On the Performance of Distributed Polling Service-based Medium Access Control

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***Abstract*—It has been shown in the literature that many MAC protocols for wireless networks have a considerable control overhead, which limits their achievable throughput and delay performance. In this paper, we study the problem of improving the efficiency of MAC protocols. We first analyze the popular p-Persistent CSMA scheme and show that it does not achieve 100% throughput. Motivated by insights from polling system theory, we then present three polling service-based MAC schemes, termed PSMACs, for improved performance. The main idea is to serve multiple data frames after a successful contention resolution, thus amortizing the high control overhead and making the protocols more efficient. We present analysis and simulation studies of the proposed schemes. Our results show that PSMAC can effectively improve the throughput and delay performance of p-Persistent CSMA, as well as providing energy savings. We also observe that PSMAC is more efficient for handling the more general and challenging bursty traffic and outperforms p-Persistent CSMA with respect to fairness.**

***Index Terms*—Media access control, multi-hop wireless networks, polling service, wireless local area networks.**

I. INTRODUCTION

MEDIUM access control (MAC) protocols play an important role in coordinating channel access among the terminals. Over the years, many MAC protocols have been proposed for wireless networks, such as ALOHA, Slotted ALOHA, carrier sense multiple access (CSMA) (with several versions), and CSMA with collision avoidance (CSMA/CA). The CSMA/CA-like IEEE 802.11 MAC has become the most popular protocol for single- or multi-hop wireless networks. However, the IEEE 802.11 MAC has a considerable control overhead. For example, Xiao and Rosdahl [1] show that the maximum achievable throughput for IEEE 802.11a is 24.7 Mb/s, which is about 45.7% of the nominal link capacity. In [2], Woo and Culler find that the RTS-CTS-DATA-ACK handshake required in transmitting a packet can constitute up to 40% overhead in a sensor platform. When used in a multi-hop environment, the problem gets even worse due to carrier sensing and spatial reuse, making it hard to provide sufficient end-to-end throughput for paths with a large number of hops [3]. In addition, the interesting study in [1] shows that by simply increasing the data rate without reducing overhead, enhanced performance is bounded even when the data rate goes to infinity. It is therefore crucial to reduce the control overhead of such wireless MAC protocols.

In this paper, we study the problem of improving the efficiency of wireless MAC protocols. For simplicity, we first consider a single-hop ad hoc network, where all nodes can hear and directly communicate with each other, and then discuss how to extend our work to multi-hop wireless networks. We examine the reservation-based p-Persistent CSMA scheme (called p-Persistent CSMA in this paper), which uses RTS/CTS for contention resolution and p-Persistent carrier sensing when sending RTS frames. This scheme differs from the standard IEEE 802.11 protocol only in the selection of the backoff interval. Instead of the *binary exponential backoff* used in the standard, a backoff interval sampled from a geometric distribution with parameter p is used. Its performance has been shown to closely approximate the standard protocol if the average backoff intervals are the same (at least from the perspective of protocol capacity) [4], [5]. We show that this scheme uses a limited-1 polling service [6] (since after each contention period, only one data frame is served) which does not achieve 100% throughput for the network.

We propose to use gated service for medium access. Polling is a general way of multiplexing service requests for a single server from multiple stations [6]. A polling system can be centralized, where a server polls the stations and controls channel access (as in Bluetooth [7]), or distributed, where stations follow a distributed protocol to contend for channel access. Once a station accesses the channel, there are three types of service policies to serve its packets: (i) *exhaustive policy*, where the server serves a station until its buffer is emptied; (ii) *gated policy*, where the server serves for a station only those requests which are already buffered in the station when this service period begins; and (iii) *limited-k policy*, where a station is served until either the buffer is emptied or the first k buffered requests are served, whichever occurs first. One special case of the limited-k service is limited-1 service,

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where at most one request is served during each service period (as in most existing MAC protocols). It has been shown that both exhaustive service and gated service are more efficient than the limited-k service, and they can guarantee bounded delay as long as the offered load is strictly less than 100% [6], [8].

Motivated by insights from polling system theory, we present three polling service-based MAC scheduling schemes, termed PSMACs, for improved performance. The main idea is to serve multiple data frames after a successful contention resolution, thus amortizing the high control overhead over multiple data frames and making the protocols more efficient. Specifically, PSMAC 1 uses the same p-Persistent strategy in sending RTS frames for contention resolution, but a winning node will use gated service to serve its queue. An improvement of PSMAC 1, PSMAC 2, maintains multiple virtual queues, one for each of its neighbors, and gated service is used for one of the non-empty virtual queues at a winning node. In this way, those nodes that are not involved in the current service can be scheduled to sleep, thus achieving energy savings. A further improvement, PSMAC 3, combines the strengths of the first two schemes. It also maintains multiple virtual queues as in PSMAC 2, but when a node wins the channel, it will use gated service to serve all its non-empty virtual queues, one at a time. Thus it has the high efficiency of PSMAC 1, and the capability of sleep-scheduling for energy savings as in PSMAC 2.

We provide a random polling-based analysis of PSMAC 1 that provides a tight estimate for the achievable average delay. We also present extensive simulation studies of the proposed schemes under various traffic models. Our analysis and simulation results show that all the three proposed schemes achieve considerable throughput and delay improvements over p-Persistent CSMA. In addition, PSMACs 2 and 3 can achieve significant energy savings by allowing node sleep-scheduling. We also find that the proposed schemes has the unique strength of handling bursty traffic, which is typical in wireless networks [9]. Specifically, when traffic gets burstier, all the three PSMAC schemes achieve a similar delay performance, and the gains over p-Persistent CSMA is larger than that under the i.i.d. Bernoulli traffic. Another interesting observation from our simulation results is that, surprisingly, such performance gains can be achieved without sacrificing fairness performance. When we consider delay-based fairness definitions, all the three PSMAC schemes achieve better fairness performance than p-Persistent MAC. Finally, we show that the proposed schemes can be extended to multi-hop or multi-channel wireless networks. We observe similar performance gains in the multi-hop environment when PSMAC 2 is used.

The remainder of this paper is organized as follows. In section II, we provide a throughput analysis for the p-Persistent CSMA scheme. We then present the three PSMAC schemes in Section III. Our simulation and analysis performance studies are presented in IV. We discuss related work in Section V. Section VI concludes this paper.

II. Throughput Analysis of p-Persistent CSMA

In this section, we provide an analysis of the throughput performance of p-Persistent CSMA (due to its similarity to the IEEE 802.11 MAC [4], [5]). The purpose is to provide a proper benchmark for the performance of the proposed schemes.

We consider a slotted-time system throughout this paper, where each time slot is the combined transmission time of an RTS and a CTS frame. Frame transmissions are aligned to the beginning of the time slots. In p-Persistent CSMA, a nonempty node, say Node A, first senses the medium at the beginning of the next time slot. If the medium is idle, Node A will transmit an RTS with probability p in the first half of the time slot. In the RTS, node A specifies the destination of its head of line frame, say Node B. If this is the only RTS sent in that time slot, Node B will reply with a CTS in the second half of the time slot; otherwise, there is a collision of multiple RTS's and no CTS will be transmitted. We assume a fixed frame length of L time slots. If the RTS/CTS dialog is successful, a data frame will be transmitted in the following L time slots, right after the time slot of the successful RTS/CTS dialog. The operation of this mechanism is illustrated in Fig. 1.[1] Note that it is similar to the *limited-1 service* in a polling system, since only one frame is transmitted in every service period.

For such random access networks, it is more interesting to study the system under heavy load for performance limits. Therefore, we make the *heavy traffic assumption* in the following analysis. That is, we assume each node has at least one data frame to transmit at any time. Letting Q be the probability that only one RTS is sent in a time slot, we have

$$Q = Np(1-p)^{N-1}. \tag{1}$$

Let S be the time measured from the time when the previous service finishes to the time when one pair of RTS/CTS succeeds (see Fig. 1). We have that $Pr(S=k) = Q(1-Q)^{k-1}$, and the mean value of S is

$$\mathrm{E}(S) = \sum_{k=1}^{\infty} kQ(1-Q)^{k-1} = \frac{1}{Q}. \tag{2}$$

The operation of p-Persistent CSMA can be modeled as a *alternating renewal process* [10]: every contention period of S will be followed by a service period of L, and S is the overhead for transmitting L time slots of data. Therefore, the average throughput of the system is

$$T = \frac{L}{L + E(S)}. \tag{3}$$

For a given network of N nodes, T is a function of the transmission probability p. We can set the first derivative of T with respect to p to 0, and obtain the optimal value p^*. With some algebra, it can be verified that p^* is a maximizer by checking the the second derivative of T with respect to p. The optimal transmission probability and the maximum throughput

[1] For simplicity, we ignore the protocol components such as Inter-Frame-Spaces (IFS) and ACK frames that are used as in the IEEE 802.11 MAC. However, these components can be modeled as a fixed amount of overhead and can be easily incorporated into the model (e.g., adding an ACK time slot after each data transmission in Fig. 1).

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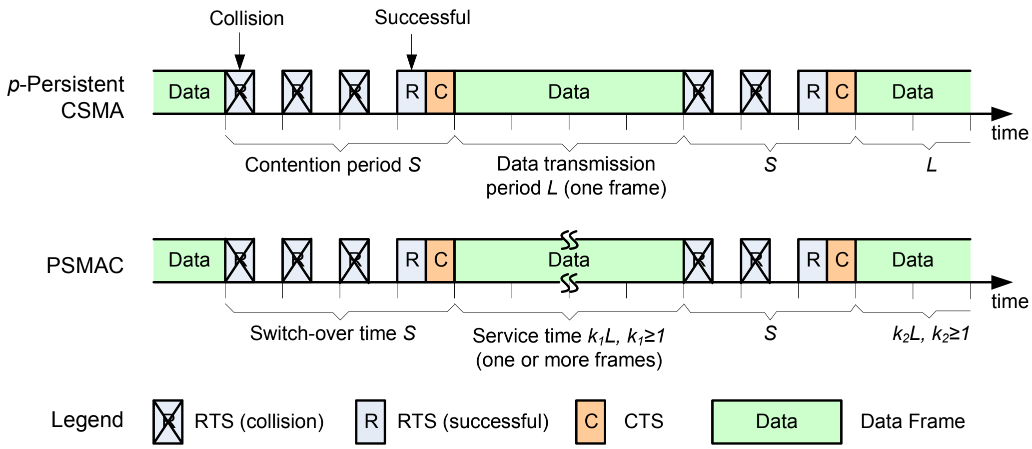

Fig. 1. Time-line illustration of p-Persistent CSMA and the proposed PSMAC schemes.

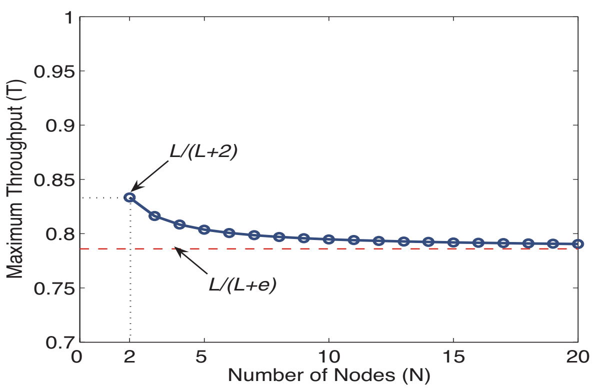

Fig. 2. The maximum throughput of p-Persistent CSMA ($L = 10$).

are

$$p^* = \frac{1}{N} \quad \text{and} \quad T^*(N) = \frac{L(1-\frac{1}{N})^{N-1}}{L(1-\frac{1}{N})^{N-1}+1}, \quad N \geq 2. \tag{4}$$

Equation (4) can also be interpreted as follows. Letting M be the number of nodes sending RTS in a time slot, we have $\Pr(M = m) = \binom{N}{m} p^m(1-p)^{N-m}$, and the average of M is $\mathrm{E}(M) = \sum_{m=1}^{N} m \binom{N}{m} p^m(1-p)^{N-m} = Np$. The optimal value p^* ensures that, on average, there is only one transmitter in each competition slot, which leads to the highest throughput. We will use $p^* = 1/N$ throughout this paper except for Section IV-E.

We plot $T^*(N)$ versus N in Fig. 2 for the case $L = 10$. It can be seen that, in the simplest case of $N = 2$, the throughput achieves its maximum of $T^*(2) = L/(L+2)$. As the number of nodes increases, the maximum throughput decreases due to the higher chance of collision. When $N \to \infty$, the maximum throughput approaches from above to a limit of $T^*(\infty) = L/(L+e)$, where e is Euler's number. For example, if $L = 10$ and $N = 20$, the maximum throughput is 79%; when $N \to \infty$, the throughput reaches its limit 78.6%. The p-Persistent CSMA scheme clearly does not achieve 100% throughput.

It is worth noting that the maximum throughput (4) is also a function of frame length L. It is possible to achieve a reasonably high throughput with p-Persistent CSMA by increasing the frame length. For example, the sum of RTS and CTS is 34 Bytes in the IEEE 802.11 MAC. If a data frame is 1000 Bytes long, we have that $L \approx 30$ and $T^* \in [91.7\%, 93.75\%]$. However, dynamic rate adaptation is usually used in IEEE 802.11 [1], where data frames are transmitted at a high bit rate (e.g., 11 Mb/s) and control frames are transmitted at a low bit rate (e.g., 1 Mb/s). In this case, we have that $L \approx 3$ and $T^* \in [52.4\%, 60\%]$. Can we reduce the protocol overhead by disabling the RTS/CTS mechanism? If data frames are directly used in contention resolution, the system reduces to Slotted ALOHA. Its throughput is Q as given in (1). It can be verified that $p^* = 1/N$ is a maximizer of Q, and the the optimal throughput is $T^* = 1/e = 36.8\%$ as $N \to \infty$, the well-known upper bound for Slotted ALOHA, which is even lower than (4).

III. Polling Service-Based MAC

It has been shown that in a polling system, exhaustive service has the highest efficiency, while limited-1 service has the lowest efficiency [6]. In this section, we present three polling service-based MAC schemes that can improve the throughput, delay, and energy performance for p-Persistent CSMA, which is essentially a limited-1 service scheme.

A. PSMAC 1

The first polling service-based scheme, termed PSMAC 1, incorporates a *gated service* for frame scheduling [6]. More specifically, all arriving frames (transit or locally generated) are queued in a common transmission buffer (or, the *global queue*). Nodes send out RTS/CTS as in p-Persistent CSMA. In the RTS, the source node specifies the destination MAC address of its *head-of-line* frame, say Node B. If this is the only RTS in the time slot, Node B will return a CTS. In the RTS, Node A will also specify how many packets will be transmitted, so that all other nodes will get this information. However, instead of sending one data frame after a successful RTS/CTS pair, all frames that have arrived at the source node before the RTS transmission, will be served back-to-back in the following slots. Other nodes will start a new round of competition (using the p-persistent method) when the current

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sequence of frame transmissions is over. The operation of PSMAC 1 is illustrated in Fig. 1.

Alternatively, *exhaustive service* can also be incorporated into this scheme [6], which is generally more efficient than gated service in a polling system. However, with exhaustive service, the source node does not know when the corresponding transmission will be over when it sends an RTS. This is because there may be new frame arrivals after the transmission starts, which will also be served during this service period. Therefore, when the source node clears its buffer, it should send a special control frame in the following time slot to notify all its neighbors, which will start a new round of competition in the next time slot. We find that gated service and exhaustive service achieve very similar performance. Hence we only present the analysis and simulations for gated service in this paper for brevity.

1) Delay Performance: With PSMAC 1, the network can be modeled as a *gated service random polling system*. The average delay of PSMAC 1 under uniform i.i.d. traffic can be analyzed as follows. By abuse of notation, we also let S denote *switch-over time*, which is the interval between two consecutive service periods in a polling system. It is measured from the time when the previous service is over, to the time when the next service starts. Since every node sends RTS/CTS as in p-Persistent CSMA (see Section II), the average switch-over time is identical to the average contention period in p-Persistent CSMA, with a geometric distribution. Its mean is given in (2), and its second moment is

$$E(S^2) = \sum_{k=1}^{\infty} k^2 Q(1-Q)^{k-1} = \frac{2-Q}{Q^2}. \quad (5)$$

The average delay of a fully symmetric random gated service polling system is

$$\mathrm{E}(D) = \frac{1}{2}\left[\frac{\delta^2}{r} + \frac{\sigma^2 + Nr\mu(1+\mu) + (N-1)r\mu}{(1-N\mu)\mu}\right], \quad (6)$$

where μ is the arrival rate to a node, σ^2 is the variance of the arrival process for a node, $r = \mathrm{E}(S)$, and $\delta^2 = \mathrm{Var}(S) = \mathrm{E}(S^2) - \mathrm{E}^2(S)$ [8]. In a symmetric system with i.i.d. Bernoulli traffic, we have that $\mu = \rho/N$ and $\sigma^2 = \rho/N - (\rho/N)^2$, where ρ is the total arrival rate to the system. We will show in Section IV that (6) provides a very good approximation for the average delay when PSMAC 1 is used.

2) Throughput Performance : In polling systems, throughput is closely related to the notion of *stability* [11], [12]. A scheme is said to stabilize the system, or achieves 100% throughput, if it can guarantee bounded delay as long as the offered load ρ is strictly less than 100% (i.e., $\rho = 1 - \epsilon$, for $0 < \epsilon \ll 1$) [6], [8].

As discussed, p-Persistent CSMA achieves a maximum throughput which is strictly less than 100% (see (4)). On the other hand, prior work on polling systems has shown that both exhaustive service and gated service can serve any offered load $\rho < 100\%$ with bounded delay [6], [8]. Therefore, the throughput of PSMAC 1 should be very close to 100% even when the RTS/CTS overhead is taken into account. We will demonstrate this point in Section IV.

B. PSMAC 2

For wireless terminals (e.g., disposable sensor nodes), it is generally crucial to conserve energy. It has been shown that a node in the sleep state consumes far less energy than in the idle, transmit, or receive state. It is therefore desirable to schedule nodes to sleep whenever possible, be it a Wireless LAN [13], a wireless sensor network [2], [14] or an ad hoc network [15]. It is also appealing to schedule nodes to sleep without sacrificing delay and throughput performance, which, however, is generally hard to achieve [2], [14], [15].

In PSMAC 2, each node maintains $N-1$ *virtual queues*, one for each of its neighbors. If there are one or more non-empty virtual queues, the node first selects one of them. The selection strategy can be round robin, uniform, or by following a priority order (e.g., longest-queue-first). The node then attempts to transmit RTS as in p-Persistent CSMA to contend for service. In the RTS, it specifies K, the number of frames backlogged in the selected virtual queue at this time, and the ID of Node B, the destination node corresponding to the selected virtual queue. If the RTS succeeds, Node B will return a CTS and *gated service will be used for this virtual queue* (i.e., K frames will be transmitted back-to-back to Node B). All other nodes which are not involved in this transmission, can be scheduled to sleep during this period and wake up when the K frame transmissions are over.[2]

We expect that the PSMAC 2 throughput is not as high as PSMAC 1, since it uses gated service only for one virtual queue instead of the global queue. However, it has the advantage if energy conservation is a major consideration. Since a node only sleeps when it is not involved in a transmission, there is no additional delay or throughput degradation incurred. Our simulation results show that the PSMAC 2 throughput is very close to 100%, and more importantly, its delay performance is very close to that of PSMAC 1 under bursty traffic.

C. PSMAC 3

For the two PSMAC schemes, PSMAC 1 is more bandwidth efficient, while PSMAC 2 is suited for energy conservation. Motivated by these observations, we further extend the scheme to obtain both advantages. In PSMAC 3, each node maintains $N-1$ virtual queues, and nodes compete for the channel by sending RTS as in PSMAC 2. When a sender successfully wins the channel, it first broadcasts an *announcement frame*. The announcement frame notifies its neighbors the lengths of all the non-empty virtual queues at the source node, as well as the order in which the virtual queues will be served. Therefore, each destination node will be notified how many frames it will receive, as well as the starting and ending times for reception. The sender then starts data transmission, clearing the virtual queues one at a time in the order as specified in the announcement frame. All other nodes, except the corresponding destination of the virtual queue currently being served, can be scheduled to sleep and to wake up when its corresponding virtual queue is to be served. If a node is

[2]Note that we can set a threshold $\bar{K}$ and schedule a node to sleep only if the expect sleep period is longer than $\bar{K}$, in order to avoid frequently switching between sleep and awake modes with very short periods.

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not one of the announced destinations, it can go to sleep and wake up when all the virtual queues at the source node are cleared.

This way, we obtain a similar service as in PSMAC 1, as well as the energy conservation capability as in PSMAC 2. There is only one additional frame (the announcement frame) as extra overhead for each burst of data transmissions, compared to PSMAC 1. Thus PSMAC 3 achieves approximately the same delay and throughput performance as PSMAC 1, and approximately the same energy savings as PSMAC 2.

D. Extension to Multi-Channel and Multi-hop Networks

So far we have considered a single hop wireless network, where all the nodes can hear each other and share a common wireless channel. It would be interesting to consider the cases of multi-hop wireless networks and multi-channel wireless networks where multiple orthogonal channels are used. Can we use the three schemes in such environments?

Extension to multi-hop wireless networks is a more complicated issue, since each node now sees a different set of neighbors and the inherent hidden terminal and exposed terminal problems should be carefully addressed. Among the three schemes, it is straightforward to adopt PSMAC 2 for a multi-hop wireless network. Its operation is similar to that of IEEE 802.11: each time one receiver is reserved by a successful RTS/CTS dialog, but a gated service is used for the virtual queue corresponding to the target receiver. As will be demonstrated in Section IV, PSMAC 2's performance on throughput, delay, and fairness approaches to those of PSMAC 1 and 3 as traffic gets bursty. This makes PSMAC 2 suitable for the multi-hop wireless environment, where traffic usually gets burstier as it traverses more hops due to large variations in wireless channel capacity [9]. PSMAC 1 and 3 require the reservation of potentially multiple receivers with a successful RTS/CTS dialog. In a multihop environment, this requires an additional three-way handshake and a sophisticated scheduling algorithm. We present the PSMAC 2 performance in a multi-hop wireless in Section IV-F, and leave the PSMAC 1 and PSMAC 3 cases for future study.

In addition to efficient scheduling (without additional hardware/resource requirements), another effective means of improving the throughput of wireless networks is using multiple radios and multiple orthogonal channels [16]–[19]. Although offering great potential, such an approach also brings about challenging scheduling problems, since now connectivity also depends on channel assignment, in addition to mobility/distance and channel dynamics [18], [19]. An effective solutions is to use a common control channel along with multiple data channels [16], [17]. With PSMAC, we can have nodes compete in the control channel for gated service of their backlogged frames in the data channels. We expect similar performance gains over traditional limited-1 service schemes as in [16], [17].

IV. Performance Evaluation

In this section, we present our performance study for the proposed schemes. The delay, throughput, energy consumption, and fairness performance of the three PSMAC schemes are compared with that of p-Persistent CSMA under the following three types of traffic:

- *i.i.d. Bernoulli traffic*: a frame arrives in each time slot with a predefined probability.
- *on-off bursty traffic*: frames are generated according to an on-off model with geometrically distributed on and off periods. This is a good model for short-range-dependent (SRD) traffic (e.g., voice over IP). The average on and off periods are five for the results reported in this section.
- *long-range-dependent (LRD) traffic*: frames are generated according to an on-off model with (truncated) Pareto distributed on and off periods. This model is much more bursty than the other two and can be used to model variable bit rate video and data traffic. For results reported in this section the average on and off periods are 26.7 and the Hurst parameter $H = 0.7$.

The *uniform* traffic pattern is used in most of the simulations, i.e., an arriving frame or burst is equal likely to be destined to each of the neighbors. In Section IV-D, we also use a non-uniform traffic pattern for the fairness performance study, where a specific neighbor has a much higher load than others. We set $L = 10$ and $N = 20$ for most of the simulations and analysis, unless specified otherwise.

The three schemes and p-Persistent CSMA are implemented using the C language. Each experiment is repeated 10 times with different random seeds. Each data point in the figures is the average of the 10 samples. We also compute 95% confidence intervals for the simulation results. Since they are generally very small, we only show the confidence intervals in the first few figures, but omit them subsequently for clarity.

A. Delay Performance

We first examine the delay of the proposed PSMAC schemes. In Fig. 3, we plot the simulated average delay of PSMACs 1 and 3, along with the analysis using (6), under i.i.d. Bernoulli uniform traffic. We find that the analytical curves matches the simulation curves, especially when the system is heavily loaded. The gap between the two curves, when the load is light, is due to the small discrepancy between our system and a random polling system. In a random polling system, after one station is served, the server may switch to an empty station, resulting in a zero service period, followed by a new switch-over period. In our system, only non-empty nodes will be served, since an empty node will not send RTS to compete for the channel. Therefore, a switch-over time is *always* followed by a non-zero service period in our system. By using the less efficient random polling system model, the analysis is actually an *upper bound* when the load is light. When the load is heavy, nodes are less likely to be empty and the two systems behave more like each other. As a result, the analysis and simulation curves converge.

The average delay of the three proposed schemes are plotted in Fig. 4 for different traffic models. It can be seen that PSMAC 1 and PSMAC 3 have the same delay performance under the entire range of load examined and for all the three traffic models. These are expected results, since from the descriptions in Section III, both PSMACs use gated service for the global queue at a winning node, while the only difference

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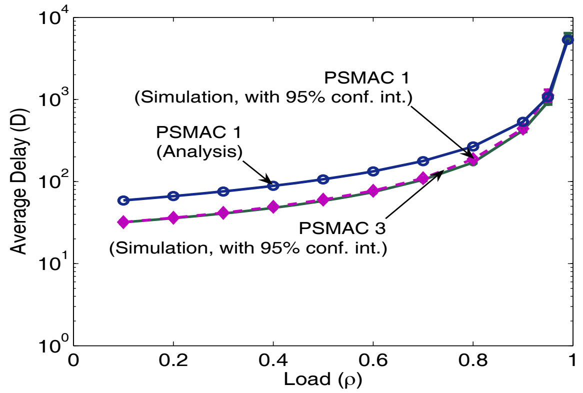

Fig. 3. Average delays under the uniform i.i.d. Bernoulli traffic.

is the order in which frames are served (the additional control frame in PSMAC 3 is negligible). That is, first-come-first-serve or one virtual queue at a time. We will show that PSMAC 3 achieves energy savings over PSMAC 1 in Section IV-C.

We also plot the delays achieved by p-Persistent CSMA in Fig. 4 as benchmarks. In all the three figures, the PSMAC schemes outperform p-Persistent CSMA in delay performance, and the improvements increase when traffic gets burstier. Specifically, the p-Persistent CSMA curve diverges when ρ is close to 79%, while the PSMAC delays are all bounded for all the traffic models and all the loads examined.

From Fig. 4(a), we also find that all the four schemes have similar average delay in the low load region. This is because under a light load, the queues or virtual queues are less likely to build up. Although gated service is used in the three proposed schemes, it usually serves queues with a single frame and thus reduces to limited-1 service as in p-Persistent CSMA. However, for the more interesting heavy load region, the PSMAC 1 and 3 delays are significantly smaller than that of p-Persistent CSMA. This is because under a heavy load, the queues are more likely to build up and gated service will be more efficient than the limited-1 service. For PSMAC 2, although load is higher, the average rate to each virtual queue, $\mu = \rho / [N(N-1)]$, is still not big enough to build up large backlogs. Thus a gated service for a virtual queue is still more like a limited-1 service, and its delay curve remains close to that of p-Persistent CSMA. Nevertheless, it still achieves a higher throughput than p-Persistent CSMA.

When traffic gets bursty, we find in Figs. 4(b) and 4(c) that all the PSMACs achieve significantly smaller delay over p-Persistent CSMA. Under bursty traffic, the backlogs of the global queues or virtual queues are more unevenly distributed. There is a high chance for the proposed PSMACs to find a queue (or a virtual queue in the case of PSMAC 2) with a large number of backlogged frames, and gated service will achieve a much better delay performance in these scenarios. A somewhat *counter-intuitive* observation is that, as traffic gets burstier, the PSMAC 2 delay curve almost completely overlaps with the PSMAC 1 curve, although it only uses gated service for a chosen virtual queue (see Figures 4(b) and 4(c)). This implies that under highly bursty traffic, the frames backlogged at a node are more concentrated in a small number of virtual queues (destined to a small subset of neighbors). In these

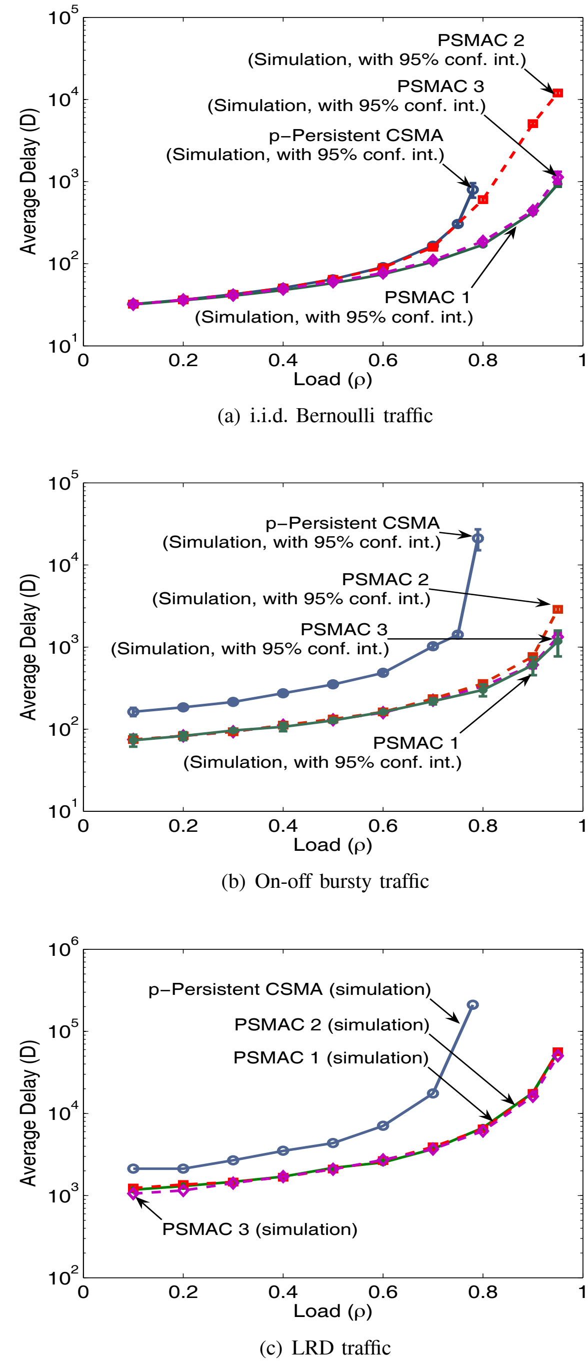

Fig. 4. Average delays under various traffic models.

cases, gated service for the global queue rather than a heavily loaded virtual queue does not make much difference.

B. Throughput Performance

For a polling system, throughput is closely related to the notion of stability [11], [12]. From Fig. 4, we find the p-Persistent CSMA curve diverges when ρ is close to 79% for all the three traffic models. That is, when the load is close to 79%, the average delay becomes unbounded (i.e., goes to ∞). This verifies our analysis in Section II, since according to (4), $T^*(N = 20, L = 10) = 79\%$. For the proposed schemes, however, bounded delays are achieved even when the

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load is very close to 100%. Therefore, PSMAC can stabilize the system [6] (see Section III-A2) and achieve significant throughput improvements over p-Persistent CSMA.

C. Energy Savings

For wireless networks, it is very important to conserve battery power, while the the most effective means of conserving energy is to schedule nodes to sleep whenever possible [14], [15]. We examine the achievable energy savings of the PSMACs in this section.

We adopt the power consumption model in [20]. The transmit, receive, idle, and sleep powers are 1400mw, 1000mw, 830mw, and 130mw, respectively. Note that we use a time slot as unit of time, and normalized powers (in units per time slot) are used in our simulations, which are 1.4, 1.0, 0.83, and 0.13 for the transmit, receive, idle, and sleep state, respectively. In Fig. 5, we plot the simulated average energy consumption, i.e., the average normalized energy consumed per node per time slot, for all the four schemes under the i.i.d. Bernoulli traffic and the on-off bursty traffic. Similar results were obtained for the LRD traffic model, but omitted for lack of space. The traffic load is $\rho = 0.7$ for both figures and we vary the number of nodes N from 2 to 20.

It can be seen that p-Persistent CSMA and PSMAC 1 consume almost the same amount of energy per node per time slot, while PSMACs 2 and 3 are much more energy efficient due to their capability of scheduling nodes to sleep. For example, in Fig. 5(a), when $N = 20$, the average energy consumption of p-Persistent CSMA is 0.8590, while the average energy consumption of PSMAC 2 is 0.4166. The normalized reduction is $(0.8590 - 0.4166)/0.8590 = 51.5\%$. Note that when $N = 2$, all the schemes have similar energy consumptions. This is because there is no way to schedule nodes to sleep when $N = 2$; when one node is transmitting, the other node must be receiving. Finally, it is worth noting that the PSMAC 2 curve approaches the PSMAC 3 curve when traffic gets burstier, as observed in the delay and throughput performance studies.

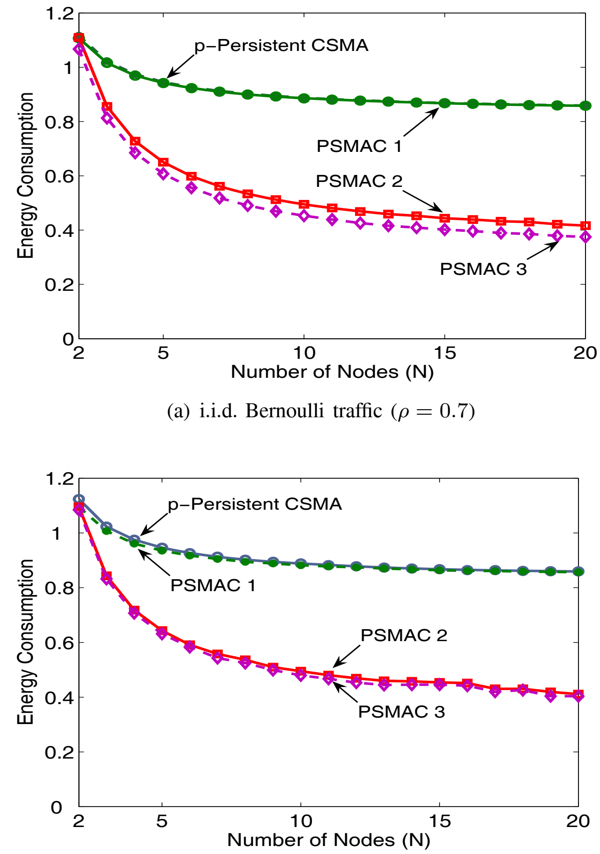
D. Fairness Performance

A general concern in using gated service is fairness, since one may expect that gated service favors heavily loaded users. Various fairness definitions have been used in the literature. We consider the user experienced performance metric, node delay, in the fairness definition. As in the case of fair resource allocation [21], node delay can be interpreted as a kind of utility function which converts lower level performance metrics such as per node channel usage to utility, although a closed-form expression is hard to find in this case.[3]

We first examine the fairness performance using the fairness index defined in [22],

$$f(D_1, D_2, \cdots, D_N) = \frac{(\sum_{i=1}^{N} D_i)^2}{N \sum_{i=1}^{N} D_i^2}, \tag{7}$$

[3]It is worth noting that if per node channel usage is used and with the notion of max-min fairness, all the four schemes will have fairness indices close to one if the offered load is within the stability region. However, equalizing per node channel usage is of less interest since when the system is stable, there is no need to restrain the channel access of some stations to save bandwidth for some other stations.



(a) i.i.d. Bernoulli traffic ($\rho = 0.7$)

(b) On-off bursty traffic ($\rho = 0.7$)

Fig. 5. Energy consumption under various traffic models.

where D_i is the average delay at Node i, $i \in [1, 2, \cdots, N]$. This fairness index generally varies from 0 to 1. When all nodes have the same average delay, we have that $f = 1$ and the system is 100% fair. As disparity increases, fairness decreases for schemes which favor only a few selected nodes. For example, when the delay of one node is dominant (i.e., $D_1 \gg D_i, \forall i \neq 1$), the fairness index is $f \approx 1/N$ (and $\lim_{N \to \infty} f = 0$ in this case). We also used the so-called worst-case fairness index in this study, which is defined as

$$f(D_1, D_2, \cdots, D_N) = \frac{\min_{i=1,\cdots,N}\{D_i\}}{\max_{i=1,\cdots,N}\{D_i\}}. \tag{8}$$

This fairness index also varies between one and zero. When all the node delays are equalized, we have $f = 1$; when one node's delay is dominant, we have $f \approx 0$.

Under the uniform traffic pattern, our simulations show that all the schemes have a similar fairness index. We omit these results for brevity. Now let us consider the more interesting *nonuniform* traffic pattern as follows. Recall that ρ is the arrival rate to the system and μ_i the arrival rate to Node i. The arrival rates to the nodes are determined as

$$\mu_i = \begin{cases} \frac{\rho}{2}, & i = 1 \\ \frac{\rho}{2(N-1)}, & 2 \le i \le N \end{cases} \quad \text{and} \quad \sum_{i=1}^{N} \mu_i = \rho. \tag{9}$$

With this non-uniform traffic pattern, Node 1 is heavily loaded, while all the other nodes are lightly and equally loaded.

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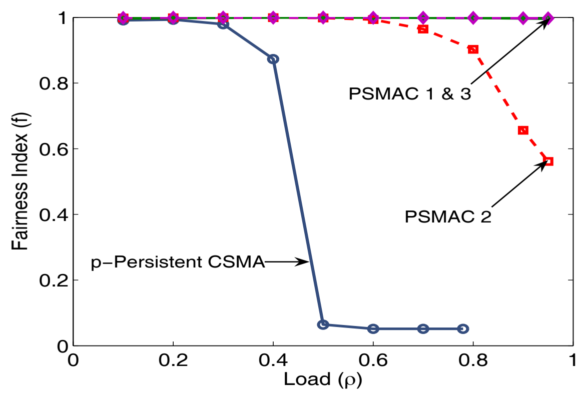
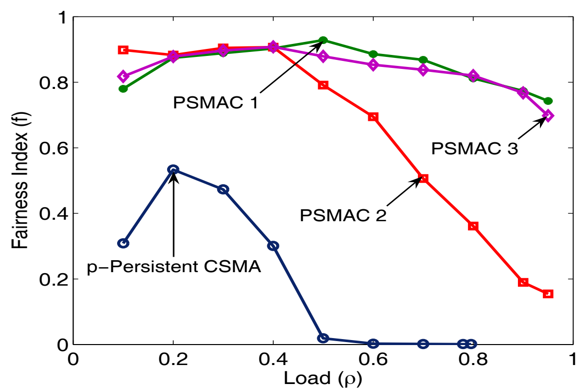


(a) Fairness definition (7)



(b) Fairness definition (8)

Fig. 6. Fairness indices under the on-off bursty traffic model.

Figure 6 shows the fairness indices achieved by the four schemes under the on-off bursty traffic. We obtain similar results for the Bernoulli and LRD traffic but omit them for brevity. It can be seen from Fig. 6(a) that when load ρ is low, the fairness indices of all the schemes are almost the same. For increased ρ, the p-Persistent CSMA curve drops quickly, while the fairness curves of PSMACs 1 and 3 remain at high values close to 1. Specifically, the p-Persistent CSMA fairness index drops to $f = 1/N = 5\%$, when ρ is beyond 50%. This indicates that one of the nodes, i.e., Node 1, has a large delay that dominates the delays of all other nodes. Similar observations can be made from Fig. 6(b) when the worst-case fairness index is used. Although in this case the PSMAC indices are lower than one, they are still significantly higher than the p-Persistent CSMA curve, which falls to zero when the load exceeds 50%.

We present the node delays in Fig. 7 for the case of $\rho = 0.7$ under the on-off bursty traffic. When p-Persistent CSMA is used, the Node 1 delay is 18147.5, which is much larger than the delays of other nodes (ranging from 320 to 350). The average node delays achieved by the three PSMACs are all lower than the corresponding p-Persistent CSMA node delay. Furthermore, the Node 1 delay is slightly lower than those of all the other nodes when PSMACs 1 and 3 are used, and slightly higher than those of all the other nodes when PSMAC 2 is used. The PSMAC fairness indices are much larger than that of p-Persistent CSMA for all the cases we studied.

These are, at first glance, *counter-intuitive results*, since, contrary to the common belief, the use of gated service does not result in poor fairness performance. Rather, the three PSMAC schemes achieve better fairness performance than p-Persistent CSMA. This is largely due to the high efficiency of the PSMAC schemes and the reduced overhead. *All* the queues are efficiently served and the delays of those lightly loaded nodes are only slightly increased (due to the heavily loaded node). Thus the benefit introduced by gated service to a heavily loaded node does not significantly increase the delays of other nodes. Fairness is not sacrificed for improved delay and throughput performance.

E. Impact of Sub-optimal p

The PSMACs require knowledge of number of one-hop neighbors (i.e., N) in order to choose the optimal value for p. In a distributed environment, this information may be difficult for each node to obtain. As a result, only sub-optimal p will be used. This is a common issue for p-persistent carrier sensing MAC schemes. To this end, we consider two possible approaches to find the number of neighbors. First, many routing protocols require maintain the list of neighbors and such information can be exploited for setting the optimal p value. Second, each node can estimate N, based on successfully detected signals [23]. We examine the impact of estimation error (i.e., sub-optimal p) on the PSMAC performance.

In Fig. 8(a), we plot the average delay from analysis for different p values. Although there are N nodes in the network, we set $N' = \xi \times N$ and $p = 1/N'$ and compute the corresponding average delay, where ξ varies from 0.5 to 1.5. It can be seen that the minimum delay is achieved at $\xi = 1$ or $N' = N$. In addition, the delay curves are quite flat around the minimizer ($\xi = 1$). The above observation is validated in our simulations. For example, when $N = 20$, we show in Fig. 8(b) the average delays for $N' = 0.8 \times N$, $N' = 1.2 \times N$, and the case when N' is randomly chosen from $[0.8 \times N, 1.2 \times N]$. We can see that the three curves are very close to each other. The impact of an error in the estimated number of one-hop neighbors is not significant.

F. Multi-hop Wireless Networks

As discussed earlier, PSMAC 2 can be easily used for multi-hop wireless networks. In this section we examine its performance using a grid network topology. The 25-node network consists of a grid of 5 by 5 nodes. The transmission range is chosen such that each node has at most 8 neighbors. Note that now winning the channel also depends on possible transmissions two hops away, and the RTS/CTS mechanism is used to solve the hidden terminal problem.

Figure 9 shows the average delay of PSMAC 2 and p-Persistent CSMA under the on-off bursty traffic model and the uniform traffic pattern. The offered load ρ can be larger than 1 due to spatial reuse. The RTS transmission probability for Node i is set to $p_i^* = 1/N_i$ where N_i is the number of its neighbors. As expected, PSMAC 2 outperforms p-Persistent CSMA in throughput and delay. The p-Persistent CSMA delay becomes unbounded when ρ is close to 2, while the PSMAC 2 delay is still bounded when ρ is 2.6 in our simulations.

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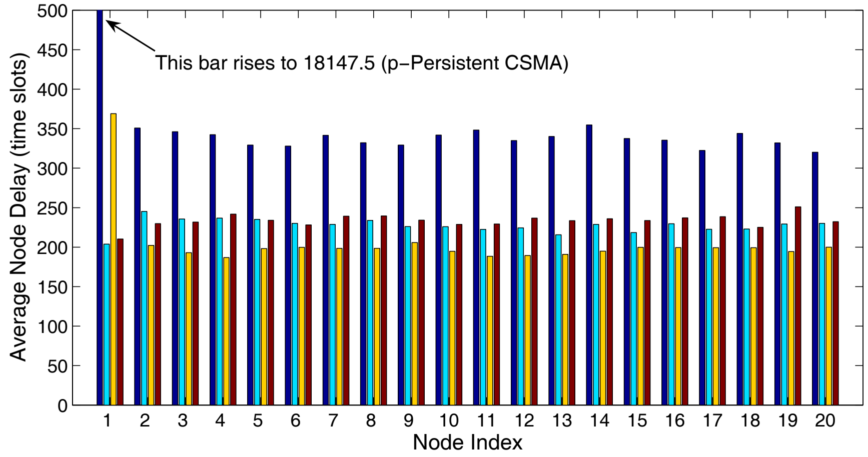
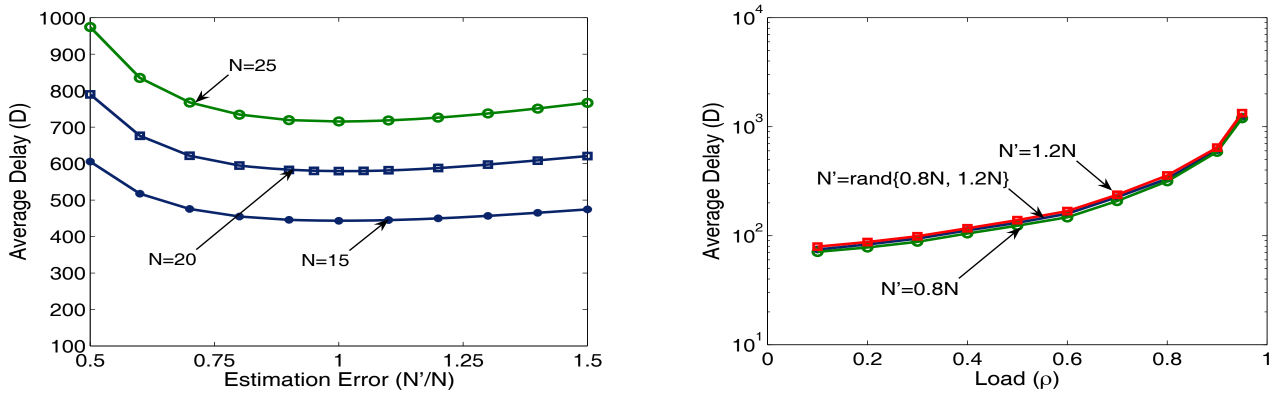


Fig. 7. Average node delays achieved by the four schemes under non-uniform on-off bursty traffic ($\rho = 0.7$). The bars in each group, from left to right, are for p-Persistent CSMA, PSMAC 1, PSMAC 2, and PSMAC 3, respectively.



(a) Analysis

(b) Simulation ($N = 20$)

Fig. 8. Impact of sub-optimal p on the PSMAC performance.

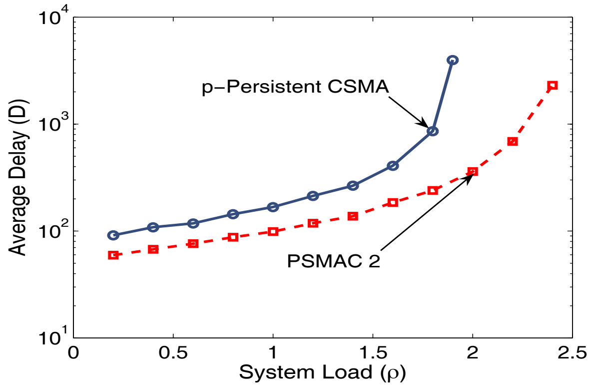


Fig. 9. Average delays of PSMAC 2 in a 25-node multi-hop grid network under the on-off bursty traffic.

There is an over 30% improvement in throughput without any additional hardware requirements. When $\rho = 2.0$, the PSMAC 2 delay is only about 5.9% of the corresponding p-Persistent CSMA delay.

V. Related Work

Efficient MAC schemes have been the subject of intensive research for years. There have been a large number of MAC schemes proposed in the literature for wired and wireless networks, such as ALOHA, Slotted ALOHA, CSMA, and CSMA/CA. This research regained considerable interest recently, largely due to the successful adoption of the IEEE 802.11 protocols [13], [24] and Bluetooth [7] for wireless LANs as well as multi-hop wireless networks [1], [2], [4], [5], [14]–[20], [25], [26]. To the best of our knowledge, none of the schemes use a gated or exhaustive service for a winning node. Using such polling services is analogous to the move from Stop-and-Wait flow control to Go-Back-N: by allowing a larger transmission window, a higher throughput can be achieved.

The master-driven architecture of Bluetooth piconets provides an ideal setting for applying polling-based scheduling. In fact, polling is adopted in Bluetooth piconets for access control, although the actual scheduling policy has not been prescribed in the current standard [7], [25]. In addition, a polling mechanism has been incorporated in the recent IEEE 802.11e Hybrid Coordination Function (HCF) [24].

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In the HCF Controlled Channel Access (HCCA) mode, the hybrid coordinator (HC) (co-located with the QoS Access Point (QAP)) controls the polling mechanism, which assigns transmission opportunities (TXOP) to QoS enhanced stations (QSTA). A TXOP is a bounded time interval in which a QSTA is allowed to transmit one or more frames. Again, the scheduling policy (i.e., how many slots to assign) is not specified. In both cases, a centralized controller is required to poll the secondary nodes, which is different from the random access and fully distributed approach taken in this research.

An analysis is presented in [1] on the throughput and delay performance bounds for the IEEE 802.11 protocols, which provides a motivation for reducing control overhead in IEEE 802.11-like wireless networks (see Section I). In two recent papers [16], [17], the authors analyze the split channel MAC schemes that are based on the RTS/CTS dialogue, and use the pure-ALOHA or p-Persistent CSMA for contention resolution. The shared channel is split, either in time or frequency, into multiple channels: one is used for control and the rest for data. Note that limited-1 service is used in [16], [17]. As discussed, our scheme can be adapted to the multi-channel case for improved performance.

VI. Conclusions

In this paper, we presented three polling service-based MAC schemes (termed PSMAC) for reducing control overhead and achieving performance gains. We presented analytical and simulation studies of a p-Persistent CSMA reservation-based scheme and the three proposed schemes, under various traffic models. The proposed PSMAC schemes achieve significant gains on throughput, delay, and energy consumption over p-Persistent CSMA. In addition, we found that PSMAC can effectively handle the more general and challenging bursty traffic. Our simulation results also show that due to the high efficiency of the proposed schemes, such performance gains can be achieved without hurting the fairness performance.

In addition to an extension to multi-channel wireless networks, security is also an important topic for future work. We consider the following two cases. First, an attacker does not follow the MAC protocol but keeps on sending at a high load. Such attackers can be treated as jammer and can be detected and removed. Second, an attacker follows the PSMAC protocol but keeps on transmitting at a high load. Exhaustive service-based schemes will be susceptible to this type of attacks since a malicious node can take the channel forever. However, the gated service PSMACs are less vulnerable to such an attack. Also a limited-k PSMAC, which enforces a limit on the maximum number of frames transmitted per polling service of a queue, may provide a trade-off between robustness and efficiency. Since both are general attacks on WLANs, we conjecture that existing schemes or extensions can be adopted to secure a PSMAC network and will study these issues in our future work.

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