and accurate analysis of 802.11 based networks.

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