

# Adaptive Carrier Sense with Enhanced Fairness in IEEE 802.15.4 Wireless Networks

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## Abstract

We propose an adaptive carrier sense (CS) scheme with enhanced fairness based on the observation that conventional adaptive CS mechanisms may lead to significant unfairness. Our experiments with an IEEE 802.15.4 testbed show that the proposed algorithm significantly improves fairness while providing competitive throughput performance.

## Index Terms

Physical carrier sense, fairness, CSMA wireless networks, localized algorithm.

## I. INTRODUCTION

Physical carrier sense is a fundamental mechanism that determines network performance in carrier sense multiple access (CSMA) wireless networks. To this end, carrier sensing is typically implemented using a carrier sense (CS) threshold; if the received signal strength at a node exceeds the CS threshold, it considers the wireless channel busy, and defers its transmission until the wireless channel becomes idle. If the CS threshold is set too large, a node's transmission may be interfered with by transmissions from other nodes due to the hidden terminal problem. On the other hand, if the CS threshold is set too small, the node attempts to transmit in a too conservative

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manner, the exposed terminal problem. Hence, choosing an appropriate value for the CS threshold that balances these two problems is of critical importance for optimizing network performance.

Recently, a number of studies attempting to tune the CS threshold have been conducted [1]–[5]. These studies typically aim to enhance the spatial reuse to improve the network throughput while maintaining a specific metric, such as packet error rate (PER) or signal-to-interference-plus-noise-ratio (SINR), at around a certain level. For example, algorithms in [3], [5] adjust the CS threshold according to the PER measured at each sender; previously, the algorithm in [1] introduced an SINR feedback mechanism from the receiver in which the sender adapted its CS threshold depending on the SINR. However, with these adaptation schemes, each node adjusts its CS threshold by considering its own performance metric, which may lead to significant throughput unfairness among the nodes.

As a means of resolving this unfairness problem and thereby improving network throughput, in this paper we propose an adaptive CS mechanism that takes account the CS threshold of neighboring nodes. We then derive a sufficient condition for the convergence of the proposed algorithm and implement the algorithm in an IEEE 802.15.4 testbed to empirically validate its performance. Our experiments show that the proposed algorithm significantly improves fairness compared to the conventional adaptive CS algorithm while maintaining the competitive throughput improvement over the IEEE 802.15.4 MAC standard.

## II. UNFAIRNESS OF CONVENTIONAL ADAPTIVE CARRIER SENSE MECHANISM

As an illustrative example, we implement the PER-based CS adaptation scheme from [3] and then conduct experiments using Crossbow MICAz motes to investigate the problem of throughput unfairness.<sup>1</sup> The adaptation rule for a conventional PER-based scheme can be described as

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

<sup>1</sup>A more detailed description of the configuration is given in Section V.

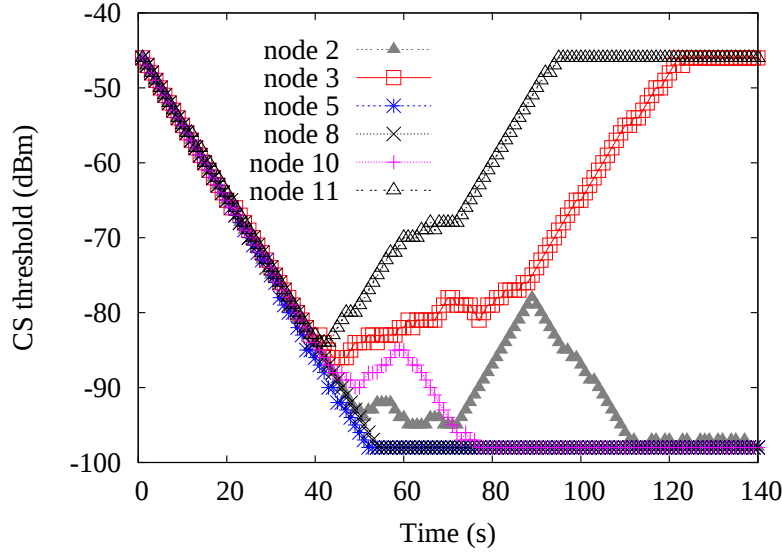


Fig. 1. Traces of CS threshold for a PER-based adaptive mechanism.

where  $x_i$  is the CS threshold of node  $i$ ,  $x_{max}$  and  $x_{min}$  are the maximum/minimum CS thresholds,  $q_i$  is the PER measured by node  $i$ ,  $q_{max}^t$  and  $q_{min}^t$  are the target maximum/minimum PERs, and  $\delta$  is the step size.

As shown in Fig. 1, the CS thresholds of nodes 3 and 11 are saturated to  $x_{max}$  ( $= -48$  dBm); others are  $x_{min}$  ( $= -98$  dBm), reasons for which are as follows. Once the thresholds of certain nodes become large, they excessively occupy the shared wireless channel, and as such smaller nodes gradually lose channel access opportunities; eventually, their CS threshold converges to  $x_{min}$ , resulting in severe throughput unfairness. In summary, conventional PER-based CS adaptation mechanisms may lead to severe throughput unfairness while attempting to improve the overall network throughput by sacrificing the throughput of certain nodes. Consequently, developing an adaptive CS mechanism with enhanced fairness is crucial.

### III. NETWORK MODEL

Consider a CSMA wireless network of  $N$  nodes, denoted by  $\mathcal{N} = \{1, \dots, N\}$ . For a given node  $i \in \mathcal{N}$ , let  $r(i) \in \mathcal{N}$  denote the respective receiver, and  $P_i$  denote the transmit power of node  $i$ . The power received at  $r(i)$  can then 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  $r(i)$ —a widely used model for wireless channel environments [6]. The magnitude of Rayleigh fading,  $F_{r(i),i}$  is independent across the nodes and is exponentially distributed with a unit mean. Next, let  $\tau_i$  denote the channel access probability of node  $i$ . Here, we assume that interference from other senders is much larger than the ambient noise, and thus do not take noise into account 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 usually be 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 referred to as 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 the node. Then, for a given node  $i$ , let  $S_i(x_i)$  denote the carrier sense set of the node, defined as  $S_i(x_i) = \{j \mid G_{i,j}F_{i,j}P_j \geq x_i\}$ . In this case, node  $i$  will be silenced if any node in  $S_i(x_i)$  transmits. Similarly, let  $L_i$  denote the silence set of node  $i$ , defined as  $L_i = \{j \mid G_{j,i}F_{j,i}P_i \geq x_j\}$ ; i.e., every node  $j \in L_i$  will be silenced when node  $i$  transmits.

#### IV. ADAPTIVE CARRIER SENSE WITH ENHANCED FAIRNESS

##### A. Algorithm Description

We propose here an adaptive CS update scheme with enhanced fairness, which consists of two steps: 1) each node calculates the CS threshold to iteratively minimize its cost function (which will be defined later in the section); and 2) 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 neighboring nodes.

Therefore, for each node  $i$ , an increase in its CS threshold  $x_i$  will result in a corresponding increase in the interference of its neighbors because node  $i$  will access the channel more frequently by caring less for others. Hence, it can be considered reasonable to impose a penalty to node  $i$  when its CS threshold increases. For this penalty, we adopt a quadratic pricing function  $P_i(x_i) = v_i x_i^2 / 2$  for each node  $i$  that is twice continuously differentiable, increasing and uniformly strictly convex in  $x_i$ .<sup>2</sup>

In addition, 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  $\mathbf{x}_{-i} := (x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_N)$ . 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  $q_i(\mathbf{x})$  increases in  $x_i$  for a given  $\mathbf{x}_{-i}$ . Thus, for a given  $\mathbf{x}_{-i}$ ,  $U_i(x_i, \mathbf{x}_{-i})$  is concave in  $x_i$  and attains its maximum when  $q_i = q_i^t$ . In this way, the PER of node  $i$  can be maintained around a target PER of  $q_i^t$  by maximizing  $U_i(\mathbf{x})$ .

With the above definitions for the pricing function  $P_i$  and the utility function  $U_i$ , a reasonable control algorithm for CS threshold should attempt to make each node  $i$  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 must solve the minimization problem:

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

<sup>2</sup>Since the relationship between the pricing function and network performance is very complex, it is generally difficult to determine an optimal pricing function. Thus, we adopt a quadratic pricing function parameterized by  $v_i$ . The choice of other structures is the subject of a future work.

Here, in order to ensure an inner equilibrium, we introduce the following technical condition on the pricing function:  $P_i(x_i)$  is further chosen to satisfy  $\partial J_i/\partial x_i < 0$  at  $x_i = x_{min}$ ,  $\partial J_i/\partial x_i > 0$  at  $x_i = x_{max}$ ,  $\forall \mathbf{x}_{-i} \in \mathcal{N}$ .

Now, consider the following discrete-time algorithm:

$$y_i(t+1) = x_i(t) - \lambda_i \frac{\partial J_i(\mathbf{x})}{\partial x_i} = x_i(t) - \lambda_i [v_i x_i - (q_i^t - q_i(\mathbf{x}))], \quad (5)$$

where  $t = 1, 2, \dots$  denotes the update time instants and  $\lambda_i$  is the step size. Then, if we let  $y_i(t+1) \equiv x_i(t+1)$ , algorithm (5) will correspond to the gradient update algorithm for solving (4), potentially sufficient for improving the overall network throughput over the standard CSMA. However, (5) still lacks consideration of fairness among neighboring nodes. To further enhance the fairness performance, we introduce the additional step of taking a weighted sum of the average CS threshold of neighbors. To attain this sum, for every update interval of  $T$ , each sender first broadcasts its current CS threshold to neighboring nodes, and the average of neighboring CS thresholds is then calculated 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 neighbors for node  $i$  that broadcast their CS threshold for the time interval  $[tT, (t+1)T)$ . Finally, the CS threshold  $x_i$  is updated as a weighted sum of  $y_i$  in (5) and  $x_{-i}^{avg}$  in (6) as

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

where  $\alpha$  is the weight factor ( $0 < \alpha \leq 1$ ).

### B. Convergence of the Proposed Algorithm

Now, we need to derive a sufficient condition for the convergence of the proposed algorithm in Section IV-A.

**Proposition 1** *The proposed algorithm converges if*

$$\lambda_i < \frac{e(1 - \tau_{max})x_{min}}{e(1 - \tau_{max})v_{max}x_{min} + K\tau_{max}|\mathcal{N}_i|} \text{ and } v_i > \frac{K\tau_{max}|\mathcal{N}_i|}{ex_{min}}, \forall i \in \mathcal{N},$$

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  $P_{max}$  is the maximum transmit power.

*Proof:* By substituting (5) and (6) into (7), we have

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

where  $f_i(\mathbf{x}) := \alpha \partial J_i(\mathbf{x}) / \partial x_i + (1 - \alpha) \left( x_i(t) - \sum_{j \in \mathcal{N}_i} x_j(t) / |\mathcal{N}_i| \right) / \lambda_i$ . Now, we use the result in [7, Proposition 1.11 p. 194] to prove the convergence of (8). First, we derive a sufficient condition for the step size  $\lambda_i$ . For the convergence of (8),  $\lambda_i$  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  $0 < \lambda_i < 1/M'$  can be easily obtained, where  $M'$  is a positive constant such that  $\partial^2 J_i(\mathbf{x}) / \partial x_i^2 \leq M'$ ,  $\forall x, i$ . Next, let  $q_i(\mathbf{x})$  denote the collision probability of node  $i$ . In this case, we have  $q_i(\mathbf{x}) = P \left[ P_{r(i)} / \sum_{k \in \Gamma_i(\mathbf{x})} G_{r(i),k} P_k F_k < \beta_{r(i)} \right]$ , and  $\Gamma_i(\mathbf{x})$  denotes the set of nodes that concurrently transmit with node  $i$ . Note that a node concurrently transmits with node  $i$  when either its transmission has been sensed by node  $i$  or when it has not sensed a transmission from node  $i$  and thus 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 the 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  $\gamma_{min} = \min_i \gamma_{r(i)}$ . From (9), we then 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  $\lambda_i$  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  $\partial f_i(\mathbf{x})/\partial x_i > \sum_{j \neq i} |\partial f_i(\mathbf{x})/\partial x_j|$  in [7, Proposition 1.11 p. 194] is satisfied if  $v_i > K\tau_{max}|\mathcal{N}_i|/(ex_{min})$ . ■

## V. EXPERIMENTAL RESULTS

To evaluate the performance of the proposed scheme, we carry out experiments with IEEE 802.15.4-compliant MICAz motes, as shown in Fig. 2. The sampling time  $T$  and the weight factor  $\alpha$  are set to 1 s and 0.7, respectively. The network topology used in the experiments is given in Fig. 3, where the sender of each pair generates UDP traffic at 80 Kb/s.

Figure 4(a) shows the aggregate throughput performance of the IEEE 802.15.4 MAC, the PER-based algorithm in [3], and the proposed algorithm, where we can observe that the throughput performance of the IEEE 802.15.4 MAC highly depends on the CS threshold. Only with an appropriate CS threshold the throughput performance can be competitive in both the proposed scheme and PER-based algorithm. However, the CS threshold depends on a number factors (e.g., power assignment, node distribution, channel status) and is not available in advance. Hence, statically assigning the CS threshold is insufficient, and thus the deployment of an adaptive CS algorithm becomes crucial. Note that, in Fig. 4(a) the PER-based algorithm and the proposed algorithm show similar throughput performance.

Figure 4(b) presents the fairness performance, measured in terms of Jain's fairness index. In the figure, it can be observed that the proposed algorithm gives significantly better fairness performance than the PER-based mechanism. Then, to further investigate the temporal behavior of the CS threshold with the proposed algorithm, the time traces of the CS threshold are given in Fig. 5. Under the proposed algorithm none of the CS thresholds are saturated to either  $x_{min}$  ( $= -98$  dBm) or  $x_{max}$  ( $= -45$  dBm), and in fact remain in the range of  $[-97, -90]$  dBm.



Fig. 2. IEEE 802.15.4 platform. Here, three components are combined using a 51 pin to 10 pin adapter. MIB600 is attached to MICAz and MTS300 to provide remote control functionality and auto-collection.

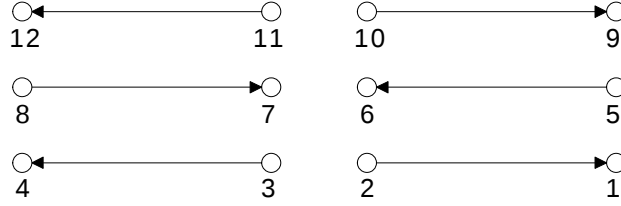


Fig. 3. Network topology for the 6 sender-receiver pairs used in the experiments.

## VI. CONCLUSIONS

In this paper, we proposed an adaptive CS scheme with enhanced fairness. Through experiments using IEEE 802.15.4-compliant MICAz motes, we confirmed that the proposed algorithm can significantly improve fairness performance while retaining throughput performance comparable to conventional schemes.

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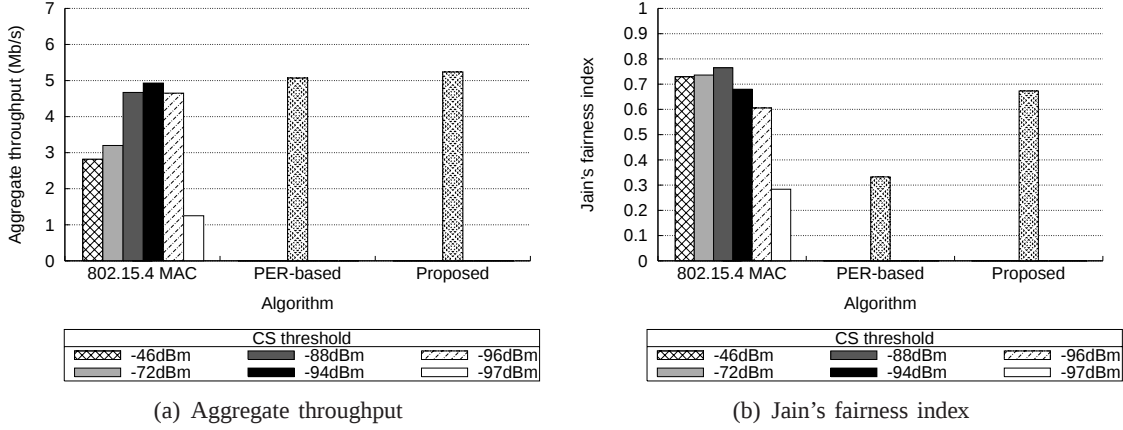


Fig. 4. Throughput and fairness performance comparison between the proposed algorithm, the PER-based algorithm [3], and the standard 802.15.4 MAC.

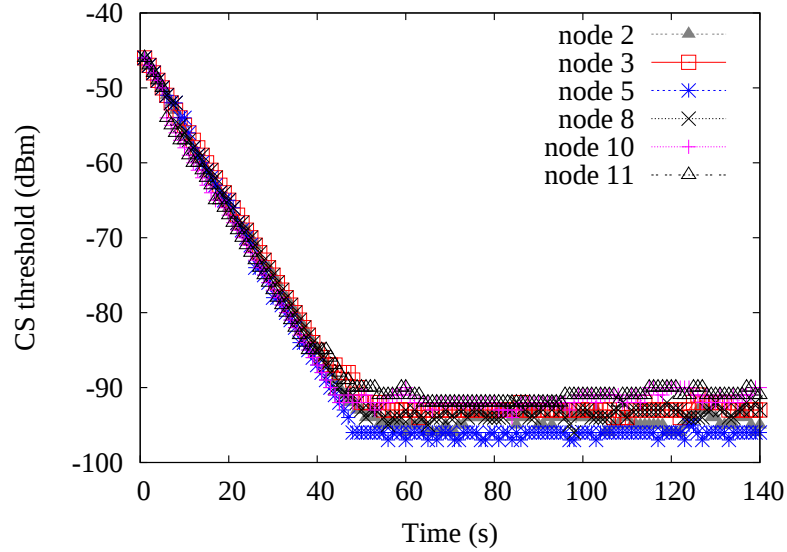


Fig. 5. Traces of the CS threshold for the proposed algorithm.

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