Adaptive Physical Carrier Sense in Topology-Controlled Wireless Networks

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Abstract—*Transmit power* and *carrier sense threshold* are key MAC/PHY parameters in carrier sense multiple access (CSMA) wireless networks. Transmit power control has been extensively studied in the context of topology control. However, the effect of carrier sense threshold on topology control has not been properly investigated in spite of its crucial role. Our key motivation is that the performance of a topology-controlled network may become worse than that of a network without any topology control unless carrier sense threshold is properly chosen. In order to remedy this deficiency of conventional topology control, we present a framework on how to incorporate physical carrier sense into topology control. We identify that joint control of transmit power and carrier sense threshold can be efficiently divided into topology control and carrier sense adaptation. We devise a distributed carrier sense update algorithm (DCUA), by which each node drives its carrier sense threshold toward a desirable operating point in a *fully distributed manner*. We derive a sufficient condition for the convergence of DCUA. To demonstrate the utility of integrating physical carrier sense into topology control, we equip a localized topology control algorithm, LMST, with the capability of DCUA. Simulation studies show that LMST-DCUA significantly outperforms LMST and the standard CSMA protocol.

Index Terms—Carrier sense multiple access wireless network, topology control, physical carrier sense, distributed algorithm.

1 Introduction

Multihop wireless networks, e.g., wireless mesh networks, have emerged to be a promising, cost-effective technology for next-generation wireless networking [1]. Their major advantage is the capability of building networks without a preinstalled central infrastructure. In particular, in carrier sense multiple access (CSMA) wireless networks, instead of using a central entity for coordinating the radio channel, a distributed access mechanism based on physical carrier sense is deployed at each node to arbitrate its channel access.

Several PHY/MAC attributes in CSMA wireless networks can be used to arbitrate channel access, to mitigate interference, and to improve network performance. Here, we focus on *transmit power* and *carrier sense threshold*, which are key control knobs for network performance because of the following reasons: The network capacity, which is the average data bits that can be transported simultaneously in the network, heavily depends on the level of spatial reuse, i.e., how many concurrent transmissions are allowed. The level of spatial reuse is characterized by physical carrier sense, which is, in turn, determined primarily by transmit power and carrier sense threshold. More specifically, under physical carrier sense, a sender senses the channel before each transmission and determines whether or not the channel is busy by comparing the received signal strength with carrier sense threshold. If the signal strength is below carrier sense threshold, the sender considers the channel to be idle and starts its transmission. Otherwise, the sender considers the channel to be busy and defers its transmission. The received signal strength is, in principle, proportional to the transmit power of the sender. Hence, both carrier sense threshold and transmit power are major control knobs for exploiting spatial reuse to improve network performance.

Although abundant studies on power control of wireless networks already exist in the context of graph-theoretic topology control, for example, [2], [3], [4], [5], [6], [7], [8], most of them have not considered the effect of the signal to interference ratio (SIR), which is critical for successful packet reception under the physical model. Moscibroda et al. [9] are perhaps the first to consider the problem of topology control under the physical SIR model. They investigated the time complexity of centralized scheduling for topology-controlled networks. However, without an infrastructure, a centralized scheduler is not so much applicable in practice. In this paper, we consider the problem in a more practical setting of CSMA wireless networks. In particular, we aim to answer the following question: how can we incorporate physical carrier sense into topology control in order to properly take into account the SIR constraint? More specifically, the technical contributions of this paper are as follows:

- First, we show that the performance of a topology-controlled network may become even worse than that of a network without any topology control if carrier sense threshold is not properly chosen. This observation implies that carrier sense threshold is crucial for improving the performance of a topology-controlled network. We identify that the joint control problem of transmit power and carrier sense threshold can be efficiently divided into topology control and carrier sense adaptation. Hence, we propose to integrate an adaptive control algorithm for carrier

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sense threshold into topology control. This incorporation of physical carrier sense into topology control enables us to eliminate the major deficiency of conventional topology control, i.e., failure to take account of the SIR constraint, and to further improve network performance.

- We formulate the control problem of carrier sense threshold as distributed optimization for each node. On one hand, each node can increase its chance for transmission by increasing its carrier sense threshold. However, on the other hand, a large carrier sense threshold will result in SIR degradation because of increased interference from concurrent transmissions. Furthermore, the larger the carrier sense threshold, the more severe the interference to other nodes. In order to balance out these conflicting factors, we first introduce a penalty function of each node for increasing its carrier sense threshold. Then, in order to guarantee a certain quality of service (QoS), we adopt a utility function, which is maximized when the packet error rate (PER) equals a given threshold. Then, our distributed optimization for each node is to minimize the overall cost function, which is defined as the difference between the penalty and the utility. We derive a sufficient condition on the convergence of an iterative algorithm for this optimization problem.
- Based on our previous work on topology control, localized minimal spanning tree (LMST) [4], we devise an exemplary algorithm, called *LMST with distributed carrier sense update algorithm (LMST-DCUA)*, to demonstrate the utility of our approach. In LMST-DCUA, each node first determines an appropriate power level with LMST, and then, adaptively tunes its carrier sense threshold to further improve network performance. Consequently, our approach of incorporating physical carrier sense into topology control plays a crucial role of bridging the gap between graph-theoretic topology control and SIR-based control of PHY/MAC attributes in CSMA wireless networks. Through simulation studies by J-Sim [10], we show the superiority of LMST-DCUA to LMST and standard CSMA.

The remainder of this paper is organized as follows: We provide an overview of related work in Section 2. The technical motivation follows in Section 3. In Section 4, we present a framework on how to incorporate physical carrier sense into topology control. In particular, we elaborate on the issue of tuning the carrier sense threshold of each node in a fully distributed manner, and devise LMST-DCUA as an exemplary joint control algorithm. We evaluate the performance of LMST-DCUA in Section 5. We conclude the paper in Section 6.

2 Related Work

2.1 Transmit Power Control

The issue of transmit power control has been extensively studied as topology control under the graph-theoretic model, where two nodes are considered neighbors and a wireless link exists between them if their distance is within the transmission range (as determined by the transmit power, the path loss model, and the receiver sensitivity) of each other [2], [3], [4], [5], [6], [7], [8]. The main objective of topology control is to preserve a certain network connectivity while mitigating interference among nodes. For example, LMST [4] is a localized algorithm that guarantees a network connectivity and provides a bound of six on the node degree. The interested reader is referred to [11] for a detailed taxonomy of conventional topology control algorithms.

Use of transmit power control for improving the network capacity under the physical SIR model has been considered, for example, in [12], [13], [14]. Monks et al. [12] proposed a power control protocol called PCMA, in which the receiver advertises its interference margin that it can tolerate on an out-of-band channel and the transmitter selects its power in order not to disrupt any ongoing transmissions. Muqattash and Krunz [13], [14] also proposed similar power control protocols called, respectively, PCDC and POWMAC. The PCDC protocol constructs the network topology by overhearing RTS/CTS packets, and the computed interference margin is announced on an out-of-band channel. The POWMAC protocol uses a single channel for exchanging the interference margin information.

As mentioned in Section 1, the first category of graph-theoretic topology control does not take account of the SIR constraint. The second category of power control algorithms, on the other hand, does not explicitly consider network connectivity. Moreover, all the protocols do not consider the effect of carrier sense threshold although it is a major determinant for spatial reuse.

2.2 Studies on Physical Carrier Sense for Improving Spatial Reuse

Recently, a number of studies have been carried out to see how physical carrier sense affects spatial reuse [15], [16], [17], [18], [19]. In these studies, carrier sense threshold was the main parameter for controlling the level of spatial reuse. Zhu et al. proposed in [15] a dynamic algorithm for adjusting the carrier sense threshold to exploit spatial reuse. Vasan et al. [16] proposed an algorithm, entitled *echos*, for online tuning of carrier sense threshold in order to allow more flows in IEEE 802.11-based hotspot wireless networks. Ma et al. [17] proposed a method of estimating the probability of collision and interference statistically. Then, they integrated this differentiation scheme with physical carrier sensing adaptation in a centralized heuristic algorithm in order to improve the aggregate throughput. Nadeem and Ji [18] proposed an enhanced DCF algorithm that exploits location information to exploit spatial reuse for given transmission rates. In [19], an efficient algorithm for joint control of carrier sense threshold and data rate was proposed.

There have also been a number of studies on the relation between physical carrier sense and Shannon capacity [20], [21], [22]. Yang and Vaidya [20] are perhaps the first to address the impact of physical carrier sense on Shannon capacity of wireless ad hoc networks, while taking account of the MAC layer overhead. Lin and Hou [21] studied the relation between carrier sense threshold and the MAC throughput in multirate wireless networks, and identified that the MAC throughput has several transitional points caused by multiple data rates. Kim et al. [22] studied the relation between physical carrier sense and Shannon capacity, and showed that, in the case that the achievable channel rate follows the Shannon capacity, spatial reuse depends on the ratio of transmit power to carrier sense threshold in a homogeneous network.

2.3 Joint Control of Transmit Power and Carrier Sense Threshold

The problem of jointly determining the transmit power and the carrier sense threshold has not been paid much attention in spite of its importance. Fuemmeler et al. [23] studied the relation between transmit power and carrier sense threshold, and showed that senders should keep the product of their transmit power and carrier sense threshold fixed at a constant. Yang et al. [24] proposed a joint control algorithm, called *LMST with carrier sense adjustment (LMST-CSA)*, where the transmit power of a node is determined by LMST, and the carrier sense threshold is determined so as to eliminate all the hidden nodes. In spite of its simplicity, LMST-CSA requires channel information such as the path loss exponent. Furthermore, it does not consider the SIR constraint, and thus, may not fully exploit spatial reuse. More importantly, in these previous studies, it has not been well addressed why joint control of transmit power and carrier sense threshold is crucial for network performance.

3 Motivation: Why Should Physical Carrier Sense Be Incorporated into Topology Control?

In this section, we demonstrate that the performance of a topology-controlled network may not be as satisfactory as expected and may even become worse than that of a network without any topology control unless physical carrier sense is properly considered. As explained in the previous section, the issue of transmit power control in wireless networks has been extensively studied in the context of topology maintenance by graph-theoretic approaches. A common notion of "neighbors" adopted in these graph-theoretic studies is as follows: two nodes are considered neighbors and a unidirectional link exists between them in the corresponding communication graph if one node is in the transmission range of the other. Note that the transmission range of a node is usually determined by the receive sensitivity constraint given in (1). Power control algorithms that adopt this notion of neighbors are collectively called topology control. Usually, the main goal of topology control is to keep the node degree low while maintaining a certain connectivity of the communication graph.

Topology control has been commonly considered to help improve network performance while maintaining network connectivity. However, by representing a wireless network as a static graph, topology control has ignored the SIR requirement, which is critical for successful transmission in the physical layer. The existence of a link between two nodes in the graph is *not sufficient* for successful physical transmission because interference from other transmissions may prevent the receiver from correct decoding. Thus, the SIR requirement should be integrated into topology control in a proper manner. Since the SIR of each transmission heavily depends on the level of contention in CSMA wireless networks, carrier sense threshold is a key control knob for resolving the lack of the SIR constraint in topology control. To illustrate the critical role of carrier sense threshold in the performance of a topology-controlled network, we give a simulation result of LMST [4] (a competitive topology control algorithm) and the baseline scheme (standard CSMA without topology control) in Fig. 1, in which the per-node throughput versus a common carrier sense threshold is shown. The details of simulation setup are given in Section 5.

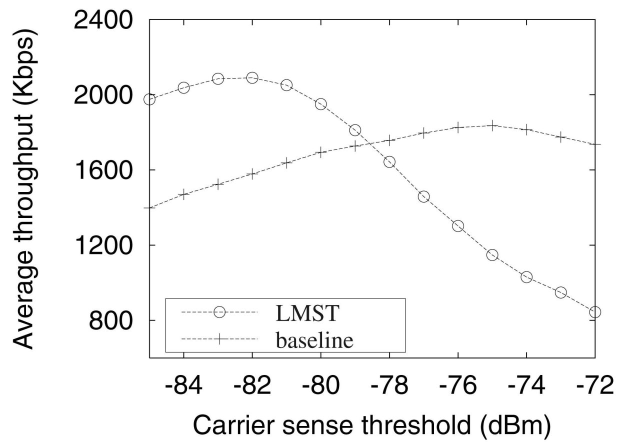

Fig. 1. Throughput comparison between LMST and baseline CSMA with respect to the common carrier sense threshold.

The following observations can be made from Fig. 1: LMST shows significantly better performance than the baseline scheme when the carrier sense threshold is relatively small. However, as the carrier sense threshold increases over a certain point (around -82 dBm in Fig. 1), the performance of LMST monotonically deteriorates, and eventually, becomes worse than that of the baseline scheme. Still, the maximum throughput with LMST over the entire range (which is attained when the carrier sense threshold is around -82 dBm) is larger than that with the baseline scheme (which is attained when the carrier sense threshold is -75 dBm). It should be noted that this performance dependency of a topology-controlled network on carrier sense threshold is not accidental with LMST, but intrinsic to the topology control problem itself. In fact, it was shown in [22], [25] that the network capacity depends on the ratio of the transmit power of each node to the carrier sense threshold of the other. Note that there is one common value for this ratio in a homogeneous network while there are as many as $N(N-1)$ values in a heterogeneous network where N is the number of nodes.

These observations imply that topology control gives better performance *only if* carrier sense threshold is properly chosen. However, a proper value for carrier sense threshold depends on various factors (e.g., power assignment, node distribution, and channel status) and is not known in advance, especially without a centralized infrastructure. Thus, for a given power assignment by topology control, an *adaptive* control algorithm for carrier sense threshold is crucial, which can drive the carrier sense threshold of each node to an appropriate value. In summary, we can conclude that topology control alone is insufficient to ensure a promising network performance, and it is critical to devise an adaptive tuning algorithm for carrier sense threshold, which can work jointly with topology control.

4 Incorporation of Physical Carrier Sense into Topology Control

In this section, we first introduce a network model and related notions used in our analysis. Then, we present a framework on how to integrate physical carrier sense into topology control. To demonstrate the utility of the framework, we equip a localized topology control algorithm, LMST, with the capability of DCUA.

4.1 Network Model

Consider a wireless network of N nodes, denoted by $\mathcal{N} = \{1, \ldots, N\}$. 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 $r(i)$ is expressed as $P_{r(i)} = G_{r(i),i} F_{r(i),i} P_i$, where $G_{r(i),i}$ represents the path gain from sender i to receiver $r(i)$. Also, $F_{r(i),i}$ models the Rayleigh fading, which is independent, exponentially distributed with unit mean. Note that Rayleigh fading is a widely used model for wireless channel environment [26]. We assume that the interference from other senders is much larger than the ambient noise in the receivers, and therefore, we ignore the receiver 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.,

$$\mathbb{E}[P_{r(i)}] = G_{r(i),i} P_i \geq \gamma_{r(i)}. \tag{1}$$

Note that the receive sensitivity constraint of (1) is usually adopted as a connectivity condition in topology control [1].

In addition, 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

$$\mathrm{SIR}_{r(i)} = \frac{P_{r(i)}}{I_{r(i)}} \geq \beta_{r(i)}, \tag{2}$$

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 SIR threshold of the receiver $r(i)$.

The *collision set* of receiver $r(i)$, denoted by $C_{r(i)}$, is defined as the set of nodes whose simultaneous transmission with node i will violate the SIR constraint of (2), i.e.,

$$C_{r(i)} = \left\{ j \,\middle|\, \frac{P_{r(i)}}{G_{r(i),j} P_j F_{r(i),j}} < \beta_{r(i)} \right\}. \tag{3}$$

Let x_i denote the carrier sense 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

$$S_i(x_i) = \{ j \mid G_{i,j} F_{i,j} P_j \geq x_i \}.$$

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

$$L_i = \{ j \mid G_{j,i} F_{j,i} P_i \geq x_j \}.$$

Thus, every node $j \in L_i$ will be silenced when node i transmits.

Further, let H_i denote the set of hidden nodes with respect to node i, which is defined as $H_i = C_{r(i)} \setminus L_i$. Thus, no node in H_i can detect the transmission of node i. Moreover, if any node in H_i transmits during the transmission of node i, the transmission of node i will fail. This is the well-known hidden node problem. Finally, let τ_i denote the channel access probability of node i once node i senses the channel idle.

For a given transmission from node i to node $r(i)$, Fig. 2 shows the relation among $S_i(x_i)$, L_i, $C_{r(i)}$, and H_i. By their definitions, the boundaries of $S_i(x_i)$, L_i, and $C_{r(i)}$ are probabilistically determined based on various factors such as the node distribution, path gain, power assignment, and carrier sense threshold. Rather than the circular boundaries usually adopted under the assumption of a homogeneous network (where every node has the same values for the parameters such as transmit power and carrier sense threshold), the boundaries under a heterogeneous network will be arbitrary shapes, as shown in Fig. 2.

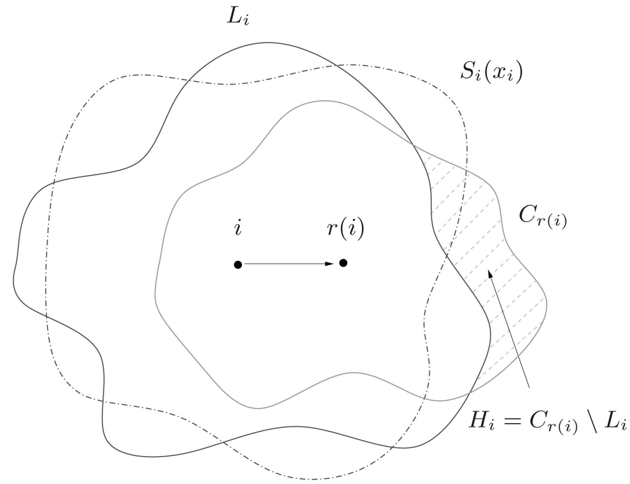

Fig. 2. Set relation among $S_i(x_i)$, L_i, $C_{r(i)}$, and H_i.

It should be noted that L_i, $C_{r(i)}$, and H_i are independent of x_i by their definitions, while $S_i(x_i)$ is a function of x_i and satisfies $S_i(y) \subset S_i(x)$ if $x < y$ from its definition. As a matter of fact, what carrier sense of each node does is *not* to prevent other nodes from transmitting, *but* to detect (before each transmission attempt) the status of the channel. Hence, even when there have been no collision by a simultaneous transmission, node i's transmission may still fail if the SIR condition (2) is violated by interruption from nodes whose transmission have not been sensed by node i and/or those which do not sense node i's transmission and attempt to transmit.

4.2 Separation between Topology Control and Carrier Sense Adaptation

Now, we look into a general problem of jointly assigning transmit power and carrier sense threshold. In this formulation, the objective is to maximize a given system performance metric J, which is defined as the sum of individual node performance J_i subject to a certain connectivity constraint. This problem can be formulated as follows:

$$\text{maximize} \left[J(\mathbf{x}, \mathbf{P}) = \sum_{i=1}^{N} J_i(\mathbf{x}, \mathbf{P}) \right] \tag{P1}$$
$$\text{subject to a connectivity constraint on } \mathbf{P},$$

where $\mathbf{x} = (x_1, \ldots, x_N)$, $\mathbf{P} = (P_1, \ldots, P_N)$, and $x_i \in [x_{\min}, x_{\max}]$, $P_i \in [P_{\min}, P_{\max}]$, $i = 1, \ldots, N$. However, it is a formidable task to find an optimal solution to (P1) for several reasons. First, (P1) is highly nonlinear in that J is a nonlinear function of $\mathbf{x}$ and $\mathbf{P}$. Furthermore, a connectivity constraint on $\mathbf{P}$ may also result in a very complex feasible region. In fact, the problem of finding an optimal power assignment $\mathbf{P}$

for given $\mathbf{x}$ with the objective of minimizing the energy cost has been shown to be NP hard [11].

Thus, instead of attempting to find an optimal solution to (P1), we introduce a two-phase control framework which provides a suboptimal solution to (P1). The key idea is to consider $\mathbf{P}$ and $\mathbf{x}$ separately based on the observation that network connectivity depends only on $\mathbf{P}$. First, we determine $\mathbf{P}$, with the objective of preserving network connectivity while mitigating MAC-level interference. This problem exactly corresponds to conventional topology control, and we can readily leverage an existing topology control algorithm for solving this problem. Once we obtain a power assignment $\mathbf{P}$, what is left is to control carrier sense thresholds $\mathbf{x}$ for further improving network performance. Through this two-step approach, we can leverage existing results in topology control and further improve network performance by tuning carrier sense thresholds $\mathbf{x}$.

4.3 Distributed Control of Carrier Sense Threshold

Given that we leverage an existing topology control algorithm for assigning transmit powers, what remains is to determine an appropriate value of the carrier sense threshold for each node. Our main idea is to formulate the problem of determining the carrier sense threshold as a distributed optimization problem with a constraint on the PER. One may also think of the SIR level at the receiver as an effective measure for the quality of communication. However, in order to send the SIR information from the receiver to the sender, an additional information feedback mechanism is required in protocol design. Thus, we choose the PER that is readily available at the sender to design a fully distributed algorithm.

4.3.1 Design Rationale of a Distributed Algorithm

If every node works in a selfish manner, each node i will simply try to increase its carrier sense threshold as much as possible in order to maximize its chance for transmission. However, this selfish behavior will result in a very unsatisfying system performance because of severely increased interference among nodes. Thus, each node should reasonably set its carrier sense threshold in order not to interfere with others significantly. Furthermore, the larger the carrier sense threshold, the lower the SIR that can be sustained at the receiver. This SIR degradation results from the fact that the average number of nodes that node i can sense decreases as the carrier sense threshold x_i increases, which leads to larger accumulative interference to node i. In summary, each node i should carefully set its carrier sense threshold x_i in order to balance out these conflicting factors.

Note that our main goal is to develop a fully distributed algorithm rather than an algorithm for maximizing the overall network performance. It will be a subject of future work how to develop a localized algorithm for maximizing the overall network throughput.

4.3.2 Introduction of a Pricing Function and a Utility Function

For each node i, increase in its carrier sense threshold x_i will result in increased interference to its neighbors because node i will access the channel more frequently by caring less for others. Hence, it is reasonable to impose a penalty to node i for increasing its carrier sense threshold x_i. Here, 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.[1] From the definition of the pricing function, as the pricing parameter v_i increases, there is less incentive for node i to increase its carrier sense threshold. Thus, qualitatively speaking, a small value of v_i will make node i access the channel in an aggressive manner while a large value of v_i will make node i behave in a conservative manner. It will be further discussed in Section 4.3.3 how to choose a reasonable value for v_i.

Furthermore, we introduce a utility function U_i in order to reflect the QoS level of each node i. Here, we use the PER in the design of a utility function since PER is a faithful measure for the QoS level of each node. In particular, the utility function U_i adopted in our analysis is defined as follows: $U_i(x_i, \mathbf{x}_{-i}) := \int_{x_{\min}}^{x_i} [q_i^{\text{th}} - q_i(\xi, \mathbf{x}_{-i})] d\xi$ based on a PER threshold q_i^{th} for each node i, where $\mathbf{x}_{-i} := (x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_N)$. With the above utility function U_i, we have $\partial U_i / \partial x_i = q_i^{\text{th}} - q_i$ and $\partial^2 U_i / \partial x_i^2 = -\partial q_i / \partial x_i < 0$ because q_i is increasing in x_i for given $\mathbf{x}_{-i}$. Thus, U_i is concave in x_i and attains its maximum when $q_i = q_i^{\text{th}}$ for given $\mathbf{x}_{-i}$. Note that the PER threshold q_i^{th} is a design parameter, which can be set according to the desired QoS level of each node i.

Intuitively speaking, the main purpose of this utility function U_i is to balance out the following two conflicting factors: increasing the chance for channel access and decreasing interference from other nodes. As x_i increases, node i can have more chance to access the channel. However, at the same time, increase in x_i will cause more interference from other nodes by ignoring more concurrent transmissions. Hence, the role of U_i is balancing these two factors by matching PER to a given threshold.

4.3.3 Distributed Optimization Formulation and Convergence of an Iterative Algorithm

With the above definitions of the pricing function P_i and utility function U_i, a reasonable control algorithm for carrier sense 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 optimization problem:

$$\min_{x_i \in [x_{\min}, x_{\max}]} J_i(x_i, \mathbf{x}_{-i}), \forall i \in \mathcal{N}. \tag{3}$$

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, we investigate the convergence property of a gradient algorithm for updating carrier sense thresholds. Consider the following discrete-time algorithm which updates the carrier sense threshold of each node to solve (3):

$$\begin{aligned} x_i(t+1) &= x_i(t) - \lambda_i \frac{\partial J_i(\mathbf{x})}{\partial x_i} \\ &= x_i(t) - \lambda_i \left[v_i x_i - \left(q_i^{\text{th}} - q_i(\mathbf{x}) \right) \right], \end{aligned} \tag{4}$$

1. Since the relation between the pricing function and network performance is very complex, it is difficult to find an optimal pricing function, in general. Hence, we simply adopt a quadratic pricing function parameterized by v_i. The choice of other structures is a subject of future work.

where $t = 1, 2, \ldots$ denotes the update time instants, and λ_i is the step size. If the cost function J_i in (3) were a function of x_i only, the convexity of J_i in x_i would be sufficient for the uniqueness of the optimal solution and (4) would converge to the solution. However, the problem structure of (3) is more complex than this separable situation because J_i not only depends on x_i, but also depends on other nodes' carrier sense thresholds, i.e., $\mathbf{x}_{-i} = (x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_N)$. Hence, the convexity of J_i in x_i for given $\mathbf{x}_{-i}$ does not guarantee the convergence of (4). Here, based on the theory of parallel and distributed computation [27], we derive a sufficient condition for the convergence of (4) as follows:

Proposition 1. *The update algorithm in (4) converges to the unique equilibrium if*

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

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 feasible transmit power.*

Proof. First, we derive the conditional collision probability of node, which is defined as the collision probability when a node attempts to transmit. There are two sources of transmission failure, i.e., collision incurred by simultaneous transmissions in $C_{r(i)}$ and the violation of the SIR constraint by multiple concurrent transmissions. Note that, with our notions, concurrent transmission depends on x_i while simultaneous transmission is independent of x_i.

Let q_i denote the conditional collision probability of node i given that a transmission attempt is made. Then, we have

$$\begin{aligned} q_i &= P[\text{Simulataneous Tx in } C_{r(i)}] \\ &\quad + P[\text{No simulataneous Tx in } C_{r(i)}] \\ &\quad \times P[\text{SIR}_{r(i)} < \beta_{r(i)} \mid \text{No simultaneous Tx in } C_{r(i)}] \\ &= r_i + (1-r_i)h_i(x_i), \end{aligned} \tag{5}$$

where $r_i := P[\text{Simultaneous Tx in } C_{r(i)}]$ and $h_i(x_i) := P[\text{SIR}_{r(i)} < \beta_{r(i)} \mid \text{No simultaneous Tx in } C_{r(i)}]$.

Now, we use the result in [27, Proposition 1.11, p. 194] to prove the convergence property of (4). First, we derive a sufficient condition on the step size λ_i. Let $f_i(\mathbf{x}) := \partial J_i(\mathbf{x})/\partial x_i$. Then, for the convergence of (4), the step size λ_i should satisfy $0 < \lambda_i < 1/M$, where M is a positive constant such that $\partial f_i/\partial x_i \leq M$, $\forall x, i$. Since $\partial r_i/\partial x_i = 0$ in (5), we have

$$\frac{\partial f_i(\mathbf{x})}{\partial x_i} = \frac{\partial^2 P_i(x_i)}{\partial x_i^2} + \frac{\partial q_i(\mathbf{x})}{\partial x_i} \leq v_{\max} + \frac{\partial h_i(\mathbf{x})}{\partial x_i}, \tag{6}$$

where $v_{\max} := \max_{i\in\mathcal{N}} v_i$. Thus, in order to derive a condition on λ_i, we need to express h_i as a function of $\mathbf{x}$. In (5), h_i can be further expressed as follows:

$$h_i = P\left[\frac{P_{r(i)}}{\sum_{k\in\Gamma_i} G_{r(i),k}P_kF_k} < \beta_{r(i)}\right], \tag{7}$$

where Γ_i denotes the set of nodes which concurrently transmits with node i. Note that Γ_i depends on $\mathbf{x}$.

In the meantime, if $z_1, \ldots, z_n$ are independent exponentially distributed random variables with means $\mathbf{E}[z_i] = 1/\lambda_i$, we have the following expression from [28]:

$$P\left[z_1 \leq \sum_{i=2}^{n} z_i\right] = 1 - \prod_{i=2}^{n}\left(\frac{1}{1+\lambda_1/\lambda_i}\right). \tag{8}$$

By using (8), (7) becomes

$$\begin{aligned} h_i &= \mathbb{E}\left[1 - \prod_{k\in\Gamma_i} \frac{1}{1 + \frac{\beta_{r(i)}G_{r(i),k}P_k}{G_{r(i),i}P_i}}\right] \\ &\approx \mathbb{E}\left[\sum_{k\in\Gamma_i} \ln\left(1 + \frac{\beta_{r(i)}G_{r(i),k}P_k}{G_{r(i),i}P_i}\right)\right], \end{aligned} \tag{9}$$

where the last approximation comes from $x \approx -\ln(1-x)$ for $x \ll 1$. With the introduction of an indicator function, (9) further becomes

$$\begin{aligned} h_i &= \mathbb{E}\left[\sum_{k\in\mathcal{N}\setminus\{i\}} \ln\left(1 + \frac{\beta_{r(i)}G_{r(i),k}P_kI_{\Gamma_i}(k)}{G_{r(i),i}P_i}\right)\right] \\ &= \sum_{k\in\mathcal{N}\setminus\{i\}} \ln\left(1 + \frac{\beta_{r(i)}G_{r(i),k}P_k}{G_{r(i),i}P_i}\right)P[k \in \Gamma_i], \end{aligned} \tag{10}$$

where an indicator function $I_{\Gamma_i}(k)$ is defined as

$$I_{\Gamma_i}(k) = \begin{cases} 1, & \text{if } k \in \Gamma_i; \\ 0, & \text{otherwise.} \end{cases}$$

Note that, in (10), $\ln(1 + \beta_{r(i)}G_{r(i),k}P_k/G_{r(i),i}P_i)$ is a constant with respect to $\mathbf{x}$ while $P[k \in \Gamma_i]$ is a function of $\mathbf{x}$.

Now, we derive an expression for $P[k \in \Gamma_i]$. In order for any node to interfere with node i's transmission, either its transmission should have not been sensed by node i or it should not sense node i's transmission and attempts to transmit. Thus,

$$P[k \in \Gamma_i] = \frac{\tau_kP_{S_i^C} + (1-\tau_k)\tau_kP_{L_i^C}}{\tau_kP_{S_i^C} + (1-\tau_k)}, \tag{11}$$

where $P_{S_i^C} := P[k \in \mathcal{N} \setminus S_i]$ and $P_{L_i^C} := P[k \in \mathcal{N} \setminus L_if]$. For notational simplicity, let $f(x_i)$ and $g(x_i)$ denote, respectively, the numerator and the denominator in (11) as a function of x_i. Then, together with $P_{S_i^C} = P[G_{r(i),k}P_kF_k \leq x_i] = 1 - e^{-x_i/(G_{r(i),k}P_k)}$ and $P_{L_i^C} = P[G_{k,i}P_iF_i \leq x_k] = 1 - e^{-x_k/(G_{k,i}P_i)}$, we have

$$\begin{aligned} \frac{\partial P[k \in \Gamma_i]}{\partial x_i} &= \frac{(g(x_i) - f(x_i))f'(x_i)}{\{g(x_i)\}^2} \\ &\leq \left(\frac{\tau_k}{1-\tau_k}\right)\frac{\partial P_{S_i^C}}{\partial x_i} \leq \frac{\tau_{\max}}{e(1-\tau_{\max})x_{\min}}, \end{aligned} \tag{12}$$

where $\tau_{\max} := \max_k \tau_k$.

In the meantime, from (1), $(G_{r(i),k}P_k)/G_{r(i),i}P_i \leq P_{\max}/\gamma_{r(i)}$, where $P_{\max}$ is the maximum feasible transmit power. Consequently, from (6), (10), and (12), we have

$$\begin{aligned} \frac{\partial f_i(\mathbf{x})}{\partial x_i} &\leq v_{\max} + \frac{\partial h_i}{\partial x_i} \leq v_{\max} + K\sum_{k\in\mathcal{N}\setminus\{i\}} \frac{\partial P[k \in \Gamma_i]}{\partial x_i} \\ &\leq v_{\max} + \frac{K(N-1)\tau_{\max}}{e(1-\tau_{\max})x_{\min}}, \end{aligned} \tag{13}$$

where $K = \ln(1 + \beta_{\max} P_{\max}/\gamma_{\min})$, $\beta_{\max} = \max_i \beta_{r(i)}$, and $\gamma_{\min} = \min_i \gamma_{r(i)}$.

Finally, from (13) and [27, Proposition 1.11, p. 194], the step size λ_i should satisfy

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

In a similar manner, from (10) and (11), we have

$$\begin{aligned} \sum_{j\in\mathcal{N}\setminus\{i\}} \left|\frac{\partial h_i}{\partial x_j}\right| &\le K \sum_{j\in\mathcal{N}\setminus\{i\}} \frac{\partial P[j\in\Gamma_i]}{\partial x_j} \\ &\le \frac{K(N-1)\tau_{\max}}{e x_{\min}}. \end{aligned} \tag{14}$$

Hence, from (14), the condition $\partial f_i/\partial x_i > \sum_{j\neq i} |\partial f_i/\partial x_j|$ in [27, Proposition 1.11, p. 194] is satisfied if $v_i > K(N-1)\tau_{\max}/(e x_{\min})$. □

Remark 1. Note that the conditions in Proposition 1 are not necessary, but sufficient. In practice, the algorithm in (4) may converge even if the conditions in Proposition 1 are not satisfied. Still, Proposition 1 provides a very useful theoretical guideline on the relation among the design parameters, i.e., λ_i and v_i, and the system parameters.

4.4 Incorporation of DCUA into Topology Control

In this section, we give an exemplary algorithm for determining transmit power and carrier sense threshold to demonstrate the utility of the proposed framework. We use a localized topology control algorithm, LMST, as the component algorithm for power control. For the completeness of the paper, we briefly summarize LMST. The interested reader is referred to [4] for a detailed account of LMST and its properties.

4.4.1 Topology Control by LMST

LMST is composed of three phases: information collection, topology construction, and determination of transmit power. In the information collection phase, the information needed by each node for topology construction is obtained by having each node periodically broadcast a Hello message using its maximal transmit power. A Hello message includes the node id and the position of the node. In this manner, each node knows which other nodes are in its neighborhood and their positions. In the topology construction phase, each node independently applies Prim's algorithm [29] to obtain its local minimum spanning tree in the neighborhood. In the power determination phase, each node takes only the one-hop, on-tree nodes as its neighbors, and determines the minimal power needed to reach all its neighbors.

A salient feature of LMST is that it is fully localized since it only depends on the information collected locally in the neighborhood. Also, LMST has been analytically proved to preserve network connectivity and to bound the node degree of every node by six in the resulting topology. Finally, the topology derived by LMST can be transformed into one with bidirectional links without impairing the network connectivity after removal of all unidirectional links.

4.4.2 Distributed Carrier Sense Update Algorithm

Now, given the power assignment by LMST, we discuss how to distributively update the carrier sense threshold of node i based on our analysis in Section 4. Our proposed algorithm, entitled DCUA, is given in Algorithm 1.[2] For each time interval of T, node i estimates its PER q_i as $q_i = n_C/n_T$, where n_C and n_T are, respectively, the total number of packet errors and the total number of transmission attempts made in the interval. Then, node i updates its carrier sense threshold x_i based on (4). Note that the notion of PER here is the same as that of the conditional collision probability in the proof of Proposition 1.

Besides the pricing parameter v_i and the step size λ_i that can be set by Proposition 1, there are two tunable parameters in Algorithm 1, i.e., T and q_i^{th}. Fortunately, network performance is quite robust to the choice of these parameters for the following reasons: In principle, the update interval T is mainly related to the convergence speed of the algorithm and is not critical to the throughput performance. Specifically, the larger the value of T, the slower the convergence speed. As long as T is large enough to properly estimate the PER q_i, network performance will not change significantly for different values of T. In the simulation study, the value of T is set to 5 seconds.

Algorithm 1. Distributed carrier sense update algorithm (DCUA)

Reset timer $t \leftarrow T$
$n_T \leftarrow 0$ and $n_C \leftarrow 0$
while (True) **do**
  if node i transmits a packet **then**
    $n_T \leftarrow n_T + 1$
    if transmission fails **then**
      $n_C \leftarrow n_C + 1$
    end if
  end if
end while
$q_i \leftarrow n_C/n_T$
$x_i \leftarrow x_i - \lambda_i(v_i x_i - (q_i^{\text{th}} - q_i))$

The PER threshold q_i^{th} is more critical to network performance than T. If q_i^{th} is set too large, network performance will degrade due to excessive transmission failures. On the other hand, if q_i^{th} is set too small, the carrier sense threshold x_i will become unnecessarily small and network performance will degrade as a result of insufficient spatial reuse. Still, our simulation results show that network performance is not very sensitive to q_i^{th} as long as q_i^{th} remains in a reasonable region, e.g., $q_i^{\text{th}} \in [0.1, 0.3]$. We will further elaborate on the effect of q_i^{th} to network performance in the next section.

5 SIMULATION STUDIES

In this section, we evaluate the performance of LMST-DCUA by comparing with LMST and standard CSMA (no-LMST) via simulation with J-Sim [10]. We use IEEE 802.11a as the PHY/MAC protocol. The default values of parameters used in the simulation are given in Table 1. In particular, since the focus of this paper is on the interaction between topology control and physical carrier sense in generic CSMA wireless

2. In order to develop a fully distributed algorithm without introducing additional information exchange, the packet error rate is calculated in Algorithm 1 by observing the event of no ACK under the assumption that ACK packet loss is insignificant. This assumption is reasonable since ACK packets are usually transmitted at the lowest data rate.

TABLE 1
Default Values of Parameters Used in the Simulation Studies

Parameter	Value	Definition
N	100	Number of nodes
L	1024 bytes	Payload size
R	6, 18, 36, 54 Mb/s	Data rate
CW	63	Fixed contention window size
$d_{\max}$	100 m	Maximal transmission range
q_i^{th}	0.2	PER threshold
λ_i	10^{-12}	Update step size
v_i	10^8	Pricing parameter
T	5 seconds	Update interval

networks, we disable the binary exponential backoff (BEB) mechanism in IEEE 802.11a and use a fixed contention window size of 63 as given in Table 1. Investigation on the interaction between the BEB algorithm and physical carrier sense will be an interesting avenue for our future research. Fig. 3 shows the network topology used for the simulation study. A total of N (=100) nodes are randomly distributed in an area of $500 \times 500\ \mathrm{m}^2$. Half of the nodes are randomly selected as sources, and for each source, a receiver is randomly selected from its one-hop neighbors. The two-ray ground model is used as the propagation model. For

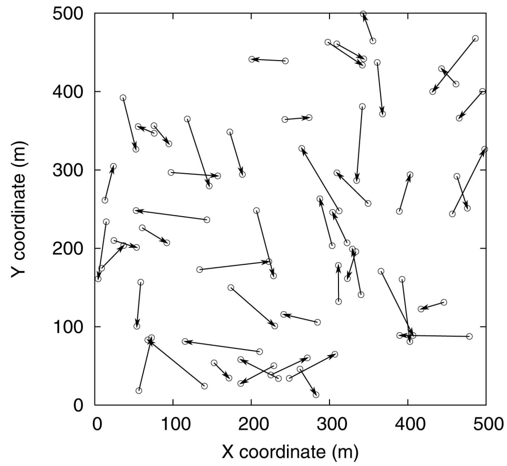

Fig. 3. The network topology used in the simulation study.

LMST and LMST-DCUA, the transmit power used by each node is determined by LMST, while for no-LMST, all nodes use the common transmit power that gives a transmission range of 100 m. All sources generate CBR traffic at their full data rate. For LMST-DCUA, every node sets the initial value of its carrier sense threshold to -85 dBm.

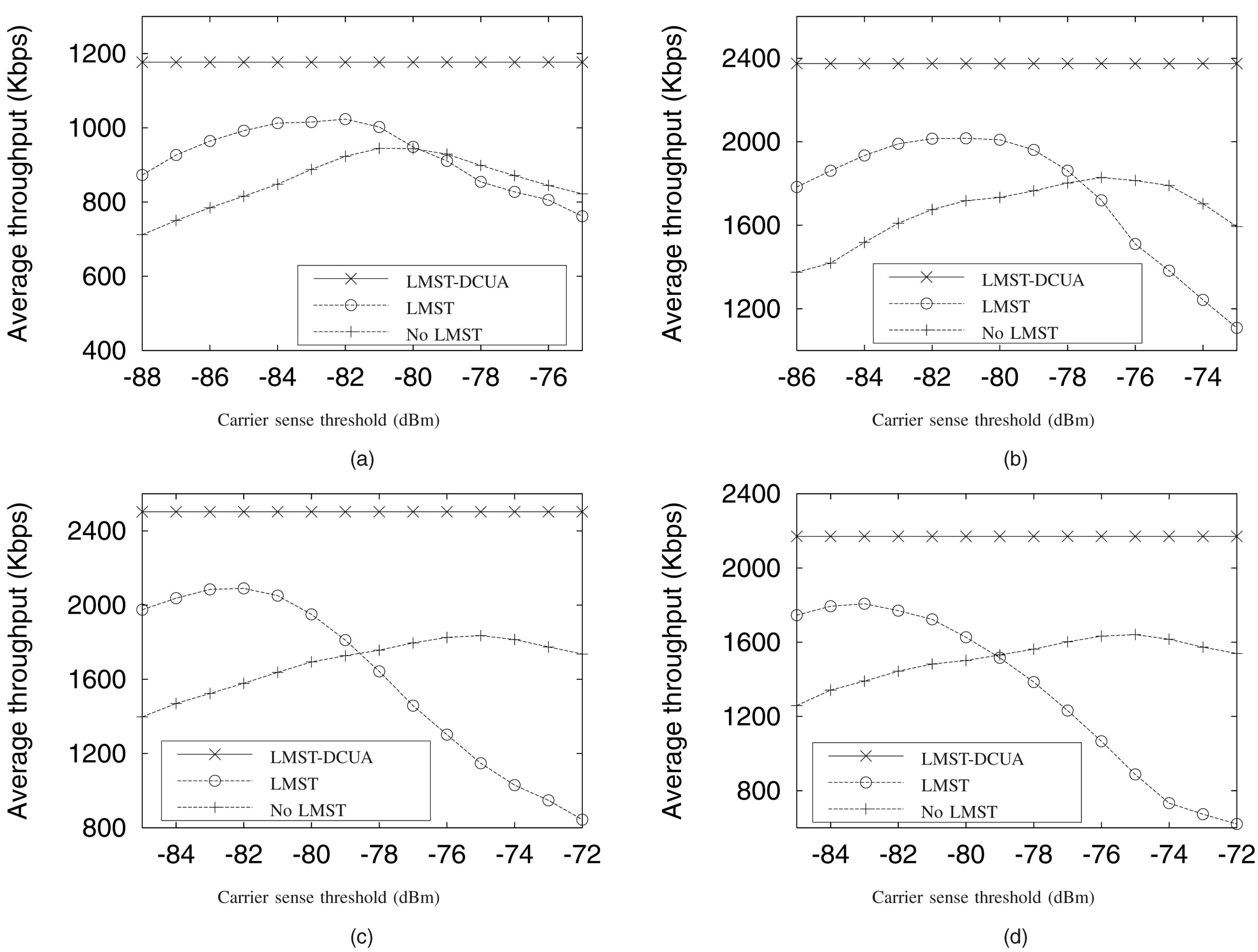

Fig. 4. Average node throughput versus carrier sense threshold. (a) Data rate $R = 6$ Mb/s. (b) Data rate $R = 18$ Mb/s. (c) Data rate $R = 36$ Mb/s. (d) Data rate $R = 54$ Mb/s.

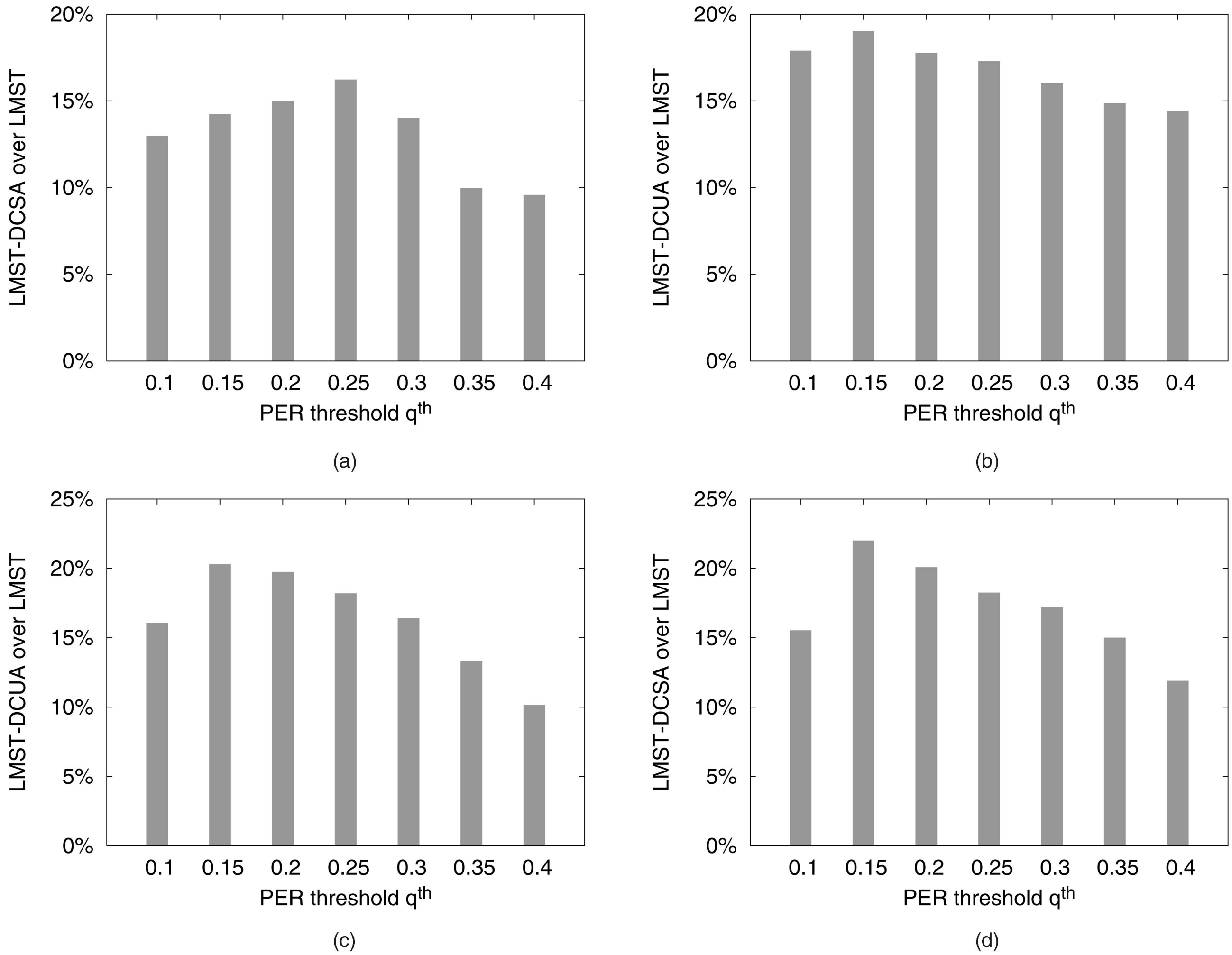

Fig. 5. Relative throughput gain of LMST-DCUA over maximal throughput of LMST versus PER threshold $q^{\rm th}$. (a) Data rate $R = 6$ Mb/s. (b) Data rate $R = 18$ Mb/s. (c) Data rate $R = 36$ Mb/s. (d) Data rate $R = 54$ Mb/s.

5.1 Node Throughput Comparison among LMST-DCUA, LMST, and Standard CSMA

Fig. 4 gives the average per-node throughput (averaged over all the nodes) versus the common carrier sense threshold for different values of $R = 6$, 18, 36, and 54 Mb/s, respectively. Note that the x-axis in Fig. 4 does not apply to LMST-DCUA, because it exercises a dynamic control algorithm for the carrier sense threshold. As shown in Fig. 4, LMST-DCUA achieves much better throughput performance than LMST as well as no-LMST at all data rates. Specifically, LMST-DCUA achieves 24.59, 29.87, 36.32, and 32.27 percent higher throughput than the maximal throughput achieved by no-LMST at $R = 6$, 18, 36, and 54 Mb/s, respectively; and 14.99, 17.78, 19.75, and 20.09 percent higher throughput than the maximal throughput achieved by LMST at $R = 6$, 18, 36, and 54 Mb/s, respectively. Furthermore, as shown in Fig. 4, if an inappropriate carrier sense threshold is chosen, both LMST and no-LMST will become even worse. Consequently, the performance of LMST-DCUA will be much better than that of LMST and no-LMST in practice.

We can also observe from Fig. 4 that the throughput achieved by LMST rapidly degrades and even becomes smaller than that with no-LMST, as the carrier sense threshold increases beyond the value that achieves the maximal throughput. This is because the number of transmission failures caused by the violation of the SIR constraint significantly increases as the carrier sense threshold increases. Since LMST uses the minimal possible transmit power subject to network connectivity, the SIR perceived at a receiver can be smaller than that with no-LMST. Furthermore, the interference from other nodes becomes more severe as the carrier sense threshold increases. These two facts lead to the performance degradation of LMST with increased carrier sense threshold. Consequently, an algorithm that uses a fixed value for the carrier sense threshold is not sufficient since the optimal carrier sense threshold depends on various factors (such as power assignment, node distribution, and traffic patterns) and is not available in advance. Therefore, DCUA is very promising in that it is self-adaptive and operates in a fully distributed manner.

5.2 Convergence Behavior of LMST-DCUA

Figs. 6a and 6b give the temporal behavior of how the carrier sense threshold adapts under LMST-DCUA when $R = 18$ Mb/s and $R = 36$ Mb/s, respectively. In particular, Fig. 6 shows the time traces of the carrier sense thresholds of five randomly selected nodes. The traces of the carrier sense thresholds for other nodes exhibit very similar trends, and hence, are not shown. As shown in Fig. 6, the carrier

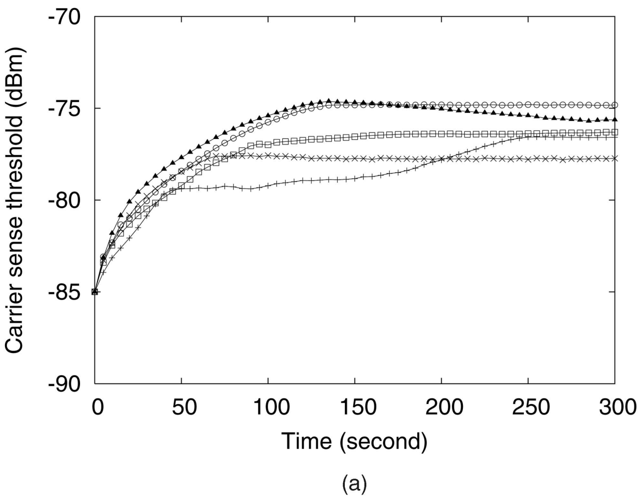

Fig. 6. Time traces of carrier sense thresholds of five randomly selected nodes. (a) Data rate $R = 18$ Mb/s. (b) Data rate $R = 36$ Mb/s.

sense threshold of each node initially starts from the default initial value of -85 dBm, and eventually, becomes stabilized. Note that the converged value of the carrier sense threshold is naturally different for each node according to its environment such as node distribution and power assignment.

5.3 Effect of PER Threshold

We now investigate the effect of the PER threshold $q^{\rm th}$ on the throughput performance of LMST-DCUA. Fig. 5 gives the relative throughput gain of LMST-DCUA over LMST versus $q^{\rm th}$ at $R = 6$, 18, 36, and 54 Mb/s. As shown in Fig. 5, the throughput performance of LMST-DCUA is not so much sensitive to $q^{\rm th}$ at all data rates as long as $q^{\rm th}$ lies in a reasonable region, e.g., $q^{\rm th} \in [0.1, 0.3]$. Note that the optimal value for $q^{\rm th}$ changes for different data rates. For example, from Fig. 5, $q^{\rm th} = 0.25$ gives the maximum throughput improvement when $R = 6$ Mb/s while $q^{\rm th} = 0.15$ does in the other cases. Hence, one can also think of developing an adaptive scheme for $q^{\rm th}$, which can update $q^{\rm th}$ according to the network operating condition. In addition, since the optimal operating point will be different for each node, heterogeneous values for $q^{\rm th}$ will further improve the overall network performance. The development of an adaptive algorithm for $q^{\rm th}$ of each node is a subject of future work.

6 Conclusion

We have presented a framework on how to incorporate physical carrier sense into topology control. The framework decouples the problem of jointly assigning the transmit power and the carrier sense threshold into two subproblems. For the first power control subproblem, we can leverage existing localized topology control algorithm. To devise an efficient solution algorithm to the second subproblem of determining carrier sense threshold, we formulate the problem as distributed optimization. Then, we derive a sufficient condition on the convergence of an iterative algorithm for solving the proposed optimization problem. Based on our analysis, we devise a fully distributed algorithm to dynamically control carrier sense threshold, entitled DCUA, so as to exploit spatial reuse while taking into account the SIR constraint. The major contribution of our work is that it bridges the gap between conventional graph-theoretic topology control and SIR-based control of PHY/MAC attributes in CSMA wireless networks.

We are currently investigating several issues. In particular, a contention resolution mechanism such as the binary exponential backoff (BEB) mechanism in IEEE 802.11 is influenced by transmit power and carrier sense threshold. Investigating the interaction between the proposed framework and a contention resolution mechanism will lead to performance improvement along another dimension.

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