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LETTER: MOBILE NETWORKS

Carrier Sense Adaptation with Enhanced Fairness in IEEE 802.15.4 WPAN

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ABSTRACT

We propose an adaptive carrier sense (CS) scheme with enhanced fairness based on an observation that the conventional adaptive CS mechanism may lead to significant unfairness. Our experimental study with an IEEE 802.15.4 WPAN testbed shows that the proposed algorithm significantly improves fairness compared to the conventional mechanism while providing competitive throughput performance. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
physical carrier sense; 802.15.4 WPAN; fairness; localized algorithm

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1. INTRODUCTION

Physical carrier sense is one of fundamental mechanisms that determine network performance in carrier sense multiple access (CSMA) wireless networks. Carrier sensing is typically implemented by using a carrier sense (CS) threshold. If the received signal strength at a node exceeds the CS threshold, the wireless channel is considered to be busy, and the transmission of the node is deferred until the wireless channel becomes idle. Consequently, if the CS threshold is set large, a node's transmission may be interfered with transmissions from other nodes due to the hidden terminal problem. On the other hand, if the CS threshold is set small, the node attempts to transmit in a conservative manner, which degrades throughput performance, known as the exposed terminal problem. Hence, how to choose an appropriate value for the CS threshold in order to balance these two problems is of critical importance for network performance.

Recently, a number of studies on tuning the CS threshold have been carried out [1–5]. These studies typically aim to enhance the spatial reuse for improving the network throughput while maintaining a specific metric, such as the packet error rate (PER) or signal-to-interference-plus-noise-ratio (SINR), around at a certain level. For example, the algorithm in [3] adjusts the CS threshold according to the PER measured at each sender. Meanwhile, the algorithm in [1] introduces an SINR feedback mechanism and the sender adapts its CS threshold depending on the SINR information. More recently, a non-cooperative game theoretic approach for adapting the CS threshold has been proposed in [5]. However, in these existing adaptation schemes, each node adjusts its CS threshold by considering its own performance metric, which may lead to significant throughput unfairness among nodes.†

In this letter, we design an adaptive CS mechanism with enhanced fairness in an analytical manner. First, we propose an adaptive CS algorithm by taking account of the CS threshold of neighbor nodes for enhancing fairness. Then, we derive a sufficient condition on the convergence of the proposed algorithm. We implement our algorithm in an IEEE 802.15.4 WPAN testbed and empirically validate its performance. Our experimental study shows that the proposed algorithm significantly improves fairness compared to the conventional adaptive CS algorithm while

†An exception is the heuristic algorithm in [4], which takes account of the fairness among neighbor nodes. However, only preliminary experimental study without analysis was carried out in [4].

maintaining the competitive throughput improvement over the standard IEEE 802.15.4 MAC.

2. UNFAIRNESS OF THE CONVENTIONAL ADAPTIVE CARRIER SENSE MECHANISM

As an illustrative example, we implement a PER-based CS adaptation scheme in Reference [3] and perform an experiment with our testbed in Figure 2(a) and the 6-pair topology in Figure 2(b). Note that a detailed description on the testbed configuration is given in Section V. The adaptation rule for the conventional PER-based scheme can be described as follows:

$$x_i(t+1) = \begin{cases} \max(x_i(t)-\delta, x_{min}), & \text{if} q_i > q^t_{max} \\ \min(x_i(t)+\delta, x_{max}), & \text{if} q_i < q^t_{min} \\ x_i(t), & \text{otherwise}, \end{cases} \quad (1)$$

where x_i is the CS threshold of node i, x_{min} and x_{max} are the minimum/maximum CS thresholds, q_i is the PER measured by node i, q^t_{min} and q^t_{max} are the target minimum/maximum PERs, and δ is the step size.

As shown in Figure 1, the CS thresholds of node 19 and 27 saturate to $x_{\max}$ (= −45 dBm) while those of others to $x_{\min}$ (= −98 dBm), which can be explained as follows: Once the thresholds of certain nodes become large, those nodes occupy the wireless channel excessively, and other nodes gradually lose their channel access opportunities. Eventually, their CS thresholds converge to $x_{\min}$, resulting in severe throughput unfairness. In summary, the conventional PER-based CS adaptation mechanism may lead to severe throughput unfairness while improving the aggregate network throughput by sacrificing the throughput of certain nodes. Consequently, it is of critical importance to develop an adaptive CS mechanism with enhanced fairness.

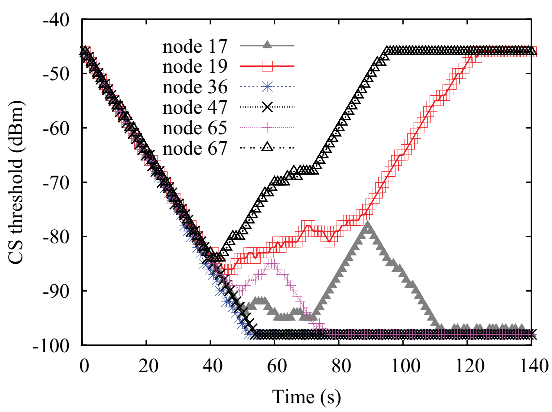

Figure 1. Time traces of the CS threshold for the PER-based adaptive mechanism [4].

3. NETWORK MODEL

Consider a CSMA-based WPAN of N nodes, denoted by $\mathcal{N} = \{1, \cdots, N\}$. For a given node $i \in \mathcal{N}$, let $r(i) \in \mathcal{N}$ denote the corresponding receiver. Let P_i denote the transmit power of node i, then the received power at $r(i)$ can be expressed as $P_{r(i)} = G_{r(i),i}F_{r(i),i}P_i$, where $G_{r(i),i}$ and $F_{r(i),i}$ respectively represent the path loss and the Rayleigh fading from sender i to receiver $r(i)$, which is a widely used model for wireless channel environments [6]. Let τ_i denote the channel access probability of node i. As the magnitude of Rayleigh fading, $F_{r(i),i}$ is independent across nodes, and is exponentially distributed with unit mean. Here, we assume that the interference from other senders is much larger than the ambient noise, and thus do not take into account the noise in our analysis.

As a necessary condition for receiver $r(i)$ to correctly decode the symbols, we introduce a receive sensitivity constraint that the expected value of $P_{r(i)}$ is larger than or equal to the receive sensitivity of $r(i)$, denoted by $\gamma_{r(i)}$, i.e.,

$$\mathbb{E}[P_{r(i)}] = G_{r(i),i}P_i \geq \gamma_{r(i)}. \quad (2)$$

Furthermore, for a successful transmission, the received power $P_{r(i)}$ should be large enough so that the interference from other nodes does not prevent the receiver from correctly decoding the symbols of node i. This condition can be usually expressed as

$$\text{SINR}_{r(i)} = \frac{P_{r(i)}}{I_{r(i)}} \geq \beta_{r(i)}, \quad (3)$$

where $I_{r(i)} = \sum_{j \neq i} G_{r(i),j}F_{r(i),j}P_j$, and $\beta_{r(i)}$ is called the SINR threshold of receiver $r(i)$.

Let x_i denote the CS threshold of node i. If the signal strength perceived at node i is larger/smaller than x_i, the channel is considered busy/idle by node i. For a given node i, let $S_i(x_i)$ denote the carrier sense set of node i, which is defined as $S_i(x_i) = \{j | G_{i,j}F_{i,j}P_j \geq x_i\}$. Hence, node i will be silenced if any node in $S_i(x_i)$ transmits. In a similar manner, let L_i denote the silence set of node i, which is defined as $L_i = \{j | G_{j,i}F_{j,i}P_i \geq x_j\}$. Thus, every node $j \in L_i$ will be silenced when node i transmits.

4. ADAPTIVE CARRIER SENSE WITH ENHANCED FAIRNESS

4.1. Algorithm Description

We propose an adaptive CS update scheme with enhanced fairness. The proposed algorithm consists of two steps: First, each node calculates its CS threshold in order to iteratively minimize its cost function (which will be defined later in this section). Second, in order to prevent severe unfairness among nodes, the actual CS threshold of each node in the next iteration is computed as a weighted sum of the value obtained in the first step and the average CS threshold of neighbor nodes.

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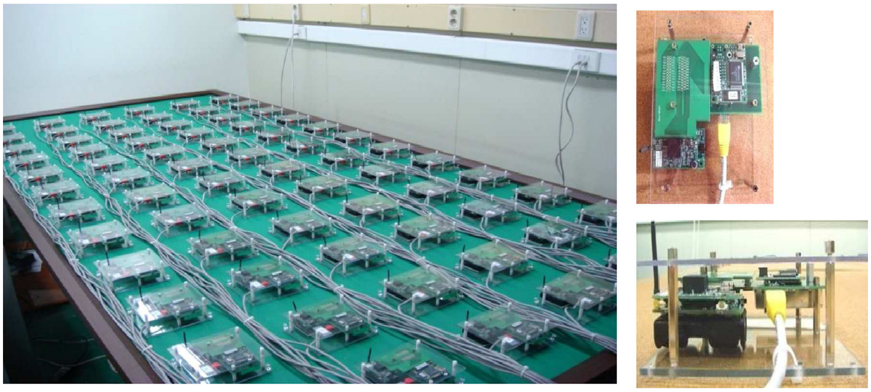
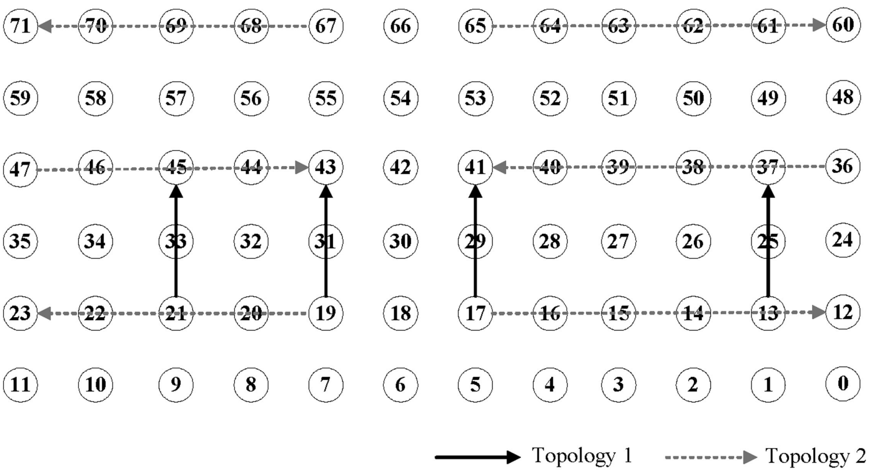


(a) IEEE 802.15.4 WPAN platform.



(b) Illustration of experimental topologies.

Figure 2. IEEE 802.15.4 WPAN testbed and the experimental topologies. (a) IEEE 802.15.4 WPAN platform. (b) Illustration of experimental topologies.

For each node i, increase in its CS threshold x_i will result in increased interference to its neighbors because, with increased x_i, node i will access the channel more frequently by caring less for other nodes. Hence, it is reasonable to impose a penalty to node i for increasing its CS threshold. We adopt a quadratic pricing function $P_i(x_i) = v_i x_i^2/2$ for each node i, which is twice continuously differentiable, increasing and uniformly strictly convex in x_i.[‡]

Furthermore, we introduce a utility function $U_i(x_i, \mathbf{x}_{-i}) := \int_{x_{min}}^{x_i} [q_i^t - q_i(\xi, \mathbf{x}_{-i})] d\xi$ based on a target PER q_i^t for each node i, where $\mathbf{x}_{-i} := (x_1, \cdots, x_{i-1}, x_{i+1}, \cdots, x_N)$. With the above utility function $U_i(\mathbf{x})$, we have $\partial U_i(\mathbf{x})/\partial x_i = q_i^t - q_i(\mathbf{x})$ and $\partial^2 U_i(\mathbf{x})/\partial x_i^2 = -\partial q_i(\mathbf{x})/\partial x_i < 0$ because $q_i(\mathbf{x})$ is increasing in x_i for given $\mathbf{x}_{-i}$. Thus, for given $\mathbf{x}_{-i}$, $U_i(x_i, \mathbf{x}_{-i})$ is concave in x_i and attains its maximum when $q_i = q_i^t$. Hence, by maximizing $U_i(\mathbf{x})$, the PER of node i can be maintained around the target PER of q_i^t.

With the above definitions of the pricing function P_i and the utility function U_i, a reasonable control algorithm for the CS threshold should make each node i try to minimize its penalty P_i while maximizing its utility U_i. Hence, if we adopt $J_i(x_i, \mathbf{x}_{-i}) := P_i(x_i) - U_i(\mathbf{x})$ as the overall cost function of node i, each node needs to solve the following minimization problem:

$$\min_{x_i \in [x_{min}, x_{max}]} J_i(x_i, \mathbf{x}_{-i}), \forall i \in \mathcal{N}. \tag{4}$$

Now, consider the following discrete-time update algorithm:

$$\begin{aligned} y_i(t+1) &= x_i(t) - \lambda_i \frac{\partial J_i(\mathbf{x})}{\partial x_i} \\ &= x_i(t) - \lambda_i \left[v_i x_i - \left(q_i^t - q_i(\mathbf{x}) \right) \right], \end{aligned} \tag{5}$$

[‡]Since the relation between the pricing function and network performance is very complex, it is generally difficult to find an optimal pricing function. Thus, we adopt a quadratic pricing function parameterized by v_i. The choice of other structures is a subject of future work.

where $t = 1, 2, \cdots$ denotes the update time instant, and λ_i is the step size. If we let $y_i(t+1) \equiv x_i(t+1)$, the algorithm (5) will correspond to a gradient update algorithm for solving (4), which might be sufficient for improving the overall network throughput over the standard CSMA. However, (5) lacks a consideration on fairness among nodes. Hence, in order to enhance the fairness performance, we introduce an additional step of taking a weighted sum of the average CS threshold of neighbors. First, for every update interval of T, each sender broadcasts its current CS threshold to neighboring nodes, and then computes the average value of neighbors' CS thresholds as follows:

$$x_{-i}^{avg}(t) = \frac{\sum_{j \in \mathcal{N}_i} x_j(t)}{|\mathcal{N}_i|}, \quad (6)$$

where $\mathcal{N}_i$ is the set of node i's neighbors that broadcast their CS threshold for the time interval of $[tT, (t+1)T)$. Finally, the CS threshold x_i is updated as a weighted sum of y_i in (5) and x_{-i}^{avg} in (6) as follows:

$$x_i(t+1) = \alpha y_i(t+1) + (1-\alpha) x_{-i}^{avg}(t), \quad (7)$$

where α is the weight factor ($0 < \alpha \leq 1$). The overall update algorithm for the CS threshold is described in Algorithm 1.

Algorithm 1 Proposed algorithm for adapting the carrier sense threshold with enhanced fairness.

Reset timer t
$N_t \leftarrow 0$ and $N_f \leftarrow 0$
Initialize $\mathcal{N}_i$ as an empty array

while $t < T$ **do**
  if node i transmits **then**
    $N_t \leftarrow N_t + 1$
    if transmission fails **then**
      $N_f \leftarrow N_f + 1$
    end if
  end if

  //j: node i's neighboring node
  if j not in the array $\mathcal{N}_i$ **then**
    append (j, x_j) to array $\mathcal{N}_i$
  end if
end while

$q_i \leftarrow N_f / N_t$
$x_{-i}^{avg} \leftarrow \sum_{j \in \mathcal{N}_i} x_j / |\mathcal{N}_i|$
$y_i \leftarrow x_i - \lambda_i \left[v_i x_i - \left(q_i^t - q_i \right) \right]$
$x_i \leftarrow \alpha y_i + (1-\alpha)\, x_{-i}^{avg}$

4.2. Convergence of the Proposed Algorithm

Now, we derive a sufficient condition on the convergence of the proposed algorithm as follows:

Proposition 1 *Algorithm* 1 *converges if*

$$\lambda_i < \frac{e(1-\tau_{max})x_{min}}{e(1-\tau_{max})v_{max}x_{min} + K\tau_{max}|\mathcal{N}_i|},$$

$$v_i > \frac{K\tau_{max}|\mathcal{N}_i|}{ex_{min}}, \forall i \in \mathcal{N},$$

where $v_{max} := \max_i v_i$, $\tau_{max} := \max_i \tau_i$, $K = \ln(1 + \beta_{max} P_{max}/\gamma_{min})$, $\beta_{max} = \max_i \beta_{r(i)}$, $\gamma_{min} = \min_i \gamma_{r(i)}$, and $\mathrm{P}_{\max}$ is the maximum transmit power.

Proof. By incorporating (5) and (6) with (7), we have

$$\begin{aligned} x_i(t+1) &= \alpha \left[x_i(t) - \lambda_i \frac{\partial J_i(\mathbf{x})}{\partial x_i} \right] + \frac{(1-\alpha)\sum_{j \in \mathcal{N}_i} x_j(t)}{|\mathcal{N}_i|} \\ &= x_i(t) - \lambda_i f_i(\mathbf{x}), \forall i \in \mathcal{N}, \end{aligned} \quad (8)$$

where $f_i(\mathbf{x}) := \alpha \partial J_i(\mathbf{x})/\partial x_i + (1-\alpha)(x_i(t) - \sum_{j \in \mathcal{N}_i} x_j(t)/|\mathcal{N}_i|)/\lambda_i$. Now, we use the result in [7,Proposition 1.11 p. 194] to prove the convergence of (8). First, we derive a sufficient condition on the step size λ_i. For the convergence of (8), λ_i should satisfy $0 < \lambda_i < 1/M$ where M is a positive constant such that $\partial f_i(\mathbf{x})/\partial x_i \leq M$, $\forall x, i$. With some algebraic manipulation, an equivalent condition can be easily obtained as $0 < \lambda_i < 1/M'$, where M' is a positive constant such that $\partial^2 J_i(\mathbf{x})/\partial x_i^2 \leq M'$, $\forall x, i$. Let $q_i(\mathbf{x})$ denote the collision probability of node i. Then, we have $q_i(\mathbf{x}) = P\left[P_{r(i)} / \sum_{k \in \Gamma_i(\mathbf{x})} G_{r(i),k} P_k F_k < \beta_{r(i)} \right]$, where $\Gamma_i(\mathbf{x})$ denotes the set of nodes that concurrently transmits with node i. A node concurrently transmits with node i either if its transmission has been sensed by node i or if it has not sensed node i's transmission and attempts to transmit. Hence, by using the outage probability expression in [8] and bounding $G_{r(i),i} P_i$ by (2), after some algebraic manipulation, we can obtain an upper bound for $\partial q_i(\mathbf{x})/\partial x_i$ as follows.

$$\frac{\partial q_i(\mathbf{x})}{\partial x_i} \leq \frac{K\tau_{max}|\mathcal{N}_i|}{e(1-\tau_{max})x_{min}}, \quad (9)$$

where $K = \ln(1 + \beta_{max} P_{max}/\gamma_{min})$, $\beta_{max} = \max_i \beta_{r(i)}$, and $\gamma_{min} = \min_i \gamma_{r(i)}$. Hence, from (9), we have the following upper bound: $\partial^2 J_i(\mathbf{x})/\partial x_i^2 \leq v_{max} + K\tau_{max}|\mathcal{N}_i| / [e(1-\tau_{max})x_{min}]$, where $v_{max} = \max_i v_i$. Thus, the step size λ_i should satisfy

$$0 < \lambda_i < \frac{e(1-\tau_{max})x_{min}}{e(1-\tau_{max})v_{max}x_{min} + K\tau_{max}|\mathcal{N}_i|}.$$

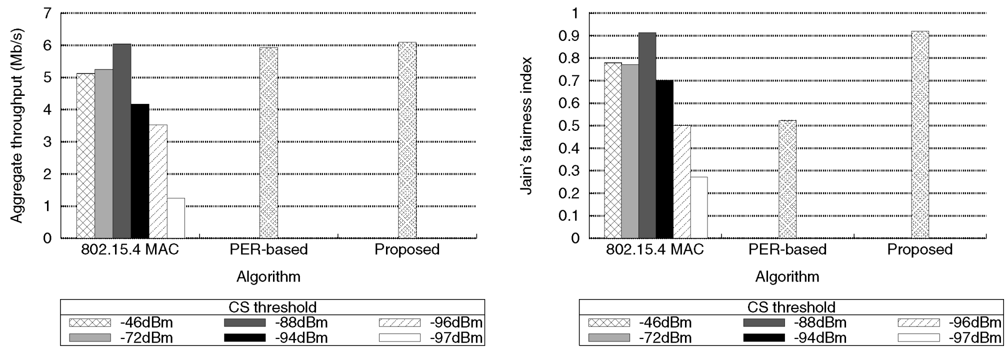
In a similar manner, the condition $\partial f_i(\mathbf{x})/\partial x_i > \sum_{j \neq i} \left| \partial f_i(\mathbf{x})/\partial x_j \right|$ in [7,Proposition 1.11 p. 194] is satisfied if $v_i > K\tau_{max}|\mathcal{N}_i|/(ex_{min})$. ■

5. EXPERIMENTAL RESULTS

In this section, we carry out an experimental study to compare the performance of the proposed algorithm with those of the standard IEEE 802.15.4 MAC and the conventional PER-based algorithm.

5.1. Testbed Setup

Figure 2 shows our testbed configured composed of IEEE 802.15.4-compliant MICAz motes with CC2420 and the experimental topologies. In our experimental study, we consider two network topologies, i.e., 4 and 6 sender–



(a) Aggregate throughput for 4 sender-receiver pairs. (b) Jain's fairness index for 4 sender-receiver pairs.

Figure 3. Throughput and fairness performance comparison between the proposed algorithm, PER-based algorithm [3], and standard 802.15.4 MAC. (a) Aggregate throughput for 4 sender-receiver pairs. (b) Jain's fairness index for 4 sender-receiver pairs.

receiver pairs as shown in Figure 2(b), where each sender generates UDP traffic with 80 Kb/s. Finally, the sampling time T and the weight factor α in Algorithm 1 are set to 1 s and 0.7, respectively.

5.2. Performance Evaluation of the Proposed Algorithm

We carry out an experimental study for comparing the aggregate throughput and the fairness performance between the standard IEEE 802.15.4 MAC, the PER-based algorithm in Reference [3], and the proposed algorithm. First, we investigate the case of 4 sender–receiver pairs. As we can see in Figure 3(a), the throughput performance of the IEEE 802.15.4 MAC heavily depends on the initial assignment of the CS threshold. For example, when the initial CS threshold is set to -88 dBm, the aggregate throughput is approximately 6 Mb/s, which is comparable to those achieved by other two schemes. On the other hand, for the other values, the throughput performance of the standard IEEE 802.15.4 MAC significantly deteriorates. In the meantime, the PER-based algorithm and the proposed one show similar throughput performance. However, if we look into the fairness performance in Figure 3(b), we can easily observe that the proposed algorithm gives significantly better fairness performance than the PER-based mechanism. Consequently, we can conclude from Figure 3 that the proposed algorithm can adaptively tune the CS threshold of each node with promising throughput and fairness. It should be noted that a proper value for the CS threshold for a given network environment is not available in advance, which supports the importance of developing an adaptive algorithm such as ours.

In order to investigate the temporal behaviour of the CS threshold with the proposed algorithm, the time traces of the CS threshold for 6 sender–receiver pairs are given in Figure 4. Under the proposed algorithm, unlike the PER-based algorithm as shown in Figure 1, none of the CS thresholds are saturated to $x_{\min}$ ($= -98$ dBm) or $x_{\max}$ ($= -45$ dBm). Instead, every CS threshold remains in a reasonable range of $[-97, -90]$ dBm. Hence, it can be verified that the CS threshold of each node converges to an appropriate value without severe unfairness and bandwidth starvation of certain nodes.

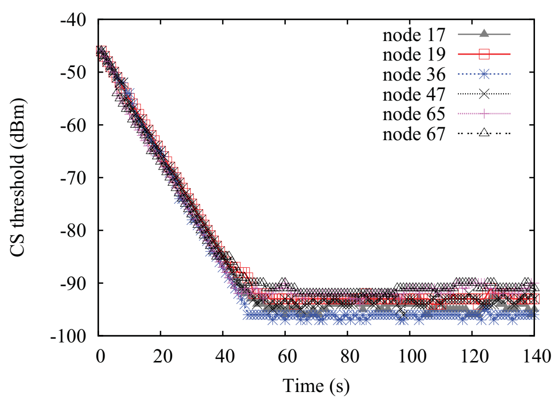


Figure 4. Time traces of the CS threshold for the proposed algorithm.

6. CONCLUSIONS

We have proposed an adaptive CS scheme with enhanced fairness. We have derived a sufficient condition on the convergence of the proposed algorithm. Then, through an experimental study, we have shown that the proposed algorithm can significantly improve fairness while retaining competitive throughput compared to the conventional adaptive scheme.

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