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Energy Efficiency of CSMA Protocols for Wireless Packet Switched Networks

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Abstract— **The finite battery power in wireless portable computing devices is a motivating factor for developing energy efficient wireless network technologies. This paper investigates energy efficiency, relating it to throughput and packet delay for both non-persistent and p-persistent CSMA, two protocols popularly applied in current wireless networks; for example, the widely adopted IEEE 802.11 WLAN standards are based on p-persistent CSMA. For high message generation by the members of a finite population, we find that non-persistent CSMA has a markedly higher energy efficiency than p-persistent CSMA for all network configurations, though the latter attains a moderately lower packet delay. We also show that when non-persistent CSMA is optimized for energy efficiency, throughput and delay are impacted negatively, whereas p-persistent CSMA can effectively optimize all three with the same network settings. Our results help illuminate the suitability of each CSMA scheme for various wireless environments and applications.**

I. Introduction

While portable computing devices and wireless networks bring users the advantages of mobile computing, the finite battery power in these devices imposes stringent constraints to the duration of their operations. This is a serious problem because RF activities are significantly more power-consuming than the device's other activities [9]. Wireless sensor networks and RFID systems also face similar challenges in order to maximize the lifespan and efficiencies of deployed sensors and RFID tags [1,8]. Since current technologies cannot provide affordable means to significantly increase battery capacity, it is important for researchers and designers of wireless networks to emphasize energy efficiency alongside the classic issues of throughput and delay [3,5,9,11]. In this paper, we investigate energy efficiency in carrier sense multiple access (CSMA) protocols that can be applied to wireless packet switched networks. We focus on two variants of CSMA: non-persistent and p-persistent. Kleinrock and Togabi introduced and extensively investigated in [16] the throughput and delay of both these algorithms under an infinite-population Poisson offered traffic model. Calì et al. showed in [6] that the MAC layer of the widely deployed IEEE 802.11 standard for wireless local area networks (WLANs) [12] can be effectively modeled as p-persistent CSMA. Accordingly, studies on the standard under different conditions [4–7] have provided valuable insights regarding the performance of p-persistent CSMA. Results concerning power consumption of p-persistent CSMA-based WLANs by Bononi et al. [4] and by Bruno et al. [5] for the common assumptions used in our analysis will be cited as needed.

Contrastingly, many random access schemes proposed for sensor and RFID networks are similar to that of non-persistent CSMA, which only senses the carrier when it is about to transmit, in order to limit time spent on monitoring the medium and conserve energy [1,8,11,19]. But because those stations do not listen to the channel continuously, it is not possible for them to receive packets during their inactive periods. For most WLAN applications this would be unacceptable, but in many wireless sensor networks and in RFID systems, often a sensor or tag has as its sole duty to transmit data to a central data collection agent. (If duplex communication is required, then there must be some access point or central agent to buffer the packets and to deliver them via a predefined delivery scheme, for example, like that used in IEEE 802.11's Power Save mode [12]. And for wireless sensor networks or RFID systems, the devices can have a low-power *wake-on radio* that detects presence of a RF signal which the central agent sends out if it wishes to collect data.) p-persistent CSMA is less well suited to those environments because its channel monitoring continuously drains the batteries. To quantify the extent to which non-persistent CSMA actually provides more power savings, and the extent to which throughput and delay may have to be sacrificed if a system is tuned to operate in a highly energy efficient manner, we derive analytic expressions for the energy efficiencies, throughputs and delays of both schemes and use them to obtain quantitative comparisons.

II. Analysis Model: Assumptions and Notations

The current usage scenarios on wireless networks no longer match the classical infinite population source model that assumes networks are lightly loaded with bursty traffic. This is especially the case with WLANs which usually are characterized by a finite number of stations generating network traffic that are more continuous, as in applications such as file transfers and video conferencing. This is also the case with RFID systems that issue an RF signal to prompt all the tags to attempt communication at the same time. To realistically model current wireless networks, we consider a finite number, M, of stations, say $2 \leq M \leq 100$, and assume each station operates in asymptotic mode, i.e., that each station always is saturated with data packets to be transmitted. Also packet durations are i.i.d. with a geometric distribution of parameter

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q measured in units of the time slot duration t_{slot}. To keep our analysis tractable, we assume each station draws a new packet for each successive retransmission; our simulations (Section IV) have shown that this assumption has negligible effect on our results, as usually is for random access schemes [4,5,6,15].

Imposing asymptotic traffic on the system forces it to operate in a critical region where it is on the verge of drifting into instability, i.e., throughput approaching zero and delay approaching infinity; this allows us to examine a protocol's fundamental performance limit. To that end, we employ the classical collision model, which assumes packets are corrupted whenever one or more are transmitted simultaneously. We do not take into account any constructive effects from the physical layer, e.g., a capture effect which allows the stronger of two simultaneously transmitted signals to be decoded correctly. We also do not consider either effects from hidden terminals [17] or propagation delays [16]. Furthermore, we assume the stations will become aware of their transmission outcomes immediately, without expending any extra energy; in this regard acknowledgements introduce only fixed overheads and hence can be neglected from the model without affecting the analysis and comparisons [5,16].

We assume a slotted-time system in which transmissions may begin only at the start of a slot. The random backoff of non-persistent CSMA will be modeled as independent sampling from a geometric distribution with parameter p; in other words for a given slot each station will attempt transmission with probability p or defer with probability $1-p$. Because stations operate in an asymptotic mode, to ensure fairness in the non-persistent CSMA protocol we slightly modify it so that a station that has just completed a successful transmission will also perform a random backoff before its next transmission attempt. Note that then, aside from the manner in which carrier sensing (CS) is performed, both CSMA protocols are now identical [18].

In our analysis each station consumes ρ_{tx} and ρ_{rx} amounts of power (in units of J/slot) when transmitting and receiving packets, respectively. For a non-persistent CSMA station, we consider that during the backoff when the radio is off, the station's other components, such as its processor or low-power wake-on radio, still consume a total of ρ_{low} J/slot. Since in practice [2,7,9] $\rho_{tx} > \rho_{rx} >> \rho_{low}$, we take account of ρ_{low} only when the radio is off. Furthermore, we assume each station takes an infinitesimally short time to determine the channel status. However, turning the radio on usually involves a burst of energy; we take this into account by considering that this burst is the total energy consumed when the radio receives for one slot, $\rho_{rx} \cdot t_{slot}$.

III. Performance Analysis

A. Throughput Analysis

We define throughput or channel efficiency, η, to be the fraction of time the channel is used for successful transmission of data packets. For the protocols in question, the channel activity can be modeled as a renewal process with a regeneration point at the end of each transmission attempt, as shown in Fig. 1.

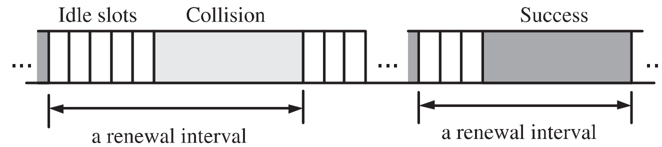

Fig. 1. The channel's activities as a renewal process with regenerative points after each transmission attempt.

In particular, each renewal interval is made up of idle slots followed by a successful or colliding transmission attempt. By renewal theoretic arguments η is the ratio of the average time used on the channel to successfully transmit a packet in a renewal interval to the average duration of a renewal interval. For p-persistent CSMA this has been shown by Bruno et al. [5] to be

$$\eta_p = \frac{\bar{l} \cdot t_{slot} \cdot P_{Succ|N_{tx} \geq 1}}{E[T_{idle}] + E[T_{tx\_Attempt} | N_{tx} \geq 1]} \,, \tag{1}$$

where $\bar{l}$ is the average packet length ($\bar{l} = 1/(1-q)$), N_{tx} is the number of stations that attempt to transmit after the idle period in a renewal interval, $E[T_{idle}]$ is the average duration of the idle period, and $E[T_{tx\_Attempt} | N_{tx} \geq 1]$ is the average duration of a transmission attempt given that there is at least one station transmitting.

By exploiting each station's i.i.d transmission probability p, Bruno et al. [5] obtained the analytical expression for the throughput of p-persistent CSMA, namely

$$\eta_p = \frac{\bar{l} \cdot t_{slot} M p (1-p)^{M-1}}{t_{slot}(1-p)^M + \bar{l} \cdot t_{slot} M p (1-p)^{M-1} + E[T_{coll}|Coll]\{1-(1-p)^M - Mp(1-p)^{M-1}\}} . \tag{2}$$

$E[T_{coll}|Coll]$, also derived in [5], is the average length of a collision involving two or more of the M stations, conditioned on the event that a collision has indeed occurred. From how we defined the protocols, the random processes defining the channel activities for both protocols are identical; therefore, (2) is also the throughput expression for non-persistent CSMA in the asymptotic mode, η_n.

B. Energy Efficiency Analysis

The energy efficiency can also be found by exploiting the protocols' regenerative behaviors and each station's i.i.d transmission probability. Similar to [4] and [5], we do this by focusing on a tagged station in the system and examining its energy consumption in a renewal period; this follows because both protocols are fair in that each station has equal average energy consumption. We define energy efficiency η_e to be the average amount of energy consumed by the tagged station to successfully transmit a packet in a renewal interval, divided by the average total energy consumed in a renewal interval:

$$\eta_e = \frac{\rho_{tx} \cdot \bar{l}}{E[Energy_{renewal\_interval}]} . \tag{3}$$

The analytical expression for energy efficiency of p-persistent CSMA, which we denote as $\eta_{e,p}$, has been derived in [5]; in the remainder of this section we focus on that of non-persistent CSMA, $\eta_{e,n}$.

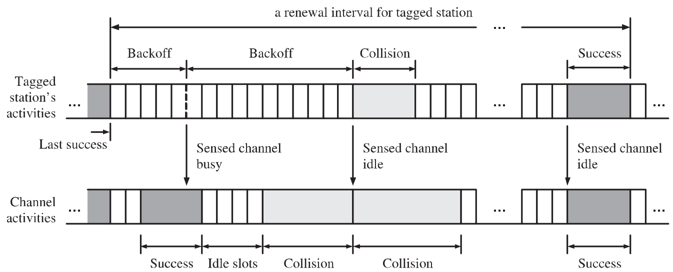

Fig. 2. The tagged station's activities as a renewal process and the underlying channel activities.

Consider the tagged station's RF activities as a renewal process and take its regenerative points to be the end of each successful transmission as shown in Fig. 2. Then for each renewal interval, before a success, the tagged station performs CS when the backoff is over to find the medium either busy or clear— subsequently attempting transmission that results in collision. Denote these two events (medium busy and collision) collectively as *interruptions* (for interruptions before success), and let the r.v. N_{inter} denote the number of interruptions in each renewal interval. Then

$$\begin{aligned} &E[Energy_{renewal\_interval}] \\ &= E\left[\sum_{n=1}^{N_{inter}+1} Energy_{backoff}^{(n)} + \sum_{n=1}^{N_{inter}} Energy_{inter}^{(n)} \right. \\ &\quad \left. + Energy_{succ}\right], \end{aligned} \tag{4}$$

where $Energy_{backoff}^{(n)}$, $Energy_{inter}^{(n)}$ and $Energy_{succ}$ are the energy spent respectively during the n^{th} backoff period, the n^{th} interruption and a successful transmission. As $Energy_{backoff}^{(n)}$ and $Energy_{inter}^{(n)}$ are each i.i.d., (4) can be rewritten as

$$\begin{aligned} &E[Energy_{renewal\_interval}] \\ &= E\big[N_{inter}+1\big]E\big[Energy_{backoff}^{(1)}\big] \\ &\quad + E\big[N_{inter}\big]E\big[Energy_{inter}^{(1)}\big] + E\big[Energy_{succ}\big]. \end{aligned} \tag{5}$$

Since every station attempts to utilize a slot with probability p, the average backoff period is $(1-p)/p$ slots, and

$$E[Energy_{backoff}^{(1)}] = \rho_{low}\frac{1-p}{p}. \tag{6}$$

To continue with the derivation, we investigate the probability that the tagged station will find the medium idle after backoff. As shown in Fig. 2, this can happen only if the previous slot is idle or if it is the end of a (successful or colliding) transmission. We call such a slot *transmittable*, because only when a station finds these slots will it begin transmission, and we denote its probability of occurrence by P_{tx_able}.

From the tagged station's point of view, the activities on the channel during its backoff also constitutes a renewal process, albeit one that is defined by the actions of the other $M-1$ stations. The regenerative points of said process are the starting times of each idle period, so the tagged station finding a transmittable slot after backoff is equivalent to finishing backoff at the start of such a renewal interval. Therefore, from renewal theory, P_{tx_able} is the probability that at a randomly chosen slot the residual lifetime equals the selected interval's lifetime.

Before we apply results from renewal theory, we note that they only apply under the assumption that the renewal process has reached the steady state conditions that provide its limiting distribution [14]. If the backoff periods are too short, this analysis method will no longer be accurate. However, in order for random access protocols to operate stably with non-zero throughput, it is necessary for each station in the system to adopt a small transmission probability (p) so that on average the backoff periods are not short [10]. We will show later that this is the case both for optimum channel efficiency and for optimum energy efficiency, both being achieved by $p << 0.1$. In fact, because these efficiencies degrade dramatically as p increases above 0.1 by virtue of the rapid increasing of collisions, the inexactitude of our renewal analysis method for short backoffs is insignificant. Indeed, our simulations (Section IV) verify that our analytical expression for energy efficiency is quite accurate.

The length of each renewal interval is determined at each renewal instant by the number of stations out of the $M-1$ that attempt to transmit and the length of their successful or colliding transmissions. The distribution for an interval's length is then given by:

$$\begin{aligned} f_1 &= P(N_{tx}=0|N_s=M-1) \\ &\quad + P(N_{tx}=1\cap L=1|N_s=M-1) \\ &\quad + P(N_{tx}>1\cap T_{coll}=1|N_s=M-1), \\ f_2 &= P(N_{tx}=1\cap L=2|N_s=M-1) \\ &\quad + P(N_{tx}>1\cap T_{coll}=2|N_s=M-1), \ldots, \end{aligned}$$

where f_i is the probability that an interval will be i slots long, N_s is the number of stations participating and L is the length of the successful transmission. For our model,

$$\begin{aligned} &P(N_{tx}=1\cap L=l|N_s=M-1) \\ &= \big[(M-1)p(1-p)^{M-2}\big]\cdot q^{l-1}(1-q), \end{aligned} \tag{7}$$

and

$$\begin{aligned} &P(N_{tx}>1\cap T_{coll}=t|N_s=M-1) \\ &= \big[1-(1-p)^{M-1}-(M-1)p(1-p)^{M-2}\big]\cdot \\ &\quad P(T_{coll}=t|Coll, N_s=M-1). \end{aligned} \tag{8}$$

Let B and γ be the selected and residual lifetime, respectively. Then from renewal theory [14],

$$P_{tx\_able} = \sum_{i=1}^{\infty} P(B=i,\gamma=i) = \sum_{i=1}^{\infty} f_i/m = 1/m, \tag{9}$$

where m is the mean renewal interval length given by

$$m = (1-p)^{(M-1)} + [(M-1)p(1-p)^{(M-2)}] \cdot \bar{l} + [1-(1-p)^{(M-1)} - (M-1)p(1-p)^{(M-2)}] \cdot E[T_{Coll}|Coll, N_s = M-1]. \quad (10)$$

The formula for $E[T_{Coll}|Coll, N_s = M-1]$, derived in [5], is

$$E[T_{Coll}|Coll, N_s = M-1] = \frac{t_{slot}}{1-\left[(1-p)^{M-1} + (M-1)p(1-p)^{M-2}\right]} \cdot \left[\sum_{h=1}^{\infty} \left\{h\left[(1-pq^h)^{M-1} - (1-pq^{h-1})^{M-1}\right]\right\} - \frac{(M-1)p(1-p)^{M-2}}{1-q}\right]. \quad (11)$$

Therefore,

$$\begin{aligned} E\left[Energy^{(1)}_{inter}\right] &= \rho_{rx}(1-P_{tx\_able}) + \rho_{tx} \cdot \bar{l} \cdot P_{tx\_able} \cdot P(Coll|N_s = M-1) \\ &= \rho_{rx}\left(1-\frac{1}{m}\right) + \rho_{tx} \cdot \frac{\bar{l}}{m}\left[1-(1-p)^{M-1}\right]. \end{aligned} \quad (12)$$

To determine $E[N_{inter}]$, we note that N_{inter} is geometrically distributed with success probability $1-P_{inter}$, where

$$\begin{aligned} P_{inter} &= (1-P_{tx\_able}) + P_{tx\_able} \cdot P(Coll|N_s = M-1) \\ &= \left(1-\frac{1}{m}\right) + \frac{1}{m}\left[1-(1-p)^{M-1}\right]. \end{aligned} \quad (13)$$

Consequently,

$$E[N_{inter}] = \frac{P_{inter}}{1-P_{inter}} = \frac{m}{(1-p)^{M-1}} - 1. \quad (14)$$

With this, we can find

$$\begin{aligned} &E[Energy_{renewal\_interval}] \\ &= \rho_{low}\frac{m}{p(1-p)^{M-2}} + \left[\frac{m}{(1-p)^{M-1}} - 1\right]\left[\rho_{rx}\left(1-\frac{1}{m}\right) + \rho_{tx} \cdot \frac{\bar{l}}{m}\left[1-(1-p)^{M-1}\right]\right] + \rho_{tx} \cdot \bar{l}. \end{aligned} \quad (15)$$

Substituting (15) into (3) completes the expression for $\eta_{e,n}$.

C. Delay Analysis

We define expected packet delay, $E[D]$, to be the average time needed to successfully transmit a packet measured from the time it was generated (which is immediately after the station's most recent successful transmission). By the regenerative nature of a station's activities and the fairness of the protocols, $E[D]$ can be found to be the average length of a tagged station's renewal period when the renewal instances are taken to be at the end of each successful transmission.

Next observe that, based on our analysis above, the expected delay for non-persistent CSMA expressed in slots, $E[D_n]$, is equation (15) without the energy considerations. Thus,

$$E[D_n] = \frac{m}{p(1-p)^{M-2}} + \left[\frac{m}{(1-p)^{M-1}} - 1\right]\left[\frac{\bar{l}}{m}\left[1-(1-p)^{M-1}\right]\right] + \bar{l}. \quad (16)$$

An identical renewal theoretic argument by Bononi et al. [4] determined the energy consumption in a renewal period for IEEE 802.11 WLANs modeled as p-persistent CSMA. It is straightforward to derive from that the expected delay for p-persistent CSMA by similarly removing its energy considerations and the IEEE 802.11 packet overheads. This delay, expressed in slots, is

$$E[D_p] = E[N_C+1]E[T_{not\_used\_slot}] + E[N_C]E[T_{tagged\_coll}] + E[T_{success}], \quad (17)$$

where:

- $E[N_C]$ is the average number of collisions the tagged station experiences before a success given by equation (14) of [4];
- $E[T_{not\_used\_slot}]$ is the average length of a not used slot given by

$$E[T_{not\_used\_slot}] = \frac{1-p}{p} \cdot \left[(1-p)^{M-1} + \bar{l}(M-1)p(1-p)^{M-2} + E[T_{coll}|Coll, N_s = M-1] \cdot \left[1-(1-p)^{M-1} - (M-1)p(1-p)^{M-2}\right]\right], \quad (18)$$

  with $E[T_{coll}|Coll, N_s = M-1]$ provided in (11);
- $E[T_{tagged\_coll}]$ is the average length of a collision that involves the tagged station. This can be straightforwardly derived based on an expression derived in [5] for the energy consumed during such a collision . Removing said expression's energy considerations, we obtain

$$E[T_{coll}|Coll, N_s = M-1] = \frac{1}{1-(1-p)^{M-1}} \cdot \sum_{x=1}^{\infty} q^{x-1} \cdot (1-q)\sum_{y=1}^{\infty} y \cdot \left[(1-pq^{y+x})^{M-1} - (1-pq^{y+x-1})^{M-1}\right]. \quad (19)$$

IV. Numerical Results: Performance Comparison and Tradeoff Considerations

In Fig. 3–6, we plot for both protocols their throughputs (η_n, η_p) and energy efficiencies ($\eta_{e,n}$,$\eta_{e,p}$) as given by analytical expressions above. These results were computed with a normalized power ratio of $0.1\rho_{tx} = \rho_{rx} = 1000\rho_{low}$; similar (but less contrasting) results follow with other ratios as long as $\rho_{tx} > \rho_{rx} >> \rho_{low}$. The network configurations under

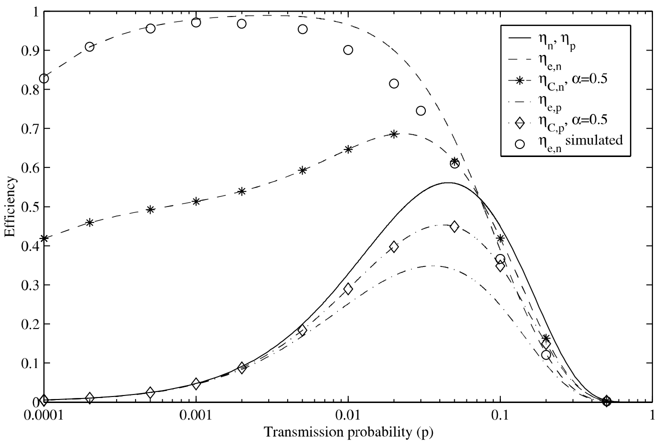

Fig. 3. Efficiencies for CSMA-based network with $M=10$ and $\bar{l}=5$.

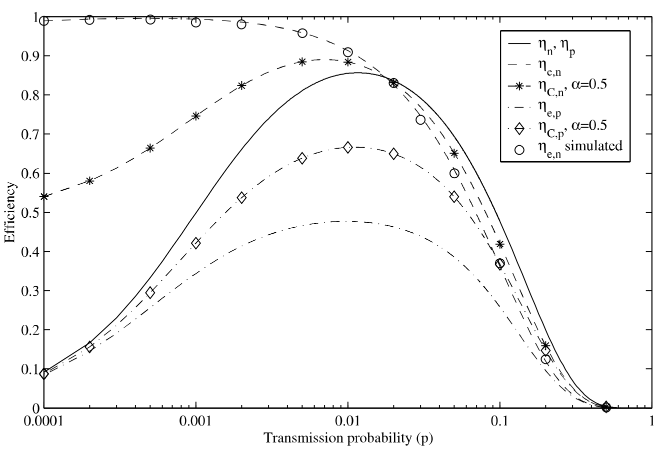

Fig. 4. Efficiencies for CSMA-based network with $M=10$ and $\bar{l}=100$.

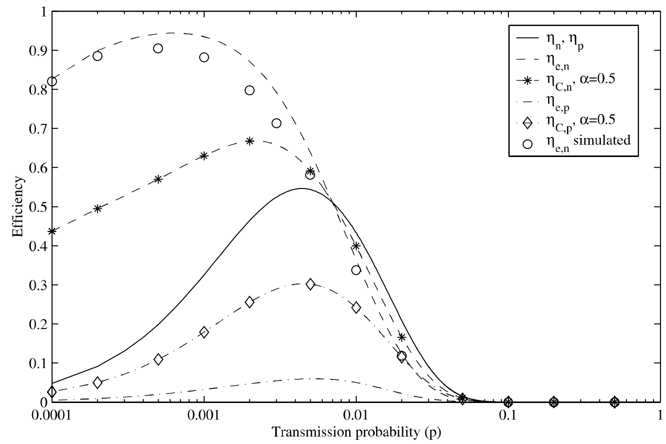

Fig. 5. Efficiencies for CSMA-based network with $M=100$ and $\bar{l}=5$.

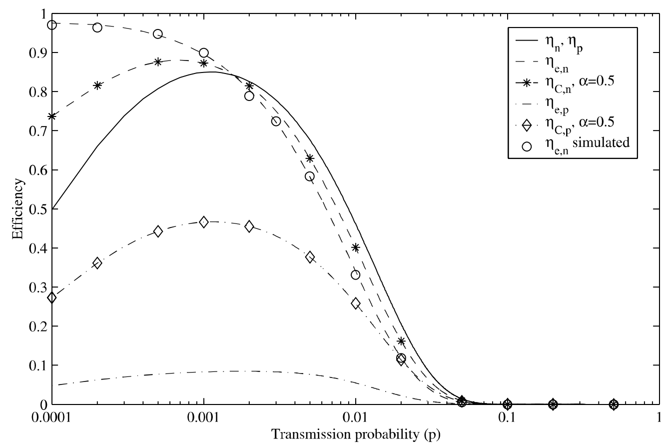

Fig. 6. Efficiencies for CSMA-based network with $M=100$ and $\bar{l}=100$.

consideration are small and large populations ($M\in\{10,100\}$) with short and long average packet lengths ($\bar{l}\in\{5,100\}$).

We observe that under all the network configurations $\eta_{e,n}$ is greater than $\eta_{e,p}$ for all transmission probabilities $p>0$ that achieve non-zero throughput; $\eta_{e,n}$ is markedly higher (more than doubled) for a wide range of p. However, the p that achieves optimal $\eta_{e,n}$ is far removed from the one that achieves the system's maximum throughput (*capacity*) for every network configuration. This is expected because it is the colliding transmissions that hurt $\eta_{e,n}$ most. Said collision probability can be lowered if each station uses a small p, while the concomitant longer backoff periods consume effectively zero additional power. So, in order to obtain high $\eta_{e,n}$, non-persistent CSMA stations need to issue long backoff periods between transmissions, leading to higher idle time in the channel. Therefore, we see that throughput can be greatly sacrificed if non-persistent CSMA is tuned only to achieve energy efficiency. On the other hand, because p-persistent CSMA stations listen to the channel during backoffs and consume ρ_{rx} J/slot, it is less energy efficient in p-persistent CSMA to employ long mean backoffs. Indeed, we observe the p achieving optimal $\eta_{e,p}$ also achieves a throughput close to the system's capacity, as was earlier reported in [5]. In effect throughput is not traded off for energy efficiency in p-persistent CSMA; the system can achieve high values of both with the same operating states. However, the associated energy efficiency is decidedly inferior to that of non-persistent CSMA.

Because achieving optimal η and optimal η_e can be conflicting events, we introduce a *combined efficiency* measure,

$$\eta_C=\alpha\cdot\eta+(1-\alpha)\eta_e \quad (\alpha\geq 0). \tag{20}$$

We plot the combined efficiency for non-persistent ($\eta_{C,n}$) and p-persistent ($\eta_{C,p}$) CSMA in Fig. 3–6 for $\alpha=0.5$ and observe that $\eta_{C,n}$ is saliently higher than $\eta_{C,p}$ for all p over all configurations. This implies that, when energy and channel efficiencies are the only factors stressed, and equally so, non-persistent CSMA is superior to p-persistent CSMA.

The $\eta_{e,n}$ values obtained via simulations are plotted in Fig. 3–6. Observe that for large $\bar{l}$, our analytical expressions provide accurate values of $\eta_{e,n}$; for small $\bar{l}$ the expressions slightly overestimate $\eta_{e,n}$ over a small range of p. Additional simulations with the station drawing a new packet for each retransmission show no discernable differences.

The effect of long backoffs is depicted in Fig. 7 wherein we have plotted the normalized average delays (D) for a network of $M=50$ with $\bar{l}=50$ (other configurations yield similar

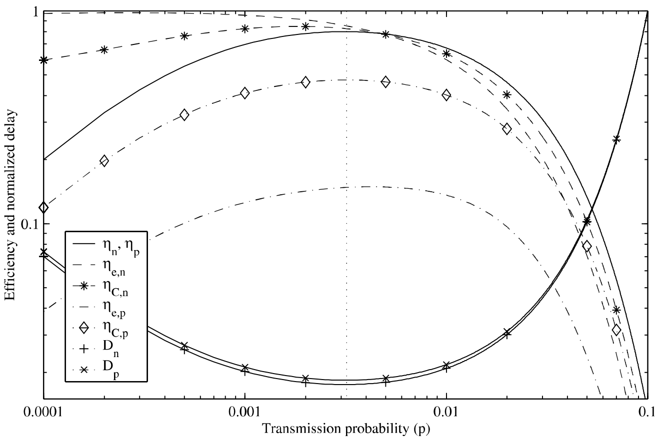

Fig. 7. Normalized delays and efficiencies for CSMA-based network with $M = 50$ and $\bar{l} = 50$. ($\eta_{C,n}$ and $\eta_{C,p}$ calculated with $\alpha = 0.5$.)

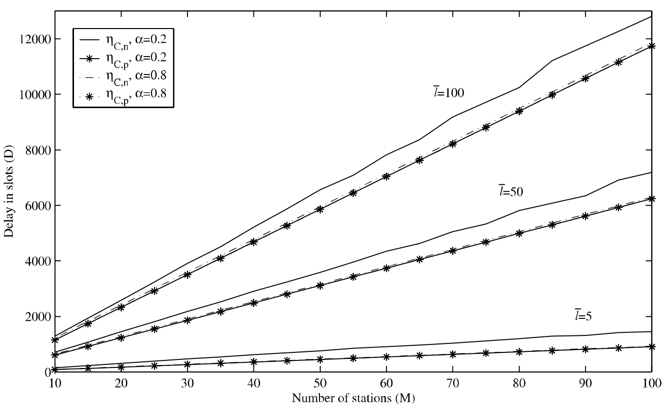

Fig. 8. Average packet delays at optimal combined efficiencies over different network configurations.

results). Note that for both protocols the p that attains the minimum delay for both (marked by dotted vertical line) is quite close to the p that achieves channel capacity. This is to be expected, since to obtain minimum D the stations have to use a p that minimizes the number of collisions with the least backoff time; naturally, this should be the p for channel capacity. From the fairness of the scheme and the renewal properties of the channel and stations' activities, it can be argued that minimum D occurs when the durations of the channel's idle periods equal the time spent on collisions, thus maximizing throughput [10]. Both protocols share this optimal p because they have the same throughput (2). Since it is energy efficient for p-persistent CSMA to transmit nearly as throughput-efficiently as possible, we see that there are no tradeoffs between optimizing $\eta_{e,p}$ and D_p. Quite to the contrary non-persistent CSMA's maximum $\eta_{e,n}$ has non-optimal D_n. Note, however, that an $\eta_{C,n}$ of $\alpha = 0.5$ allows non-persistent CSMA to achieve good efficiencies without trading off much of D_n.

Finally we plot in Fig. 8 the delays incurred with optimized η_C for $\alpha = 0.2$ and $\alpha = 0.8$, which emphasize energy and throughput, respectively. From it, we first note that this D exhibits a linearly increasing relationship with population for both schemes. We also see that, as expected, there are little differences in D_p for both emphases, whereas D_n is far more sensitive to energy efficiency considerations. Moreover, we observe that p-persistent CSMA has a moderately lower delay over all the configurations. At the extreme, this difference is up to 300 slots. To put this into context, as IEEE 802.11b [13] uses slot lengths of 20 μs, this means that about 6 ms of additional delay would be incurred if one were to opt for a more energy-conscious non-persistent CSMA.

V. Conclusion

We investigated the energy efficiencies of non-persistent and p-persistent CSMA over various network configurations and also studied their tradeoffs with throughput and packet delay. Our results should help illuminate the relative suitability of both CSMA schemes for the various new environments that will be introduced as we continue to progress into the age of broadband wireless communication.

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