Packet size variability affects collisions and energy efficiency in WLANs

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***Abstract*—Wireless local area networks (WLANs) support a wide range of applications, with various packet sizes. This diversity is set to increase in 802.11e WLANs which effectively allow very large packets controlled by a transmission opportunity (TxOP) parameter. This paper demonstrates a new phenomenon which occurs as a result of this diversity: When a network carries some large packets and many small packets, the collision probability after a large packet is much larger than predicted by previous models. This can be important because collision probability determines the number of packet transmissions, and hence the energy consumption. We propose a candidate model which captures this effect.**

I. INTRODUCTION

In recent years, WLANs have become very popular and are widely deployed, due to the rapid increase in demand for Internet access at any time and any place through WiFi-enabled mobile devices such as laptops and personal digital assistants (PDAs).

Internet applications over WLANs consist of not only conventional applications such as email, file transfer or web surfing but also delay-sensitive ones such as voice and video. For this reason, there exists a variety of packet sizes in WLANs. This variability increases further when service differentiation is introduced in WLANs using the enhanced distributed channel access (EDCA) mechanism defined in the IEEE 802.11 standard [1]. This is because EDCA allows a source to send a burst of packets without contending again for the channel once it has gained channel access, with the length of the burst controlled by a parameter called TxOP.

The contribution of this paper is to demonstrate that this variability in packet sizes can cause an increase in the collision probability of small packets which is much larger than predicted by previous models. The collision probability is of importance because the energy consumption of the battery powered mobile devices depends on the number of packet transmissions, which is directly related to the collision probability.

The majority of existing analytical models to evaluate the performance of MAC protocol in WLANs have been based on a fundamental assumption introduced in a seminal paper of Bianchi [2] which stated that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet of a source collides with constant and independent probability. The main contribution of this paper is to show that the existence of big packets in WLANs can make the above assumption inappropriate in estimating the collision probability of sources sending small packets. The inaccuracy stems from the fact that packets may experience different collision probabilities at different times, i.e., the collision probability is not homogeneous across time slots in the system. In particular, we will investigate the conditions where this effect is significant in a general carrier sense multiple access (CSMA) networks and show example scenarios of IEEE 802.11e EDCA WLANs in which we allow significant difference in the packet size among different types of traffic by varying TxOP. We also propose an analytical model that captures this effect and use it to optimize IEEE 802.11e EDCA parameters to minimize collision probability.

The remainder of the paper is organized as follows. Section II reviews standard models of CSMA-based protocols. Section III investigates the impact of big packets on sources sending small packets. Then, Section IV provides a detailed description of conditions to see the impact. A concrete example is provided in Section V, which defines a specific scenario covering the impact of big packets, proposes a model capturing the impact in that scenario, and evaluates the model. Finally, Section VI demonstrates the need for an accurate model of collision probability when optimizing protocol parameters for energy efficiency.

II. BACKGROUND: MEAN FIELD MODELS FOR CSMA

The effect described in this paper applies to all networks based on carrier sense multiple access (CSMA) which have significant persistence, such as the dominant IEEE 802.11 standards. CSMA is a media access control (MAC) mechanism in which a station wishing to transmit will first sense if another station is transmitting. If the channel is sensed "idle" then the station will transmit. If the channel is sensed as "busy" the station will wait until the channel becomes idle, and then attempt to transmit after a small random time which we call the persistence time; the higher the persistence, the smaller the random persistence time. If two stations attempt to transmit at approximately the same time, a *collision* will occur, and the sender will "back off" by waiting for a random time before attempting to retransmit. In many such systems, such as 802.11, the random times are measured in "slots". These slots are short when the system is idle, but a single slot can also be an extended period during which the channel is busy.

The probability of a transmission suffering a collision is the probability of another packet being transmitted at the same time. This depends on the detailed dynamics of the arrival and backoff mechanisms of the protocol. In networks of saturated station, a very successful approach was introduced by Bianchi [2]. This approach uses a mean-field approximation, in which all stations are assumed to behave independently, so that in each slot, each station chooses whether or not to transmit, independent of other stations and of past decisions. In particular, the collision probability is the same for the first time a packet is transmitted as for any subsequent retransmissions.

The collision probability of a packet from a tagged station is defined as the probability that, when that packet is transmitted in a given slot, at least one other station also transmits. In Bianchi's model, the collision probability is [2]

$$p = 1 - (1-\tau)^{n-1} \tag{1}$$

where τ is the "attempt probability", defined as the probability that a given station attempts to transmit in a given slot, and n is the number of stations.

Bianchi studied WLANs with saturated stations, which implies all transmission attempts occur in synchronized slots. Because the backoff is measured in terms of slots, and new arrivals are synchronized with old departures, the collision probability does not depend on the distribution of the slot times, and hence on the distribution of packet sizes.

This mean-field approximation (1) has been widely used; see for example [3], [4]. This includes its application to unsaturated (unsynchronised) systems. Even papers which model 802.11e EDCA [5], [6], [7] assume the existence of big packets has no effect on this approximation.

However, we will now argue that there are scenarios in which it is inappropriate, specifically cases in which there are large numbers of small packet and a small number of much larger packets.

III. MAIN FINDING: IMPACT OF BIG PACKETS

Consider a WLAN with a large number N_u of unsaturated sources sending small packets, each with rate λ, and one source sending big packets of size L_b and transmission duration T. In this scenario, it is possible for sufficient small packets to accumulate during the transmission of a large packet, that the collision probability of small packets is significantly under-estimated by the mean field approximation (1).

While a large packet is being sent, on average $N_u \lambda T$ new small packets will arrive to the system. These will all attempt to transmit within the short persistence time, which in 802.11 is uniformly distributed up to 32 slots. As a result, the longer the big packet is, the more small packets will attempt to transmit soon afterwards, and the higher the collision probability during that period.

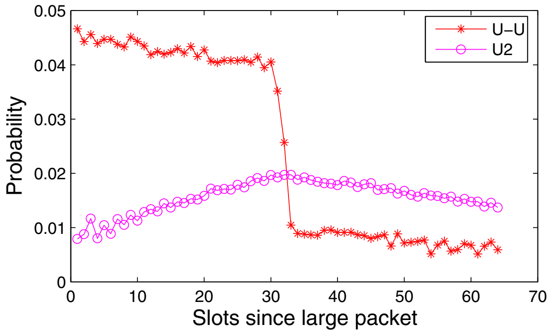

Fig. 1. Collision probability between small packets in each slot of 64 slots right after a large packet (U-U) and the number of retransmission attempts of small packets in each slot normalized by dividing by the total number of retransmissions of small packets in those 64 slots (U2). ($L_b = 6000$ bytes.)

This issue is illustrated in Figure 1. The curve U-U shows the probability that a small packet will collide with another small packet as a function of the number of slots since the most recent big packet. This is clearly elevated in the 32 slots corresponding to packets which arrived during the busy period. The scenario is for an 802.11e EDCA network, in which a station which wins a contention can send a burst of packets, whose length is called TxOP. This has an effect analogous to a single long packet. To balance the throughput, it is also possible to increase the initial persistence period (minimum contention window, $CW_{\min}$). In the example shown in Figure 1, one greedy source has an "effective" packet size of $L_b = 6000$ bytes by using a large TxOP, and its $CW_{\min}$ is increased in proportion to 192 slots. The small packets were from 10 sources sending 100 byte packets with a rate of 30 packets/s. These sources were quasi-periodic, in that the inter-packet time varied slightly around $1/30$ second to eliminate phase effects.

Due to the effect of large packets, there exist high-contention and low-contention periods, which makes the contention level of slots not homogeneous. However, the mean-field approximation (1) assumes that the contention level is the same for every slot, which does not take into account the effect of large packets.

In systems such as 802.11, in which backoff intervals are measured in slots rather than absolute time, this effect primarily affects the first transmission attempt. On retransmission attempts, the sources are synchronized to the slot times, and are no more likely to transmit after a large (busy) slot than an idle slot. As a result, the collision probability of the first attempt is significantly larger than that of retransmissions. This is in contrast to the effect identified in [8] which occurs with unsaturated sources with large buffers. In that case, the collision probability of the first attempt can be significantly lower than retransmission attempts, because the first attempt may occur when few stations have packets to transmit, whereas retransmissions only occur during times of congestion.

The impact of large packets on collision probability of a small packet on its first attempt and retransmission attempts is illustrated in Figure 2, which shows the probability that a small packet will collide with (a) another small packet, on its first attempt (U1-U), (b) another small packet on a retransmission attempt (U2-U), (c) another small packet, as determined from (1) with τ being the attempt probability of

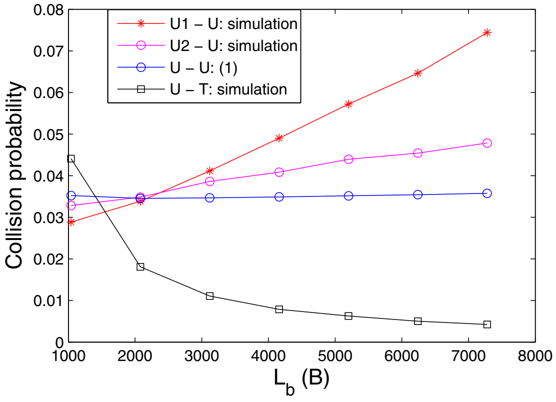

Fig. 2. The classification of the collision probability of a small packet. (Scenario: an 802.11e EDCA WLAN with one greedy source sending large packets of L_b bytes, 10 quasi-periodic sources sending small packets of 100 bytes with rate of 30 packets/s.)

a small packet measured from simulation (U-U (1)), or (d) a large packet (U-T). The same scenario is applied here as in Figure 1, with one greedy source sending large packets and 10 quasi-periodic sources sending small packets of 100 bytes with a rate of 30 packets/s. In Figure 2, the "effective" packet size L_b of the greedy source is varied by adjusting TxOP, and its $CW_{\min}$ is increased in proportion.

As can be seen from Figure 2, when the size of big packets increases, U1-U increases significantly while U2-U increases slowly. This shows that, as big packets' size increases, the collision probability of a small packet on its first attempt becomes higher than that on retransmission attempts and the gap between those becomes bigger.

The estimated based on (1) is even lower than U2-U, which can be understood as follows. Without considering the effect of large packets, the collision probability of a small packet estimated by the mean-field approximation (1) will be similar to the 192-32=160-slot low-contention period, the start of which is shown in Figure 1. The curve U2 in Figure 1 shows the number of retransmission attempts of small packets in each slot of 64 slots after a large packet, normalized by dividing by the total number of retransmissions of small packets in those 64 slots. Retransmissions are much more likely to occur in the high-contention period than at other times, as in [8]. This means that the presence of large packets also increases the collision probability of retransmissions beyond that predicted by (1), although less than for initial transmissions.

The significant decrease in U-T in Figure 2 occurs because of the increase in $CW_{\min}$ of the greedy source. This demonstrates that increasing TxOP and $CW_{\min}$ can make collisions with delay-insensitive packets negligible. The rest of this paper will focus on collisions between the unsynchronized delay-sensitive packets.

IV. WHEN DOES THIS EFFECT OCCUR?

Given the marked discrepancy between these simulation results and Bianchi's successful model, it is fair to ask why this effect has not been described before. Let us now consider the conditions under which this effect occurs.

A. *Variable packet size*

This effect will only occur when the expected number of arrivals, $N_u\lambda T$, is large (at least comparable to 1). If all packets are of equal duration T, then this corresponds to a heavily overloaded system. The fraction of time spent sending first attempts of unsynchronized packets, not counting retransmissions, is $N_u\lambda T_u$ where T_u is the size of such packets. In order for this to consume less than 100% of the resources and still to have $N_u\lambda T$ large, it is necessary that T be much larger than T_u. When this ratio is 1500/64, the maximum possible ratio under standard 802.11, the phenomenon only has a small effect on the parameters usually studied, namely packet delay and throughput. However, the introduction of 802.11e will make the effect more important.

B. *Unsaturated sources*

The arrival rate of small-packet sources should be small enough so that the queue of small-packet sources rarely builds up. The first attempt of a packet which arrives to a non-empty queue will be synchronized with the slot structure induced by 802.11. Such packets do not contribute to the inspection paradox of large numbers of packets arriving while the big packets are being transmitted.

C. *Moderate spacing between big packets*

According to the inspection paradox [9], when a small packet first comes and senses channel busy, it is more likely to see a long busy period than short busy period or idle slot. However, if the spacing between big packets is too large compared with the time to clear the backlog of unsaturated sources, then many small packets will still observe the "background noise" of independent small transmissions, which is captured well by the mean-field model. Conversely, if the spacing between big packets is small compared to the time to clear the backlog, then congestion periods will overlap each other, and the collision probability is again fairly constant in time.

The issues of this and the previous subsection are illustrated in Figure 3. Let p_{u1} and p_{u2} be the collision probability of a small packet on its first attempt and retransmission attempts respectively. The figure shows the ratio of p_{u1} and p_{u2} in two scenarios of an 802.11e EDCA WLAN with N_u quasi-periodic sources sending 100 byte packets with the rate of λ and one greedy source sending big packets with size L_b. The ratio of p_{u1} and p_{u2} is shown as a function of the time interval between big packets which is varied by changing $CW_{\min}$ of the greedy source denoted by W_t.

When W_t is small, the impact of big packets is small. This is partly because the contention does not have time to abate between transmissions, and partly because the probability that the queue of small-packet sources builds up is higher. When W_t is very high, the impact of big packet is again small because the probability that a small packet comes and senses channel busy due to the transmission of big packets is small.

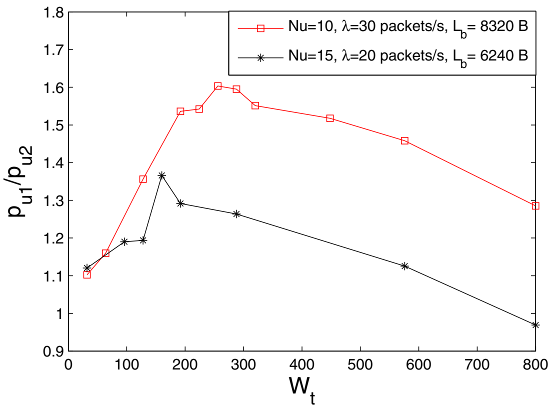

Fig. 3. The ratio of the collision probability of a small packet on its first attempt and retransmission attempts. (Scenario: an 802.11e EDCA WLAN with one greedy source sending large packets of L_b bytes, N_u quasi-periodic sources sending small packets of 100 bytes with rate of λ.)

The impact of big packets is most pronounced for W_t near 200 or 300, when W_t is high enough for the backlog of unsaturated sources to clear between big packets, but small enough that a large proportion of the unsynchronized packets arrive during the transmission of big packets.

D. Summary

The effect described in this paper is largest when the following conditions occur:

- $N_u \lambda T$ is large (at least comparable to 1), which implies that
- the ratio of big packets' size and small packets' size is reasonably large;
- The time interval between big packets is of the same order as the time to clear the backlog of unsaturated sources caused by a busy period;
- Stations sending small packets are very unsaturated, so that minimal queue builds up even during the big packet transmissions;
- The number of unsaturated stations is large.

Moreover, the impact is clearer when the arrival process of small packets at a source is quasi-periodic than when it is Poisson, because this maximizes the number of unsynchronized arrivals.

V. CASE STUDY: 802.11E

In this section, we look at a particular scenario that covers the impact of big packets, propose a model capturing that impact and evaluate the model.

Consider an 802.11e EDCA WLAN with a number of low-rate realtime sources N_u with inter-arrival rate λ and several greedy data sources N_t sending data to an access point. Greedy data sources send big packets by using large TxOP while realtime sources send small packets. Then, to balance the traffic load in the network, when a greedy data source sends bigger packets, it must increase the time interval between its attempts by using higher CW_{min}. The traffic load in the network is kept at a level which rarely makes the queue of realtime traffic build up.

According to the analysis in Section III, the existence of big packets from greedy data sources can make the collision probability of a small packet from realtime sources on its first attempt much different from retransmission attempts.

A. Analytical model

Next, we develop a model for the above scenario. In this model, greedy data traffic is modeled as saturated sources while low-rate real-time traffic is modeled as low-rate non-saturated sources. Because there exist saturated stations, the packet from non-saturated stations comes and senses channel busy most of the time. Then, it can be assumed that there is the synchronization in channel access between saturated and non-saturated stations. For the detailed assumptions, description and explanation of the model, refer to [10]. The summary of the model is presented as following.

Let W_t, W_u be the minimum contention window of saturated stations and non-saturated stations, respectively; η be TxOP of saturated stations, which is the number of packets a saturated station can send in a burst [1]; l_{sat} and l_{nonsat} be the payload length of a packet from saturated stations and non-saturated stations, respectively.

Let τ_t and τ_u be the probability that saturated stations and non-saturated stations, respectively, attempt to transmit in a given slot.

Let p_t be the collision probability of a packet from saturated stations; p_u be the collision probability of a packet from non-saturated stations; p_{u1} and p_{u2} be the collision probability of a packet from non-saturated stations on its first attempt and retransmission attempts, respectively.

The inputs to our model are N_u, N_t, W_t, W_u, η, λ, l_{sat} and l_{nonsat}.

The core of the model are fixed point equations which are used to find the collision probability and attempt probability of stations. The summary of fixed point equations are given as follows:

$$\tau_u = \frac{\lambda A}{\frac{S_t}{\eta}\left(\frac{W_t}{2(1-2p_t)} + \frac{1}{2(1-p_t)}\right)} \tag{2a}$$

$$\tau_t = \frac{2}{\frac{W_t(1-p_t)}{1-2p_t} + 1} \tag{2b}$$

$$p_t = 1-(1-\tau_t)^{N_t-1}(1-\tau_u)^{N_u} \tag{2c}$$

$$p_{u1} = B \tag{2d}$$

$$p_{u2} = 1-(1-\tau_t)^{N_t}(1-\tau_u)^{N_u-1} \tag{2e}$$

where the values of A and B depend on whether we treat p_{u1} and p_{u2} the same (see Section V-A1) or not (see Section V-A2); S_t is the throughput of each saturated station in packets/s, which analogously to [2] is given by:

$$S_t = \frac{a_s\ \eta}{E[Y]} \tag{3a}$$

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[1] This differs slightly from [1] in which TxOP is a duration.

where

$$
\begin{aligned}
E[Y] &= a_i T_i + a_u T_u + a_{tc} T_{tc} + a_{ts} T_{ts} && (3b)\\
a_s &= \tau_t (1-\tau_t)^{N_t-1} (1-\tau_u)^{N_u} && (3c)\\
a_i &= (1-\tau_t)^{N_t} (1-\tau_u)^{N_u} && (3d)\\
a_u &= \left(1-(1-\tau_u)^{N_u}\right)(1-\tau_t)^{N_t} && (3e)\\
a_{ts} &= N_t \tau_t (1-\tau_t)^{N_t-1} (1-\tau_u)^{N_u} && (3f)\\
a_{tc} &= 1-(a_i+a_u+a_{ts}) && (3g)
\end{aligned}
$$

where Y is a R.V. representing the duration of a slot and E[] denotes the mean of a R.V.; a_s is the probability that the tagged saturated station successfully transmits in a given slot; T_i, T_u, T_{tc}, and T_{ts} are, respectively, the duration of idle slots, slots during which transmissions of only non-saturated stations occur, slots during which collision involving at least one saturated station occurs, and slots during which a successful transmission of saturated stations occurs; a_i, a_u, a_{tc}, and a_{ts} are the probability that a slot has the duration of T_i, T_u, T_{tc}, and T_{ts}, respectively.

Then, p_t, p_{u1}, p_{u2}, τ_t, τ_u, and S_t can be determined by solving equations (2a)–(2e) using numerical techniques.

1) Traditional approach: Previous works have assumed that the collision probability of a packet from non-saturated stations is the same for every attempt. Using this assumption in (2), we have

$$p_u = p_{u1} = p_{u2} = B \tag{4a}$$

where p_{u2} is determined by (2e), and A is given by

$$A = \frac{1}{1-p_u} \tag{4b}$$

2) New approach: Unlike the traditional approach, we determine the collision probability of a packet from non-saturated stations on its first attempt and retransmission attempts separately. Then, A and B are given by:

$$A = 1 + \frac{p_{u1}}{1-p_{u2}} \tag{5a}$$

$$B = p_b \left(1-(1-\tau_t)^{N_t}(1-\frac{1}{W_u})^{N_{uc}}(1-\tau_{u2})^{N_u-N_{uc}-1}\right) \tag{5b}$$

where p_b is the probability that an arriving packet at non-saturated station finds the channel busy; N_{uc} is the average number of small packets on their first attempt from other non-saturated stations that will contend with the tagged small packet on its first attempt; τ_{u2} is the probability that a non-saturated station attempts to retransmit in a given slot. Those are given as follows:

$$
\begin{aligned}
p_b &= 1-\frac{(1-p_{u2})T_i}{E[Y_u]} && (5c)\\
N_{uc} &= (N_u-1)\lambda(2E[T_{res}]+p_b(W_u-1)E[Y_u]) && (5d)\\
\tau_{u2} &= \left(\frac{p_{u1}}{1+p_{u1}-p_{u2}}\right)\tau_u && (5e)
\end{aligned}
$$

where T_{res} is the residual service time of packets from other stations observed by an arriving packet at the tagged non-saturated station; Y_u is a R.V. representing the duration of a backoff slot experienced by a packet from a non-saturated station, the mean of which is calculated similar to (3b) where N_u is replaced with N_u-1 in the expression of a_i, a_u, a_{ts}.

TABLE I
MAC AND PHYS PARAMETERS FOR 802.11B SYSTEM

Parameter	Symbol	Value
Data bit rate	r_{data}	11 $Mbps$
Control bit rate	r_{ctrl}	1 $Mbps$
PHYS header	T_{phys}	192 μs
MAC header	l_{mac}	288 $bits$
UDP/IP header	l_{udpip}	160 $bits$
ACK packet	l_{ACK}	112 $bits$
Slot time	T_i	20 μs
SIFS	T_{sifs}	10 μs

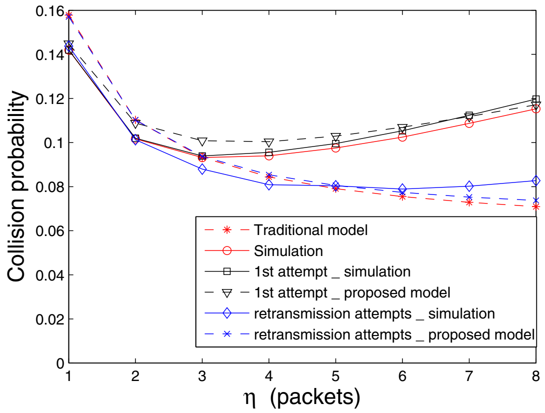

Fig. 4. Collision probability of a small packet from non-saturated sources. ($N_u = 10$, $N_t = 2$, $\lambda = 30$ packets/s, $l_{sat} = 1040$ bytes, $l_{nonsat} = 100$ bytes, $W_u = 32$, $W_t = \eta W_u$.)

B. Evaluation

In this section, we demonstrate that, in appropriate circumstances, the proposed model (2), (3), (5) captures important qualitative properties of the collision probabilities which are not captured by the traditional model (2), (3), (4), based on (1). This is done by comparing these models with simulations performed using the *ns-2* simulator (version 2.33) [11], combined with an EDCA [12].

Consider a network which consists of N_u non-saturated sources sending small packets and N_t saturated sources sending bursts of η packets. These stations will send packets to an access point in ideal channel conditions. As for Figures 1 and 2, saturated sources increase the spacing between their packets (W_t) in proportion to their TxOP (η) to balance the throughput. The packet inter-arrival times of unsaturated sources are uniformly distributed in the range $1/\lambda \pm 10\%$, to model voice traffic with enough jitter to avoid phase effects. The rate was sufficiently low that queues rarely built up.

Both saturated stations and non-saturated stations use the user datagram protocol (UDP). The MAC and physical layer parameters were the default values in IEEE 802.11b, as shown in Table 1.

The collision probability of a small packet from non-saturated stations is shown in Figure 4 as a function of TxOP of saturated stations (η). This figure shows the collision probability determined from the traditional model and simulation, and the collision probability on the first attempt and retransmission attempts determined from the proposed model and simulation. The traditional model incorrectly predicts the collision probability to decrease monotonically, while the proposed model can capture the right trend of the collision probability on both the first and retransmission attempts.

The behavior can be understood by comparing with Fig. 2. When η increases, the first attempt collision probability initially decreases because the increase in W_t decreases U-T. When U-U begins to dominate, the collision probability increases, with U1-U increasing more markedly. The proposed model does not capture the eventual increase in the retransmission collision probability, which occurs when the increase in U2-U exceeds the decrease in U-T.

VI. APPLICATION TO ENERGY EFFICIENCY

The energy consumption of a wireless transmitter is proportional to the number of packets transmitted. Since collisions are wasted transmissions, an energy-saving design will seek system parameters which reduce collisions, possibly at the expense of higher delay.

A natural tradeoff in an 802.11e network is to encourage delay-insensitive stations to transmit seldom (large $CW_{\min}$), and to achieve fair throughput by sending very large bursts when they do send (large TxOP). Delay-sensitive stations will still send frequent small packets, leading to the burstiness effect studied in this paper.

If the tradeoff between TxOP and $CW_{\min}$ is chosen using the standard model (1), then Fig. 2 suggests that an excessively large TxOP will be selected. In fact, Fig. 4 suggests an infinite TxOP may minimize the predicted collision probability.

In contrast, the proposed model allows the optimal TxOP to be determined quite accurately. The collision probability of a small packet from non-saturated sources can be determined by taking the weighted sum of p_{u1} and p_{u2},

$$p_u = \left(\frac{1}{A}\right) p_{u1} + \left(\frac{A-1}{A}\right) p_{u2}, \tag{6}$$

where A is the mean number of attempts per small packet, which is given by (5a).

Fig. 5 shows the optimal TxOP determined from this model for a typical situation, which is quite close to that from simulation.

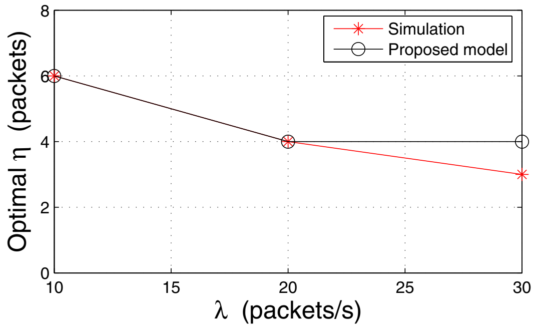

Fig. 5. Value of TxOP of greedy sources (η) which minimizes collision probability of small packets, as determined by (a) the proposed model which considers bursty collisions, and (b) simulation. The optimal η predicted from the traditional model is infinite, and off the scale of the graph. ($N_u = 10$, $N_t = 2$, $l_{sat} = 1040$ bytes, $l_{nonsat} = 100$ bytes.)

VII. CONCLUSION

This paper has considered wireless networks with heterogeneous packet sizes, in which some sources are unsaturated. It has shown that the accumulation of small packets during the transmission of a large packet can cause the collision probability of small packets to be much larger than predicted by previous models. This effect is particularly marked on the packet's first transmission attempt. When this occurs, it invalidates the common assumption that collision probabilities are independent and identically distributed. We have also proposed a model capturing this effect which can be used to optimize energy consumption of a station by minimizing its collision probability. We have shown that this effect has important implications, which should not be ignored in future models of CSMA-based networks with high heterogeneity of packet sizes.

ACKNOWLEDGMENT

This work was supported by ARC grant FT0991594.

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