

# Traffic-adaptive, Flow-specific Medium Access Control for Wireless Networks

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**Abstract**—In this paper, we formally introduce the novel concept of traffic-adaptive, flow-specific medium access control and show that it outperforms contention, non-contention and hybrid medium access schemes. A traffic-adaptive, flow-specific mechanism is proposed that utilizes flow-specific queue size statistics to select between medium access modes. A general model for traffic-adaptive, flow-specific medium access control is developed and it is shown that hybrid medium access as well as traditional contention-based and non-contention schemes can be seen as special cases of the more general flow-specific access. The proposed traffic-adaptive, flow-specific mechanism is applied to Cooperative Wireless Sensor Network Medium Access Control (CWS-MAC) to provide representative simulation results.

**Keywords**—wireless; medium access; flow-specific; application-aware; contention; non-contention; hybrid; cross-layer.

## I. INTRODUCTION

Wireless medium access solutions generally fall into two categories: contention-based and scheduled (contention-free). It has been well established that the collision-free approach of scheduled schemes, such as [1], provide high throughput in high demand scenarios at the expense of overhead and packet delay. In comparison, contention-based approaches, such as [2], [3], provide low delay times at low to moderate network loads, but performance begins to degrade rapidly as the network becomes saturated.

Initial work has been done in the wireless sensor network field to combine the benefits of both approaches in response to changing network load. Most notably, [4] provides a contention-based approach that utilizes TDMA framing to provide “hints” for contention resolution. In these types of approaches, though, medium access is tailored to overall network conditions, not to the characteristics of the individual flows.

In [5], we proposed a solution that has the capability to provide medium access on a *per flow* basis. Designed to support both low demand, delay sensitive control traffic and high demand, delay tolerant data traffic, Cooperative Wireless Sensor Medium Access Control (CWS-MAC) is a distributed, fixed, flow-specific, contention and non-contention-based medium access scheme. However, to fully realize the potential performance gains, a flow-specific scheme must be responsive to changes in traffic characteristics within each flow. Accordingly, the primary objective of this work is to present an

adaptive medium access solution that can not only accommodate multiple flows with different traffic characteristics, but also respond to traffic changes *within a given flow*.

The contribution of this paper is three-fold. First, traffic-adaptive, flow-specific medium access control is formally defined and proven to provide better performance than contention-based, non-contention-based and hybrid medium access schemes. Second, a general model for a traffic-adaptive, flow-specific medium access control is developed and contention-based, contention-free as well as hybrid approaches are shown to be special cases of this general flow-specific model. Third, a queue-based, traffic-adaptive, flow-specific medium access control mechanism is proposed and applied to CWS-MAC to provide relevant simulation results.

The organization of this paper is as follows. Section II formally introduces the concept of traffic-adaptive, flow-specific medium access and provides a proof of its performance advantage over existing approaches. In Section III, a queue-based, traffic-adaptive, flow-specific mechanism is proposed and a general model for a traffic-adaptive, flow-specific medium access control is developed. Section IV applies this proposed mechanism to the CWS-MAC protocol and presents accompanying simulation results.

## II. TRAFFIC-ADAPTIVE, FLOW-SPECIFIC MEDIUM ACCESS

We first formally define the terms flow-specific medium access and traffic-adaptive, flow-specific medium access and provide an example to illustrate the concept and compare its performance to that of existing approaches.

**Definition:** Flow-specific medium access control is a medium access approach that provides medium access on a per flow basis. It is capable of simultaneously providing different medium access schemes to different traffic flows.

**Definition:** Traffic adaptive, flow-specific medium access control is a flow-specific medium access approach that is capable of dynamically switching between multiple medium access schemes to respond to traffic variations within a given flow.

As an illustrative example, we examine an aggregate flow that is comprised of two individual packet flows. We assume that the load of the first flow is low while the load of the

second flow varies from low to high. The aggregate flow demand, then, will vary with the second flow. This example models the behavior of an event-based wireless sensor network that includes both a control flow to provide sensor coordination within the network and a data flow that corresponds to sensor data transmission to a designated sink. Prior to event detection, the demand of both flows is low (perhaps in a periodic reporting state). Upon event detection, the control flow remains relatively low demand (control packets are small in size and are only needed periodically to update sensor parameters) while the data flow will increase dramatically as recorded event data is forwarded to the sink.

In this example, contention-based [2],[3] and non-contention-based [7] schemes will treat the flows in aggregate and provide either contention-based or non-contention-based access to this combined flow. A traffic-adaptive, hybrid scheme [4] will again treat the flows together, but will transition from contention-based to non-contention-based medium access when the demand of the aggregate flow reaches some threshold. In contrast, a traffic-adaptive, flow-specific approach will treat the two flows individually by continuing to provide contention-based medium access to the low demand control flow while the data flow is transitioned from contention-based to non-contention-based access as its load increases.

Defining the aggregate delay performance as the weighted sum of the delay performance for the individual flows, we can evaluate and compare the delay performance of the different approaches for this two-flow example [3],[4],[7]. In Figure 1, we plot the mean aggregate packet delay as a function of aggregate load for the four approaches. The normalized load of the first flow is fixed at 0.1 while the load of the second flow is allowed to vary from 0.0 to 0.8. We can clearly see that while the hybrid approach takes advantage of the lower delays of CSMA in the low contention region and TDMA in the high contention region, the traffic-adaptive, flow-specific approach offers better overall delay performance in the high contention region by allowing the low demand control flow to remain in the contention-based mode.

Figure 1 illustrates the advantage of a traffic-adaptive, flow-specific approach in this particular example. In the following theorem and associated corollary, we extend this to the general case and show that the traffic-adaptive, flow-

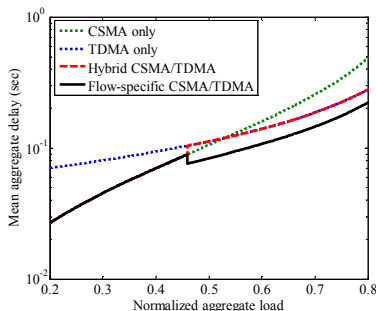


Figure 1. Packet delay plotted as a function of normalized load for slotted nonpersistent CSMA [3], TDMA [7], hybrid and flow-specific medium access (using CSMA/TDMA). Channel rate is 1 Mbps, packet size is 1000 bits, there are 100 slots in a TDMA frame (each slot is one packet length in duration) and  $\alpha = 0.01$  for the CSMA schemes. CSMA plot assumes steady state.

specific approach outperforms contention, non-contention and aggregate hybrid medium access schemes provided that the per flow switchover point between the access modes is chosen correctly.

**Theorem:** Given a suitable switching point is chosen at which a flow will transition between medium access schemes, flow-specific medium access will provide as good or better delay performance than contention, non-contention, and hybrid medium access schemes.

*Proof:* First, let us consider the case of the contention-based medium access scheme. Without a loss of generality, we will assume that the mean packet delays  $D_i$  for the  $N$  individual flows  $i$  are ordered as in  $D_1 \leq D_2 \leq \dots \leq D_m \leq \dots \leq D_{N-1} \leq D_N$ . The switching point between access schemes is then chosen such that  $D_i^c \leq D_i^{nc}$  for all  $i=1:m$  and  $D_i^c > D_i^{nc}$  for all  $i=(m+1):N$  where  $D_i^c$  is the contention-based access scheme delay for flow  $i$  and  $D_i^{nc}$  is the non-contention-based access scheme delay for flow  $i$ . The mean overall delay can then be shown to be equivalent to

$$D_{flow} = \sum_{i=1}^m \left( \frac{\lambda_i}{\lambda} \right) D_i^c + \sum_{i=m+1}^N \left( \frac{\lambda_i}{\lambda} \right) D_i^{nc} \quad (1)$$

where  $\lambda_i$  is the arrival rate for flow  $i$  and the aggregate arrival rate  $\lambda$  is the sum of the individual flow arrival rates. Using proof by contradiction, suppose the contention-based medium access scheme provides lower aggregate mean delay than the flow-specific scheme or  $D_{flow} > D_{cont}$ . Expanding these,

$$\sum_{i=1}^m \left( \frac{\lambda_i}{\lambda} \right) D_i^c + \sum_{i=m+1}^N \left( \frac{\lambda_i}{\lambda} \right) D_i^{nc} > \sum_{i=1}^N \left( \frac{\lambda_i}{\lambda} \right) D_i^c. \quad (2)$$

This can be shown to imply that  $D_i^c < D_i^{nc}$  for some  $i=(m+1):N$  which contradicts our assumption regarding the switching point. Thus,  $D_{flow} \leq D_{cont}$  and flow-specific medium access will provide as good or better delay performance than a contention-based scheme. The non-contention case is proven in a similar manner. Finally, the hybrid scheme can be considered as either a contention scheme when the aggregate load is below the switching point or a non-contention scheme when it is above. Accordingly, it can be broken into two cases and is proved in a similar manner as well. *Q.E.D.*

Further details for this proof are available in [8].

**Corollary:** Given a suitable switching point is chosen at which a flow will transition between medium access schemes and that there exist at least two flows which are in two different medium access modes, flow-specific medium access will provide better delay performance than contention, non-contention, and hybrid medium access schemes.

*Proof:* This corollary directly follows the theorem since it can be shown that the equality in performance only occurs when  $m$

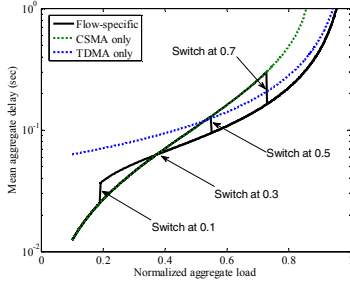


Figure 2. Flow-specific delay plotted against the normalized load and our compared to CSMA and TDMA for various switchover points.

is either 1 or  $N$ . The constraint that there exists at least one flow in each of the contention and non-contention modes implies that  $1 < m < N$  and, therefore, that the delay performance of the traffic-adaptive, flow-specific approach is strictly better than the other schemes.

As can be seen from this discussion, the performance of a traffic-adaptive medium access scheme is tied to the selection of the switching point [4]. Returning to our two flow example, the impact of the selection of the switching point can be plainly seen in Figure 2 where we plot mean aggregate delay versus normalized aggregate load for four different switching points. In the next section, we propose a queue-based, traffic-adaptive mechanism to dynamically implement this switching point.

### III. TRAFFIC-ADAPTIVE, FLOW-SPECIFIC MEDIUM ACCESS MECHANISM

To realize the potential performance gains identified above, we propose a traffic-adaptive, flow-specific mechanism in this section that utilizes flow-specific queue size statistics and develop a general traffic-adaptive, flow-specific medium access control performance model. In the final two subsections, we examine two-flow and single-flow variants in detail and demonstrate that contention, non-contention and hybrid schemes are special cases of the general flow-specific model.

#### A. Traffic-adaptive, flow-specific medium access mechanism

Using queue size as an indicator of flow-specific traffic demand, our traffic-adaptive, flow-specific medium access mechanism operates as follows. As flow load exceeds a predetermined threshold, measured in terms of the flow-specific queue size, the flow is switched from one access mode to another. Each flow (or each set of flows if we choose to group a set of similar flows together) will have its own queue and associated thresholds. These thresholds,  $\theta_{1,f,m}$  and  $\theta_{2,f,m}$ , define the switching point discussed in the previous section and can be unique for each flow  $f$  and medium access mode  $m$  as shown in Figure 3. The single-flow, two-mode (contention and non-contention) case is illustrated in Figure 4. When the queue size exceeds  $\theta_1$ , the appropriate flow is switched from contention-based to non-contention-based medium access. Similarly, when the queue size drops below  $\theta_2$ , the flow is switched from non-contention-based to contention medium access. In the next section, we develop a general model that provides insight into the choice of these thresholds.

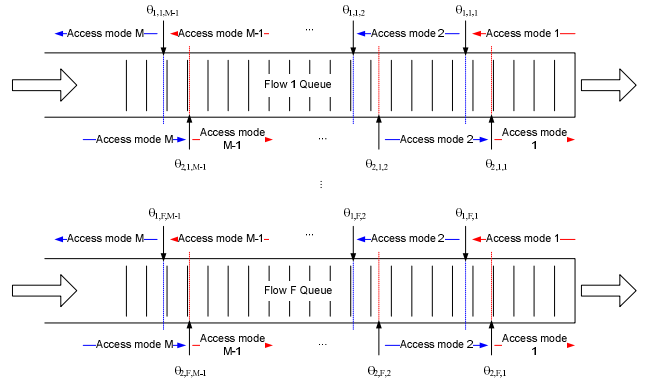


Figure 3. Queue models and associated thresholds for general traffic-adaptive, flow-specific medium access model

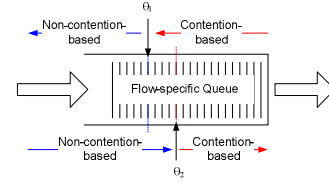


Figure 4. Two-access mode version of the proposed traffic-adaptive, flow-specific mechanism using the flow-specific queue and associated thresholds.

#### B. A general performance model for traffic-adaptive, flow-specific medium access

Traffic-adaptive, flow-specific medium access can be modeled as a finite state machine as shown in Figure 5. Each state is uniquely specified by a vector that reflects the access mode of each flow. The number of states required,  $\Phi$ , is, therefore, a function of the number of flows,  $F$ , and the number of unique medium access modes,  $M$ , as  $\Phi = (M)^F$ . If we assume that the underlying, individual queues are M/M/1, then this finite-state model can be viewed as a hidden Markov model [9]. To determine the steady state probabilities  $\pi_s$  associated with the individual observable states  $s$ , we must first derive the state probabilities of the hidden Markov model and then establish the relationships between these Markov states and the observable states. In the special case where  $\theta_{1,f,m} = \theta_{2,f,m}$  (i.e., a system with no hysteresis), each probability  $\pi_s$  is a function of a unique, non-overlapping set of the underlying Markov state probabilities. With these steady state probabilities, the mean throughput  $S$  and delay  $D$  for the flow-specific medium access scheme can then be developed as

$$S = \sum_{s=1}^{\Phi} \pi_s S_s \text{ and } D = \sum_{s=1}^{\Phi} \pi_s D_s \quad (3)$$

where  $S_s$  and  $D_s$  are the mean throughput and delay, respectively, experienced in state  $s$ .

In general, the medium access scheme for flow  $f$  will transition from one access mode  $m_i$  to the next mode  $m_{i+1}$  when the number of packets in the flow-specific queue

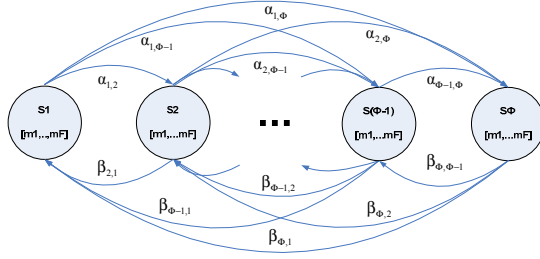


Figure 5. General traffic-adaptive, flow-specific finite-state model.

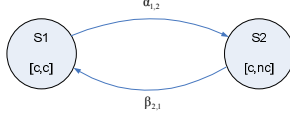


Figure 6. Simplified 2-state model for two-flow, flow-specific, medium access for example of Section II.

exceeds the threshold  $\theta_{1,f,m_i}$  denoted by  $\alpha_{s,s+1}$  in Figure 5. Similarly, the transition from  $s+1$  to  $s$  occurs when the number of packets drops below  $\theta_{2,f,m}$  denoted by  $\beta_{s+1,s}$ . The probability of these transitions is a function of both the number of packets  $N_f$  in the flow-specific queue  $f$  and the utilization in the current observed state. The utilization  $\rho_{m,s,f}$  is unique to the access mode  $m$ , the state  $s$ , and the flow  $f$  and is calculated as [8]

$$\rho_{m,s,f} = \frac{\lambda_f D_{m,s}}{1 + \lambda_f D_{m,s}} \quad (4)$$

where  $\lambda_f$  is the packet arrival rate for flow  $f$  and  $D_{m,s}$  is the mean delay for access mode  $m$  in state  $s$ . In the following section, we will examine this relationship closer for the two-flow, two-mode case and develop both throughput and delay expressions for the example of Section II.

### C. Two-flow, two-mode (contention, non-contention) case

It requires a four-state model to represent a two-flow, flow-specific medium access scheme such as one capable of providing both contention and non-contention access modes. We can make a set of simplifying assumptions to allow us to compare the performance of this traffic-adaptive mechanism to that of the ideal case in the example of Section II. Without a loss of generality, we assume that it is flow 1 that remains in the contention-based access mode. Accordingly,  $\alpha_{1,2}$  and  $\beta_{2,1}$  are the only non-zero transition rates, states S3 and S4 are not achievable and the full model of Figure 5 can be reduced to the two-state model of Figure 6.

Again assuming that the underlying hidden Markov process is M/M/1, the bilevel hysteretic service-rate control work of [10] can be adopted to arrive at steady state probabilities given by [8]

$$\pi_{S2} = \frac{\Delta(\rho_{c,1,2})^{\theta_{2,2}-1}(\rho_{nc,2,2})(1-\rho_{c,1,2})}{(1-(\rho_{c,1,2})^\Delta)(1-\rho_{nc,2,2})} P_0 \quad (5)$$

$$\pi_{S1} = 1 - \pi_{S2}$$

where

$$P_0 = \left( \frac{1}{(1-\rho_{c,1,2})} - \frac{\Delta(\rho_{c,1,2})^{\theta_{2,2}-1}(\rho_{c,1,2} - \rho_{nc,2,2})}{(1-(\rho_{c,1,2})^\Delta)(1-\rho_{nc,2,2})} \right)^{-1} \quad (6)$$

and  $\Delta = \theta_{2,2} - \theta_{1,2}$  is the extent of the hysteresis loop created by  $\theta_{1,2}$  and  $\theta_{2,2}$ . The associated state throughputs and delays are then

$$S_{S1} = S^c \text{ and } S_{S2} = \frac{\lambda_1}{\lambda} S_1^c + \frac{\lambda_2}{\lambda} S_2^{nc} \quad (7)$$

$$D_{S1} = D^c \text{ and } D_{S2} = \frac{\lambda_1}{\lambda} D_1^c + \frac{\lambda_2}{\lambda} D_2^{nc}$$

where  $S^c$  and  $D^c$  are the throughput and delay, respectively, of the aggregate flow in the contention mode. Substituting (5) and (7) into (3), we can then develop the resulting aggregate mean throughput and delay expressions. This analysis can be extended to the two-flow,  $M$ -mode case with  $M > 2$  using the more general variable service rate work of [11]. Details are again available in [8].

Using the parameters of the example in Section II, we plot mean aggregate delay as a function of normalized load in Figure 7 for  $\theta_1 = 20$  and  $\theta_2 = 5$ . It can be seen that, as expected, the flow-specific scheme performs as well as CSMA when the aggregate load is low and outperforms all three approaches when a flow exists in both the contention and non-contention modes. The role of  $\theta_1$  as the switching point can be clearly seen in Figure 8 where we plot both delay and throughput as a function of load for various values of  $\theta_1$ . At the optimum value for  $\theta_1$  (close to 20 packets in this example), the mechanism transitions to contention-free operation as the delay curves intersect. At values below optimum, the scheme transitions too early and the aggregate delay at low loads suffers. For values of  $\theta_1$  above optimum, the scheme transitions late and the heavy load begins to overwhelm the contention-based mode, the delay grows and the throughput saturates (and will eventually drop off).

### D. Single-flow, two-mode case: Hybrid medium access

The model of Figure 6 can be further simplified if we examine the single-flow case. This case can be shown to be equivalent to the hybrid case where multiple flows are treated in aggregation. Thus, hybrid approaches represent a special case of the more general flow-specific approach. To demonstrate this, we note that there is a single, aggregate queue in a hybrid scheme, so  $\theta_{1,2}$  and  $\theta_{2,2}$  reduce to  $\theta_1$  and  $\theta_2$ ,

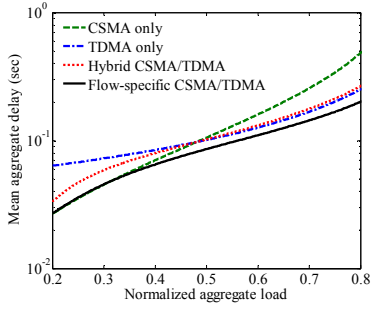


Figure 7. Packet delay plotted as a function of normalized load for slotted nonpersistent CSMA, TDMA, hybrid using CSMA/TDMA and flow-specific medium access using CSMA/TDMA with  $\theta_1 = 20$  and  $\theta_2 = 5$ .

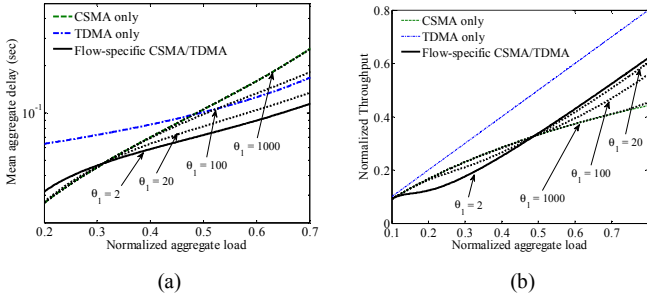


Figure 8. Mean aggregate (a) delay and (b) throughput plotted as a function of the normalized aggregate load for multiple values of  $\theta_1$ .

respectively, and  $\rho_{c,1,2}$  and  $\rho_{nc,2,2}$  reduce to  $\rho_c$  and  $\rho_{nc}$ , respectively. Since  $S_1$  and  $S_2$  are equivalent to  $S^c$  and  $S^{nc}$ , respectively, and  $D_1$  and  $D_2$  are equivalent to  $D^c$  and  $D^{nc}$ , respectively, the overall mean throughput is  $S = \pi_c S^c + \pi_{nc} S^{nc}$  and delay is  $D = \pi_c D^c + \pi_{nc} D^{nc}$ . Furthermore, it is straightforward to show that the contention only [2],[3] and non-contention [7] schemes are trivial single-flow, single-mode cases of the general flow-specific model. Details are again available in [8].

#### IV. SIMULATION RESULTS

To generate a set of representative simulations, we apply the proposed flow-specific, traffic-adaptive mechanism to CWS-MAC [5], a fixed, flow-specific medium access scheme. We begin with an overview of the basic CWS-MAC protocol and then provide OPNET simulation results.

##### A. CWS-MAC

An overview of the CWS-MAC mechanism is provided in Figure 9 and parameters include the slot size,  $t_s$ , the minislot size,  $t_{ms}$ , the number of minislots,  $k$ , and the lengths of the control beacon,  $t_b$ , and interframe space,  $t_{IFS}$ . The underlying non-contention-based medium access mechanism is provided by a TDMA scheme in which nodes are assigned slots for transmission of their non-contention flow packets. The contention-based medium access mechanism is superimposed on top of the TDMA framing through the use of an interframe space and a contention beacon that effectively give the

contention-based flow global (across node) priority over the non-contention-based flow. A node with contention flow packets to transmit signals its intent to seize the current TDMA slot by transmitting a contention beacon. A node with non-contention packets to transmit must wait for the duration of the interframe space and then sense the medium. If the medium is free (i.e., no contention beacon has been transmitted in its two-hop neighborhood), the node may transmit its non-contention packets. If a beacon is detected, the slot owner defers and the slot is effectively seized as a contention slot. To ensure the non-contention flow is not “choked off,” a portion of the original TDMA slot is set aside for use by the slot owner for non-contention packet transmission. To reduce collisions among competing nodes with contention-based traffic to transmit within the two-hop neighborhood, the contention slot is subdivided into a series of transmission minislots. Using a version of slotted ALOHA [6], a node will transmit in a minislot with some predetermined probability (calculated as the inverse of the number of minislots in [5]) and an acknowledgement mechanism is included to recover from collisions.

##### B. Simulation results for traffic-adaptive CWS-MAC

In this section, simulation results using the OPNET Modeler suite are provided to demonstrate the effectiveness of the traffic-adaptive, flow-specific scheme. For the simulations, flow 1 load is kept steady at 800 bits/sec (8 packets/sec with a packet size of 100 bits). Flow 2 load is ramped up from zero to a maximum of the channel data rate of 1 Mbps (using a packet size of 1000 bits). Flow 1 represents the fixed rate control flow in the example of Section II, while flow 2 represents the variable data flow. In both cases, the packet size is constant and the packet interarrival times are exponentially distributed. The results were generated with a neighborhood size of 8 nodes where each node is assigned a single slot, a slot size of 0.1 s, a minislot size of 1 ms, a control beacon length of 1 ms, an interframe space of 0.1 ms, and 50 minislots per time slot. The transmission probability in each minislot was chosen as the inverse of the size of the neighborhood. The plotted results are based on Monte Carlo simulations averaged across 100 runs.

End-to-end delay and normalized throughput for both flows are presented in Figures 10(a) and 10(b), respectively. With  $\theta_1 = 3$  close to optimum, it can be seen that the scheme transitions flow 2 from contention-based to contention-free access as the contention-based mode becomes saturated and the

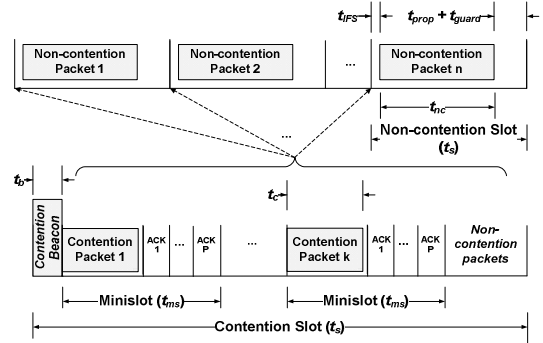


Figure 9. An overview of CWS-MAC mechanism and frames.



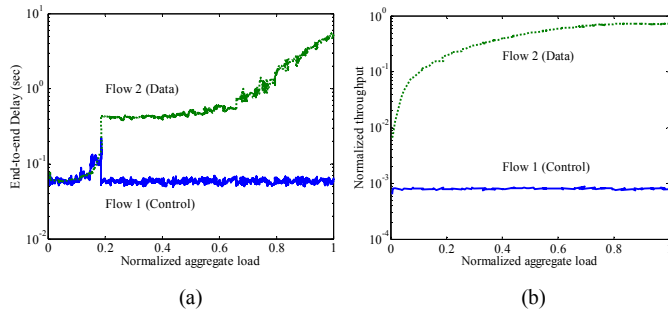


Figure 10. (a) End-to-end delay and (b) normalized throughput for flow 1 (control) and flow 2 (data) plotted against normalized aggregate load ( $\theta_1 = 3$ ).

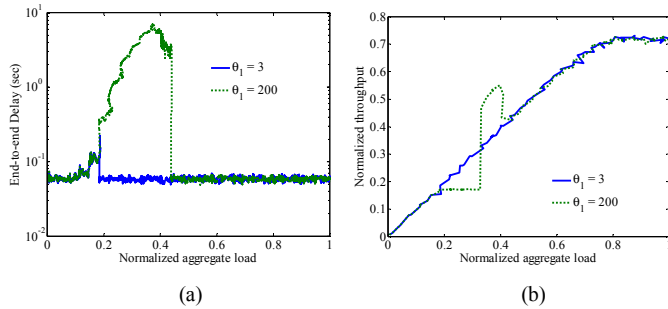


Figure 11. (a) Flow 1 end-to-end delay plotted as a function of normalized aggregate load for  $\theta_1 = 3$  and  $\theta_1 = 200$ . (b) Flow 2 throughput plotted as a function of normalized aggregate load for  $\theta_1 = 3$  and  $\theta_1 = 200$ .

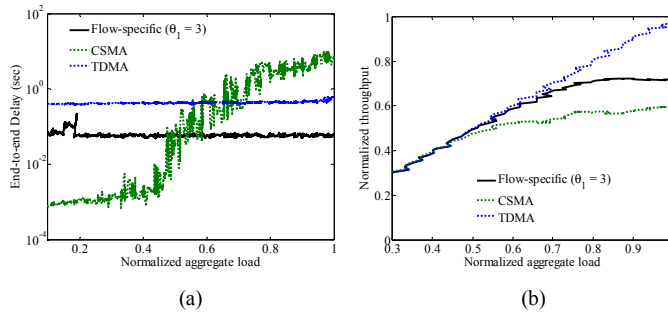


Figure 12. (a) Flow 1 end-to-end delay and (b) flow 2 throughput compared to CSMA and TDMA for  $\theta_1 = 3$ .

end-to-end packet delay begins to rise. This transition protects the delay bound on flow 1 while providing higher throughput for the heavy load of flow 2. In Figures 11(a) and 11(b), we can compare the performance of different values of  $\theta_1$  by taking a closer look at the delay of flow 1 and the throughput of flow 2. For the non-optimum choice of  $\theta_1 = 200$ , we see that the contention-based mode become saturated prior to transition and the flow 1 delay in Figure 11(a) rises sharply while the flow 2 throughput in Figure 11(b) levels off. Figures 12(a) and 12(b) provide a comparison of the flow-specific end-to-end delay and throughput to that of CSMA and TDMA, respectively. It can be seen that the delay of flow 1 at low loads is better than TDMA while the throughput of flow 2 at high loads is better than CSMA. The CSMA results provided represent best case delay performance as they assume head-of-the-queue privilege for flow 1 and do not include an acknowledgment mechanism.

## V. CONCLUSIONS

In this paper, we formally introduced the concept of traffic-adaptive, flow-specific medium access and showed that, given a suitable switching point, it outperforms traditional contention, non-contention, and hybrid medium access schemes. We proposed a queue-based, traffic-adaptive mechanism and developed a general performance model for traffic-adaptive, flow-specific medium access. We demonstrated that the contention, non-contention, and hybrid approaches are special cases of this general medium access model. Finally, we applied the traffic-adaptive mechanism to CWS-MAC, a fixed, flow-specific medium access scheme and provided simulation results that validated the effectiveness of the traffic-adaptive, flow-specific approach.

## REFERENCES

- [1] V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, "Energy-efficient, collision-free medium access control for wireless sensor networks," *Wireless. Networks*, vol. 12, no. 1, pp. 63-78, Feb. 2006.
- [2] N. Abramson, "The Aloha system - Another alternative for computer communications," *Proc. of the AFIPS Fall Joint Comp. Conf.*, 1970, vol. 37, pp. 281-285.
- [3] L. Kleinrock, and F. Tobagi, "Packet switching in radio channels: Part I - Carrier sense multiple-access modes and their throughput-delay characteristics," *IEEE Trans. on Commun.*, vol. 23, no. 12, pp. 1400-1416, Dec. 1975.
- [4] I. Rhee, A. Warrier, M. Aia, and J. Min, "Z-MAC: A hybrid MAC for wireless sensor networks," *Proc. of the 3rd Intl Conf. on Embedded Networked Sensor Systems*, San Diego, California, Nov. 2005, pp. 90-101.
- [5] T. O. Walker, M. Tummala, and J. McEachen, "Distributed, flow-based priority medium access control for cooperative multihop wireless sensor networks," *Proc. of the 41st Ann. Hawaii Intl. Conf. on System Sciences*, Hawaii, Jan. 2008.
- [6] L.G. Roberts, "ALOHA packet system with and without slots and capture," *Comp. Commun. Review*, vol. 5, pp. 28-42, Apr. 1975.
- [7] S. Lam, "Delay analysis of a time division multiple Access (TDMA) channel," *IEEE Trans. on Commun.*, vol. 25, no. 12, pp. 1489-1494, Dec. 1977.
- [8] T. O. Walker, M. Tummala, and J. McEachen, "Traffic-adaptive, flow-specific medium access for wireless networks," Naval Postgraduate School, Monterey, CA, Tech. Rep., in draft.
- [9] H. Stark and J. W. Woods, *Probability and Random Processes with Applications to Signal Processing (Third Edition)*. Upper Saddle River, NJ: Prentice Hall, 2002.
- [10] R. F. Gebhard, "A queueing process with bilevel hysteretic service-rate control," *Naval Res. Log. Quart.*, vol. 14, pp. 55-68, 1967.
- [11] M. Yadin and P. Naor, "On queueing systems with variable service capacities," *Naval Res. Log. Quart.*, vol. 14, pp. 43-54, 1967.
- [12] C. Zhu and M. S. Corson, "A five-phase reservation protocol (FPRP) for mobile ad hoc networks," *Proc. of 17th Ann. Joint Conf. of the IEEE Comp. and Commun. Societies*, Mar. 1998, pp. 322-331.
- [13] S. Parthasarathy and R. Gandhi, "Distributed algorithms for coloring and domination in wireless ad hoc networks," *Proc. Conf. on Foundations of Software Tech. and Theoretical Comp. Science*, Dec 2004, pp. 447-459.
- [14] I. Rhee, A. Warrier, J. Min and L. Xu, "DRAND: Distributed randomized TDMA scheduling for wireless ad-hoc networks," *Proc. of the 7th ACM Intl. Symp. on Mobile Ad Hoc Networking and Computing*, Florence, Italy, May 2006, pp. 190-201.