

Effective Carrier Sensing in CSMA Networks under Cumulative Interference

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Abstract—This paper proposes the concept of *safe carrier-sensing range* under the *cumulative interference model* that guarantees interference-safe (also known as hidden-node-free) transmissions in CSMA networks. Compared with a previous related concept of safe carrier-sensing range under the commonly assumed but less realistic pairwise interference model, we show that the safe carrier-sensing range under the cumulative interference model is larger by a *constant* multiplicative factor. For example, the factor is 1.4 if the SINR requirement is 10dB and the path-loss exponent is 4 in a noiseless case. We further show that the concept of a safe carrier-sensing range, although amenable to elegant analytical results, is inherently not compatible with the conventional power-threshold carrier-sensing mechanism (e.g., that used in IEEE 802.11). Specifically, the absolute power sensed by a node in the conventional carrier-sensing mechanism does not contain enough information for the node to derive its distances from other concurrent transmitting nodes. We show that, fortunately, a new carrier-sensing mechanism called Incremental-Power Carrier-Sensing (IPCS) can realize the carrier-sensing range concept in a simple way. Instead of monitoring the absolute detected power, the IPCS mechanism monitors every increment in the detected power. This means that IPCS can separate the detected power of every concurrent transmitter, and map the power profile to the required distance information. Our extensive simulation results indicate that IPCS can boost spatial reuse and network throughput by up to 60% relative to the conventional carrier-sensing mechanism under the same carrier-sensing power thresholds. If we compare the maximum throughput in the interference-free regime, the throughput improvement of IPCS is still more than 15%. Last but not least, IPCS not only allows us to implement the safe carrier-sensing range, but also ties up a loose end in many other prior theoretical works that implicitly used a carrier-sensing range (interference-safe or otherwise) without an explicit design to realize it.

Index Terms—carrier-sensing range, cumulative interference model, CSMA, WiFi, IEEE 802.11, SINR constraints, spatial reuse.

1 INTRODUCTION AND OVERVIEW

Due to the broadcast nature of wireless channels, signals transmitted over wireless links can mutually interfere with each other. Optimizing spatial reuse and network throughput under such mutual interferences has been an intensely studied issue in wireless networking. In particular, it is desirable to allow as many links as possible to transmit together in an interference-safe (or collision-free) manner. The problem of interference-safe transmissions under the coordination of a centralized TDMA (Time-Division Multiple-Access) scheduler has been well studied (e.g., see [2]–[7]). Less well understood is the issue of interference-safe transmissions under the coordination of a distributed scheduling protocol.

The CSMA (Carrier-Sense Multiple-Access) protocol, such as IEEE 802.11, is the most widely adopted distributed scheduling protocol in practice. As the growth of 802.11 network deployments continues unabated, we are witnessing an increasing level of mutual interference among transmissions in such networks. It is critical to establish a rigorous conceptual framework upon which effective solutions to interference-safe transmissions can be constructed.

Within this context, this paper has three major contributions listed as follows (more detailed overview is given in the succeeding paragraphs):

- 1) We propose the concept of a *safe carrier-sensing range* that guarantees interference-safe transmissions in CSMA networks under the *cumulative interference model*.
- 2) We show that the concept is implementable using a simple Incremental-Power Carrier-Sensing (IPCS) mechanism.
- 3) We demonstrate that implementation of the safe carrier-sensing range under IPCS can significantly improve spatial reuse and network throughput as compared to the conventional absolute-power carrier-sensing mechanism.

Regarding 1), this paper considers the cumulative interference model (also termed physical interference

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This work is supported by AoE grant E-02/08 from the UGC of the Hong Kong SAR, China, the General Research Funds (Project Number 412511 and 414911) established under the University Grant Committee of the Hong Kong Special Administrative Region, China.

model in [8]), in which the interference at a receiver node includes the cumulative power received from all the other nodes that are currently transmitting (except its own transmitter). This model is more realistic, but is much more difficult to analyze than the widely studied pairwise interference model (also termed the protocol interference model in [8]) in the literature. Under the cumulative interference model, a set of simultaneously transmitting links are said to be *interference-safe* if the SINRs (Signal-to-Interference-plus-Noise Ratios) at these links' receivers are above a threshold. Given a set of links \mathcal{L} in the network, there are many subsets of links, $\mathcal{S} \subset \mathcal{L}$, that are interference-safe. The set of all such subsets $\mathcal{F} = \{\mathcal{S} \mid \text{the SINRs of all links in } \mathcal{S} \text{ are satisfied}\}$ constitutes the feasible interference-safe state space. For centralized TDMA, all subsets are available for scheduling, and a TDMA schedule is basically a sequence $(\mathcal{S}_i)_{i=1}^n$ where each $\mathcal{S}_i \in \mathcal{F}$. For CSMA, because of the random and distributed nature of the carrier-sensing operations by individual nodes, the simultaneously transmitting links \mathcal{S}^{CS} may or may not belong to \mathcal{F} . Let $\mathcal{F}^{CS} = \{\mathcal{S}^{CS} \mid \text{simultaneous transmissions of links in } \mathcal{S}^{CS} \text{ are allowed by the carrier-sensing operation}\}$. The CSMA network is said to be interference-safe if $\mathcal{F}^{CS} \subseteq \mathcal{F}$. This is also the condition for the so-called hidden-node free operation [9]. However, this issue was studied under the context of an idealized pairwise interference model in [9] rather than the practical cumulative interference model of interest here. In this paper, we show that if the carrier-sensing mechanism can guarantee that the distance between every pair of transmitters is separated by a *safe carrier-sensing range*, then $\mathcal{F}^{CS} \subseteq \mathcal{F}$ can be guaranteed and the CSMA network is interference-safe even under the cumulative interference model. The safe carrier-sensing range established in this paper is a tight upperbound and achieves good spatial reuse.

Given the above result, the next important issue to address is how to implement a carrier-sensing mechanism such that every pair of simultaneous transmitting nodes is separated by the targeted carrier-sensing range. This brings us to 2) above. In the conventional carrier sensing based on a power threshold (e.g., that of the *basic mode* in IEEE 802.11), each transmitter monitors the absolute power received. This power consists of the sum total of powers received from all the other transmitters. It is impossible to infer from this absolute power the exact separation of the node from each of the other transmitters. This is thus not compatible with the concept of safe carrier-sensing range, and leads to poor spatial reuse. To address this, we propose a simple mechanism that monitors the incremental power changes over time, IPCS, which enables us to map the power profile to the required distance information. We believe that this mechanism, although simple, has a significant contribution as it shows that the theoretical concept

of *safe carrier-sensing range* can be implemented rather easily in practice. It also ties up a loose end in many other prior theoretical works that implicitly assume the use of a carrier-sensing range (interference-safe or otherwise) without an explicit design to realize it. That is, IPCS can be used to implement the required carrier-sensing range in these works, not just our *safe carrier-sensing range* here.

Given the implementability of a safe carrier-sensing range, the next issue is how tight the simultaneously transmitting nodes can be packed. This brings us to 3) above. In the conventional carrier-sensing mechanism, to ensure that the detected absolute power is below the carrier-sensing power threshold, the separation between a newly active transmitter and other existing active transmitters must increase progressively as the number of concurrent transmissions increases. That is, the cost of ensuring interference-safe transmissions becomes progressively higher and higher in the "packing process". This reduces spatial reuse and the overall network throughput. Fortunately, with IPCS, the required separation between any pair of active transmitters remains constant as the *safe carrier-sensing range*, and is independent of the number of concurrent transmissions. Indeed, our simulation results indicate that IPCS mechanism can improve the spatial reuse and the network throughput by up to 60% compared with the conventional carrier-sensing mechanism under the same carrier-sensing power thresholds. If we compare the maximum throughput in the interference-free regime, the throughput improvement of IPCS is still more than 15%.

1.1 Related Work

In the literature, most studies on carrier sensing (e.g., [9]–[15]) are based on the pairwise interference model. For a link under the pairwise interference model, the interferences from the other links are considered one by one. If any two links can transmit concurrently without a collision, then it is assumed that there is no collision overall. Ref. [9] established the carrier-sensing range required to prevent hidden-node collisions in CSMA networks under the pairwise interference model. Ref. [14] studied the use of power control to increase network capacity again under the pairwise interference model. The resulting separations between transmitting nodes in [9] and [14] are overly optimistic and cannot eliminate hidden-node collisions if the more accurate cumulative interference model is adopted.

A number of recent papers studied the CSMA networks under the cumulative interference model (e.g., [16]–[19]). An earlier unpublished technical report of ours [16] derived the safe carrier-sensing range under the cumulative interference model. The technical report, however, did not include the IPCS realization presented in this paper. Neither did Ref. [17]–[19] address the implementation of a carrier-sensing

TABLE 1
Summary of the Related Work

Interference Models	Pairwise Interference Model	Cumulative Interference Model
Absolute power carrier sensing	many (e.g., [9], [10])	[18], [19]
Incremental power carrier sensing	This paper	This paper

range based on power detection. Ref. [17] studied the asymptotic capacity of large-scale CSMA networks with hidden-node-free designs. The focus of [17] is on an “order” result rather than a “tight” result. For example, in the noiseless case where $\gamma_0 = 10dB$ and $\alpha = 4$, the safe carrier-sensing range derived in [17] is $8.75d_{\max}$. In this paper, we show that setting the safe carrier-sensing range to $5.27d_{\max}$ is enough to prevent hidden-node collisions.

The authors in [18], [19] attempted to improve spatial reuse and capacity by tuning the transmit power and the carrier-sensing range. Although the cumulative interference model is considered in [18], [19], spatial reuse and capacity are analyzed based on a carrier-sensing range. In particular, they assumed that the transmitters of concurrent transmission links can be uniformly packed in the network. As discussed in this paper, such uniform packing cannot be realized using the current 802.11 carrier-sensing mechanism. Therefore, the results in [18], [19] are overly optimistic without an appropriate carrier-sensing mechanism. IPCS fills this gap so that the theoretical results of [18], [19] remain valid. We summarize the key related models and results in the literature in Table 1*.

In this paper, we focus on 802.11 networks operating with the basic access mode. We do not consider virtual carrier sensing (i.e., the RTS/CTS mode). Ensuring interference-safe operation under virtual carrier sensing is rather complicated even under the pairwise interference model (see [12] for details); when the cumulative interference model is considered, the use of RTS/CTS requires more modifications at the MAC layer of the 802.11 protocol in order to ensure interference-safe transmissions.

2 SYSTEM MODEL

2.1 Cumulative Interference Model

We represent links in a wireless network by a set of distinct and directed transmitter-receiver pairs $\mathcal{L} = \{l_i, 1 \leq i \leq |\mathcal{L}|\}$. Let $\mathcal{T} = \{T_i, 1 \leq i \leq |\mathcal{L}|\}$ and $\mathcal{R} = \{R_i, 1 \leq i \leq |\mathcal{L}|\}$ denote the set of transmitter nodes and the set of receiver nodes, respectively. A

*. This paper focuses on the incremental-power carrier-sensing (IPCS) mechanism under the cumulative interference model. But IPCS proposed in this paper can also deal with the pairwise interference model.

receiver decodes its signal successfully if and only if the received Signal-to-Interference-plus-Noise Ratio (SINR) is above a certain threshold. We adopt the cumulative interference model, where the interference is the sum of the received powers from all transmitters except its own transmitter. We assume that radio signal propagation follows the log-distance path model with a path loss exponent $\alpha > 2$. The path gain $G(T_i, R_j)$ from transmitter T_i to receiver R_j is:

$$G(T_i, R_j) = G(d_0) \cdot \left(\frac{d(T_i, R_j)}{d_0} \right)^{-\alpha},$$

where $d(T_i, R_j)$ is the Euclidean distance between nodes T_i and R_j , and $G(d_0)$ is the reference path gain at the reference distance d_0 [20]. Without loss of generality, we assume $d_0 = 1$ and use G_0 to denote the reference path gain at $d_0 = 1$. So the path gain $G(T_i, R_j)$ is

$$G(T_i, R_j) = G_0 \cdot d(T_i, R_j)^{-\alpha}.$$

In 802.11, each packet transmission on a link l_i consists of a DATA frame in the forward direction (from T_i to R_i) followed by an ACK frame in the reverse direction (from R_i to T_i). The packet transmission is said to be successful if and only if both the DATA frame and the ACK frame are received correctly. Let \mathcal{L}' (\mathcal{L}'') denote the set of links that transmit concurrently with the DATA (ACK) frame on link l_i . Under the cumulative interference model, a successful transmission on link l_i needs to satisfy the following conditions:

$$\frac{P_t \cdot G(T_i, R_i)}{N + \sum_{l_j \in \mathcal{L}'} P_t \cdot G(S_j, R_i)} \geq \gamma_0, \quad (\text{DATA frame}) \quad (1)$$

and

$$\frac{P_t \cdot G(R_i, T_i)}{N + \sum_{l_j \in \mathcal{L}''} P_t \cdot G(S_j, T_i)} \geq \gamma_0, \quad (\text{ACK frame}) \quad (2)$$

where P_t is the transmit power, N is the average noise power, and γ_0 is the SINR threshold for a successful reception. We assume that all nodes in the network use the same transmit power P_t and adopt the same SINR threshold γ_0 . For a link l_j in \mathcal{L}' (\mathcal{L}''), S_j represents the sender of l_j , which can be either T_j or R_j . This is because both DATA and ACK transmissions on link l_j may cause interference to link l_i .

2.2 Existing Carrier Sensing Mechanism in 802.11

If there exists a link $l_i \in \mathcal{L}$ such that not both (1) and (2) are satisfied, then there is a collision in the network. In 802.11, carrier sensing is designed to prevent such collisions. In this paper, we assume carrier sensing by energy detection. Consider a link l_i . If transmitter T_i senses a power $P^{CS}(T_i)$ that exceeds a power threshold P_{th} , i.e.,

$$P^{CS}(T_i) > P_{th}, \quad (3)$$

then T_i will not transmit and its backoff countdown process will be frozen. This will prevent the DATA frame transmission on l_i . A proper choice of P_{th} can prevent collisions without significantly reducing spatial reuse in the network.

2.3 Carrier-sensing Range Concept

In most studies of 802.11 networks, the concept of a carrier-sensing range (CSR) is introduced. Consider two links, l_i and l_j . If the distance between transmitters T_i and T_j is no less than the carrier-sensing range, i.e.,

$$d(T_i, T_j) \geq CSR, \quad (4)$$

then it is assumed that T_i and T_j cannot carrier sense each other, and thus they can initiate concurrent transmissions on links l_i and l_j . The pairwise relationship can be generalized to a set of links $S^{CS} \subseteq \mathcal{L}$. If condition (4) is satisfied by all pairs of transmitters in set S^{CS} , then all links in S^{CS} can transmit concurrently.

The carrier-sensing range (and the corresponding power threshold used in the practical protocol design) is crucial to the throughput performance of CSMA-type networks. If CSR is too large, spatial reuse will be unnecessarily limited. If CSR is not large enough, then hidden-node collisions may occur, due to the violation of (1) or (2). We now define a *safe carrier-sensing range* that always prevents the hidden-node collisions in 802.11 networks under the cumulative interference model:

Definition 1 (Safe- $CSR_{cumulative}$): Let $S^{CS} \subseteq \mathcal{L}$ denote a subset of links that are allowed to transmit concurrently under a carrier-sensing range CSR . Let $\mathcal{F}^{CS} = \{S^{CS}\}$ denote all such subsets of links in the network. A CSR is a safe carrier-sensing range under the cumulative interference model (denoted as *Safe- $CSR_{cumulative}$*) if for any $S^{CS} \in \mathcal{F}^{CS}$ and for any link $l_i \in S^{CS}$, both conditions (1) and (2) are satisfied, with $\mathcal{L}' = \mathcal{L}'' = S^{CS} \setminus \{l_i\}$.

2.4 Mapping CSR to P_{th}

The carrier-sensing range concept is widely used to capture the carrier-sensing mechanism in 802.11 (e.g., [9]–[14], [18], [19]). The carrier-sensing range describes the minimum distance requirement between every pair of transmitters of the links that can concurrently transmit. Therefore, the carrier-sensing range is a *pair-wise* concept. However, the current energy-detection carrier-sensing mechanism in 802.11 compares the detected absolute power with a power threshold P_{th} . The detected power consists of the sum total of powers received from all the other transmitters. From this absolute detected power, it is impossible for a node to infer the exact separation between it and each of the other transmitters. Thus, the concept of carrier-sensing range cannot be realized in a precise manner. In short, there is a gap between the pair-wise

carrier-sensing range concept and the absolute power detection carrier-sensing mechanism.

Nevertheless, if we really want to ensure that the separation between any pair of transmitters is no less than the carrier-sensing range CSR , the carrier-sensing power threshold P_{th} can be set as:

$$P_{th} = P_t G_0 (CSR)^{-\alpha}. \quad (5)$$

This is, however, a very conservative way to set the power threshold. It makes use of the fact that if the aggregate power received from all transmitters is less than P_{th} , then the power from any of the transmitters is less than P_{th} . Hence, the minimum separation of CSR can be guaranteed. Effectively, we are treating the power sensed as the power from one individual transmitter only. For example, using the above power threshold, we observe that the separation between concurrent transmitters will increase progressively as more links join in the simultaneous transmissions (detailed explanation is in Section 4.1). In other words, the carrier-sensing range concept cannot be implemented effectively with the current carrier-sensing mechanism. A consequence of this is that the spatial reuse is reduced unnecessarily.

In this paper, we propose a new Incremental-Power Carrier-Sensing (IPCS) to fill the gap of effective implementation of the carrier-sensing range concept. In particular, setting the carrier-sensing power threshold as in (5) in IPCS allows precise implementation of the carrier-sensing range CSR (see Section 4 for details).

3 SAFE CARRIER-SENSING RANGE UNDER CUMULATIVE INTERFERENCE MODEL

In this section, we derive a sufficient condition for *Safe- $CSR_{cumulative}$* . When discussing the hidden-node free design, it is required that the receivers are operated with the “RS (Re-Start) mode”.

3.1 The Need for RS (Re-Start) Mode

It is shown in [9] that even when the carrier-sensing range is sufficiently large to satisfy the SINR requirements of simultaneous transmitting nodes, transmission failures can still occur due to the “Receiver-Capture effect”.

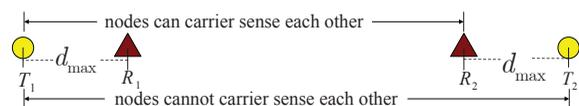


Fig. 1. Collision due to “Receiver-Capture effect”

Consider a two-link example shown in Fig. 1, where $d(T_1, T_2) > CSR$ and $d(T_1, R_2) < CSR$. So the transmitters T_1 and T_2 cannot carrier-sense each other, but

R_2 can sense the signal transmitted from T_1 . Suppose that CSR is set large enough to guarantee the SINR requirements on l_1 and l_2 (both the DATA frames and the ACK frames). If T_1 transmits first, then R_2 can sense the signal of T_1 . The default operation in most 802.11 products is that R_2 will not attempt to receive the later signal from T_2 , even if the signal from T_2 is stronger. This will cause the transmission on link l_2 to fail. It is further shown in [9] that no matter how large the carrier-sensing range is, we can always come up with an example that leads to transmission failures, if the "Receiver-Capture effect" is not dealt with properly. This kind of collisions can be solved with a receiver "RS (Re-Start) mode". In some commercial WiFi chips (e.g., the Atheros WiFi chips), the RS mode is supported. With RS mode, a receiver will switch to receive the stronger packet as long as the SINR threshold γ_0 for the later link can be satisfied. In the above example, when T_2 transmits to R_2 , because the power from T_2 is much larger than the power from T_1 , R_2 will switch to receive the packet of T_2 in the RS mode. In the following discussion, we also make the same assumption that the receivers are operated with the "RS (Re-Start) mode".

3.2 Safe Carrier-sensing Range under Cumulative Interference Model

Ref. [9] studied the safe carrier-sensing range under the *pairwise interference model* in the noiseless case. The threshold is given as follows:

$$Safe-CSR_{pairwise} = \left(\gamma_0^{\frac{1}{\alpha}} + 2\right) d_{\max}, \quad (6)$$

where $d_{\max} = \max_{i \in \mathcal{L}} d(T_i, R_i)$ is the maximum link length in the network. However, the pairwise interference model does not take into account the cumulative nature of interferences from other links. The threshold given in (6) is overly optimistic and is not large enough to prevent hidden-node collisions under the *cumulative interference model*, as illustrated by the three-link example in Fig. 2.

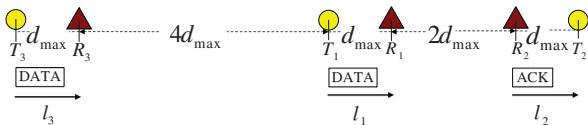


Fig. 2. Setting the carrier-sensing range as $Safe-CSR_{pairwise}$ is insufficient to prevent hidden-node collisions under the cumulative interference model

In Fig. 2, suppose that the SIR requirement $\gamma_0 = 8$ and the path-loss exponent $\alpha = 3$. According to (6), it is enough to set the carrier-sensing range as $\left(\gamma_0^{\frac{1}{\alpha}} + 2\right) d_{\max} = 4d_{\max}$ and the carrier-sensing power threshold $P_{th} = P_t G_0 (4d_{\max})^{-3} =$

$0.0156 P_t G_0 d_{\max}^{-3}$. In Fig. 2, there are three links: l_1 , l_2 , and l_3 with the same link length d_{\max} . The distance $d(R_1, R_2)$ equals $2d_{\max}$ and the distance $d(T_1, R_3)$ equals $4d_{\max}$. Since the distance $d(T_1, T_2) = 4d_{\max} = \left(\gamma_0^{\frac{1}{\alpha}} + 2\right) d_{\max}$, from (4), we find that T_1 and T_2 can simultaneously initiate transmissions since they cannot carrier sense each other. We can verify that the SIR requirements of both DATA and ACK transmissions on l_1 and l_2 are satisfied. This means l_1 and l_2 can indeed successfully transmit simultaneously.

Suppose that l_3 wants to initiate a transmission when T_1 is sending a DATA frame to R_1 , and R_2 is sending an ACK frame to T_2 . Transmitter T_3 senses a power $P^{CS}(T_3)$ given by

$$\begin{aligned} P^{CS}(T_3) &= P_t G_0 \cdot (5d_{\max})^{-3} + P_t G_0 \cdot (8d_{\max})^{-3} \\ &= 0.00995 \cdot P_t G_0 d_{\max}^{-3} < P_{th}. \end{aligned}$$

This means that T_3 cannot sense the transmissions on l_1 and l_2 , and can therefore initiate a DATA transmission. However, when all these three links are active simultaneously, the SIR at R_1 is

$$\frac{P_t G_0 (d_{\max})^{-3}}{P_t G_0 (6d_{\max})^{-3} + P_t G_0 (2d_{\max})^{-3}} = 7.714 < \gamma_0.$$

This means the cumulative interference powers from l_2 and l_3 will corrupt the DATA transmission on l_1 due to the insufficient SIR at R_1 . This example shows that setting the carrier-sensing range as in (6) is not sufficient to prevent collisions under the cumulative interference model. Choosing the parameters $\alpha = 3$ and $\gamma_0 = 8$ is just for an easy illustration. In fact, we can always construct a three-link example like Fig. 2 with the same conclusion for any choice of α and γ_0 .

We next establish a threshold for $Safe-CSR_{cumulative}$ so that the system will remain interference safe under the cumulative interference.

Conjecture 1: The densest packing of concurrent transmitters leads to the worst cumulative interference power at a particular receiver.

Based on Conjecture 1, we have the following theorem:

Theorem 1: Setting

$$Safe-CSR_{cumulative} = (K_1 K_2 + 2) d_{\max}, \quad (7)$$

where

$$K_1 = \left(6\gamma_0 \left(1 + \left(\frac{2}{\sqrt{3}}\right)^\alpha \frac{1}{\alpha - 2}\right)\right)^{\frac{1}{\alpha}}, \quad (8)$$

and

$$K_2 = \left(\frac{P_t G_0}{P_t G_0 - \gamma_0 d_{\max}^\alpha N}\right)^{\frac{1}{\alpha}}, \quad (9)$$

is sufficient to ensure interference-safe transmissions under the cumulative interference model.

Proof: With the receiver's RS mode, in order to prevent hidden-node collisions in 802.11 networks, we only need to show that condition (7) is sufficient to

guarantee the satisfaction of both the SINR requirements (1) and (2) of all the concurrent transmission links.

Let \mathcal{S}^{CS} denote a subset of links that are allowed to transmit concurrently under the *Safe-CSR_{cumulative}* setting in (7). Consider any two links l_i and l_j in \mathcal{S}^{CS} , we have

$$d(T_j, T_i) \geq \text{Safe-CSR}_{cumulative} = (K_1 K_2 + 2)d_{\max}.$$

Because both the lengths of links l_i and l_j satisfy

$$d(T_i, R_i) \leq d_{\max}, \quad d(T_j, R_j) \leq d_{\max},$$

we have the following relationships based on the triangular inequality

$$\begin{aligned} d(T_j, R_i) &\geq d(T_j, T_i) - d(T_i, R_i) \geq (K_1 K_2 + 1)d_{\max}, \\ d(R_j, T_i) &\geq d(T_i, T_j) - d(T_j, R_j) \geq (K_1 K_2 + 1)d_{\max}, \\ d(R_j, R_i) &\geq d(R_i, T_j) - d(T_j, R_j) \geq K_1 K_2 d_{\max}. \end{aligned}$$

We take the most conservative distance $K_1 K_2 d_{\max}$ in our interference analysis (i.e., we will pack the links that transmit concurrently in a tightest manner given the *Safe-CSR_{cumulative}* in (7)). Consider any two links l_i and l_j in \mathcal{S}^{CS} . The following four inequalities are satisfied:

$$\begin{aligned} d(T_i, T_j) &\geq K_1 K_2 d_{\max}, \quad d(T_i, R_j) \geq K_1 K_2 d_{\max}, \\ d(T_j, R_i) &\geq K_1 K_2 d_{\max}, \quad d(R_i, R_j) \geq K_1 K_2 d_{\max}. \end{aligned}$$

Consider any link l_i in \mathcal{S}^{CS} . We will show that the SINR requirements for both the DATA frame and the ACK frame can be satisfied. We first consider the SINR requirement of the DATA frame. The SINR at R_i is:

$$\text{SINR} = \frac{P_t G_0 d^{-\alpha}(T_i, R_i)}{\sum_{l_j \in \mathcal{S}^{CS}, j \neq i} P_t G_0 d^{-\alpha}(S_j, R_i) + N}.$$

For the received signal power, we consider the worst case that $d(T_i, R_i) = d_{\max}$. So we have

$$P_t G_0 d^{-\alpha}(T_i, R_i) \geq P_t G_0 d_{\max}^{-\alpha}. \quad (10)$$

To calculate the worst case cumulative interference power, we consider the case that all the other concurrent transmission links have the densest packing, in which their link lengths are equal to zero. The links then degenerate to nodes. The minimum distance between any two links in \mathcal{S}^{CS} is $K_1 K_2 d_{\max}$. The densest packing of nodes with the minimum distance requirement is the hexagon packing [21] (as shown in Fig. 3).

If link l_j is the first layer neighbor link of link l_i , we have $d(S_j, R_i) \geq K_1 K_2 d_{\max}$. Thus we have

$$\begin{aligned} P_t G_0 d^{-\alpha}(S_j, R_i) &\leq P_t G_0 (K_1 K_2 d_{\max})^{-\alpha} \\ &= \frac{1}{(K_1 K_2)^\alpha} \cdot P_t G_0 d_{\max}^{-\alpha}, \end{aligned}$$

and there are at most 6 neighbor links in the first layer.

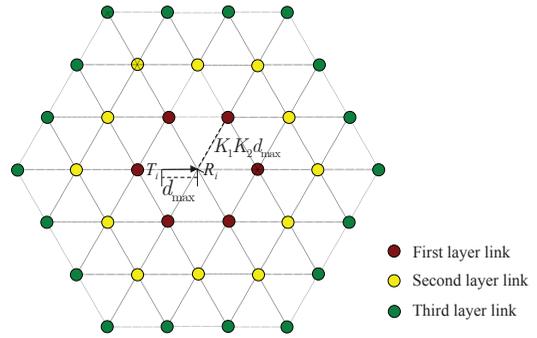


Fig. 3. The packing of interfering links in the worst case

If link l_j is the n th layer neighbor link of link l_i with $n \geq 2$, we have $d(S_j, R_i) \geq \frac{\sqrt{3}}{2} n \cdot K_1 K_2 d_{\max}$. Thus we have

$$\begin{aligned} P_t G_0 d^{-\alpha}(S_j, R_i) &\leq P_t G_0 \left(\frac{\sqrt{3}}{2} n K_1 K_2 d_{\max} \right)^{-\alpha} \\ &= \frac{1}{\left(\frac{\sqrt{3}}{2} n K_1 K_2 \right)^\alpha} P_t G_0 d_{\max}^{-\alpha}, \end{aligned}$$

and there are at most $6n$ links in the n th layer.

So the cumulative interference power satisfies:

$$\begin{aligned} &\sum_{l_j \in \mathcal{S}^{CS}, j \neq i} P_t G_0 d^{-\alpha}(S_j, R_i) \\ &\leq \left(6 \left(\frac{1}{K_1 K_2} \right)^\alpha + \sum_{n=2}^{\infty} 6n \left(\frac{2}{\sqrt{3} n K_1 K_2} \right)^\alpha \right) P_t G_0 d_{\max}^{-\alpha} \\ &= 6 \left(\frac{1}{K_1 K_2} \right)^\alpha \left(1 + \sum_{n=2}^{\infty} n \left(\frac{2}{\sqrt{3} n} \right)^\alpha \right) P_t G_0 d_{\max}^{-\alpha} \\ &= 6 \left(\frac{1}{K_1 K_2} \right)^\alpha \left(1 + \left(\frac{2}{\sqrt{3}} \right)^\alpha \sum_{n=2}^{\infty} n \left(\frac{1}{n} \right)^\alpha \right) P_t G_0 d_{\max}^{-\alpha} \\ &= 6 \left(\frac{1}{K_1 K_2} \right)^\alpha \left(1 + \left(\frac{2}{\sqrt{3}} \right)^\alpha \sum_{n=2}^{\infty} \frac{1}{n^{\alpha-1}} \right) P_t G_0 d_{\max}^{-\alpha} \\ &\leq 6 \left(\frac{1}{K_1 K_2} \right)^\alpha \left(1 + \left(\frac{2}{\sqrt{3}} \right)^\alpha \frac{1}{\alpha - 2} \right) P_t G_0 d_{\max}^{-\alpha}, \quad (11) \end{aligned}$$

where (11) follows from a bound on Riemann's zeta function.

According to (10) and (11), we find that the SINR of the DATA frame of link l_i at the receiver R_i satisfies:

$$\begin{aligned} \text{SINR} &= \frac{P_t G_0 d^{-\alpha}(T_i, R_i)}{\sum_{l_j \in \mathcal{S}^{CS}, j \neq i} P_t G_0 d^{-\alpha}(S_j, R_i) + N} \\ &\geq \frac{P_t G_0 d_{\max}^{-\alpha}}{6 \cdot \left(\frac{1}{K_1 K_2} \right)^\alpha \left(1 + \left(\frac{2}{\sqrt{3}} \right)^\alpha \frac{1}{\alpha - 2} \right) \cdot P_t G_0 d_{\max}^{-\alpha} + N} \\ &= \frac{P_t G_0 d_{\max}^{-\alpha}}{\left(\frac{P_t G_0 d_{\max}^{-\alpha}}{\gamma_0} \right) \cdot \left(\frac{P_t G_0 - \gamma_0 d_{\max}^\alpha N}{P_t G_0} \right) + N} \\ &= \gamma_0, \end{aligned} \quad (12)$$

where (12) follows from the definitions of K_1 and K_2 as shown in (8) and (9), respectively. So the DATA frame transmission on l_i can be guaranteed to be successful. The proof that the SINR requirement of the ACK frame on link l_i can be satisfied follows a similar procedure as above. So condition (7) is sufficient to satisfy the SINR requirements of the successful transmissions of both the DATA and ACK frames. This means that condition (7) is sufficient for preventing hidden-node collisions in CSMA networks under the cumulative interference model. \square

Condition (7) provides a sufficiently large carrier-sensing range that prevents the hidden-node collisions in CSMA networks. Therefore, there is no need to set a CSR larger than the values given in (7). Otherwise the spatial reuse will be decreased unnecessarily.

The terms K_1 and K_2 in (7) reflect the impact of the cumulative interference power from other concurrent transmission links and the background noise power on the safe carrier-sensing range setting, respectively. So we refer to K_1 and K_2 as interference factor and noise factor, respectively.

3.3 The Noise Factor K_2

The noise factor K_2 is a function of the SNR margin (also called the noise margin). Let ρ denote the SNR margin, which can be defined as

$$\rho = \frac{P_t G_0}{\gamma_0 d_{\max}^\alpha N}.$$

The value of ρ is always no less than 1. In other words, the transmit power should be large enough to satisfy the SNR requirement γ_0 in the case that there is only one link in the network. The noise factor K_2 is a function of the SNR margin:

$$K_2 = \left(\frac{\rho}{\rho - 1} \right)^{\frac{1}{\alpha}}.$$

The term K_2 is no less than 1. When the SNR margin $\rho = 1$ (i.e., $0dB$), the noise factor $K_2 = \infty$. According to (7), we find that $Safe-CSR_{cumulative} = \infty$. The physical meaning is that if the transmit power P_t just meets the SNR target threshold γ_0 , then it is not possible to have multiple concurrent transmitting links. Figure 4 shows the noise factor K_2 as a function of the SNR margin ρ . Different curves represent different choices of the path-loss exponent α . From Fig. 4, we find that as the SNR margin ρ increases, the noise factor K_2 decreases rapidly. As the SNR margin goes to infinity, the noise factor K_2 converges to 1. When $K_2 = 1$, condition (7) is simplified to $Safe-CSR_{cumulative} = (K_1 + 2)d_{\max}$. In this case, the safe carrier-sensing range requirement is only affected by the cumulative interference power. The closer K_2 is to 1, the smaller the noise power impacts on the safe carrier-sensing range requirement. In practice, the

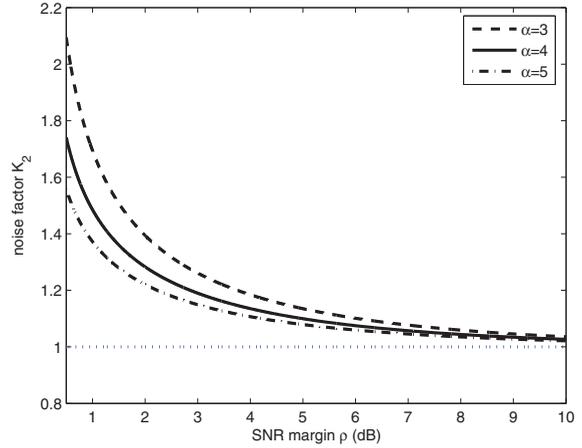


Fig. 4. The noise factor K_2 as a function of the SNR margin

802.11 network operates with an SNR margin ranging from $6dB$ to $10dB$ [22]. From Fig. 4, we can find that the noise factor K_2 is very close to 1, and the impact of the noise power to the safe carrier-sensing range requirement is small.

3.4 The Impact of Interference Models

Let us consider the impact of different interference models to the safe carrier-sensing range requirements. In order to have a clear comparison between different interference models, we set the noise power $N = 0$. So we have $Safe-CSR_{cumulative} = (K_1 + 2)d_{\max}$. Let us compare $Safe-CSR_{cumulative}$ with $Safe-CSR_{pairwise}$ with different values of γ_0 and α . For example, if $\gamma_0 = 10$ and $\alpha = 4$, which are typical for wireless communications,

$$\begin{aligned} Safe-CSR_{pairwise} &= 3.78 \cdot d_{\max}, \\ Safe-CSR_{cumulative} &= 5.27 \cdot d_{\max}. \end{aligned}$$

Compared with $Safe-CSR_{pairwise}$, $Safe-CSR_{cumulative}$ needs to be increased by a factor of 1.4 to ensure successful transmissions under the cumulative interference model.

Given a fixed path-loss exponent α , both $Safe-CSR_{pairwise}$ and $Safe-CSR_{cumulative}$ increase in the SIR requirement γ_0 . This is because the separation among links must be enlarged to meet a larger SIR target. For example, if $\alpha = 4$, we have

$$\begin{aligned} Safe-CSR_{pairwise} &= \left(2 + \gamma_0^{\frac{1}{4}} \right) d_{\max}, \\ Safe-CSR_{cumulative} &= \left(2 + \left(\frac{34}{3} \gamma_0 \right)^{\frac{1}{4}} \right) d_{\max}. \end{aligned}$$

The ratio of $Safe-CSR_{cumulative}$ to $Safe-CSR_{pairwise}$ is

$$\frac{Safe-CSR_{cumulative}}{Safe-CSR_{pairwise}} = \frac{2 + \left(\frac{34}{3} \gamma_0 \right)^{\frac{1}{4}}}{2 + \gamma_0^{\frac{1}{4}}},$$

which is an increasing function of γ_0 , and converges to a constant as γ_0 goes to infinity:

$$\begin{aligned} \sup_{\gamma_0} \frac{\text{Safe-CSR}_{\text{cumulative}}}{\text{Safe-CSR}_{\text{pairwise}}} &= \lim_{\gamma_0 \rightarrow \infty} \frac{\text{Safe-CSR}_{\text{cumulative}}}{\text{Safe-CSR}_{\text{pairwise}}} \\ &= \lim_{\gamma_0 \rightarrow \infty} \frac{2 + \left(\frac{34}{3}\gamma_0\right)^{\frac{1}{4}}}{2 + \gamma_0^{\frac{1}{4}}} = \left(\frac{34}{3}\right)^{\frac{1}{4}} \approx 1.8348. \end{aligned}$$

Figure 5 shows the ratio $\frac{\text{Safe-CSR}_{\text{cumulative}}}{\text{Safe-CSR}_{\text{pairwise}}}$ as a function of the SIR requirements γ_0 . Different curves represent different choices of the path-loss exponent α . The ratio $\frac{\text{Safe-CSR}_{\text{cumulative}}}{\text{Safe-CSR}_{\text{pairwise}}}$ increases when γ_0 increases or α decreases. For each choice of α , the ratio converges to a constant as γ_0 goes to infinity. This shows that, compared with the pairwise interference model, the safe carrier-sensing range under the cumulative interference model will not increase unboundedly.

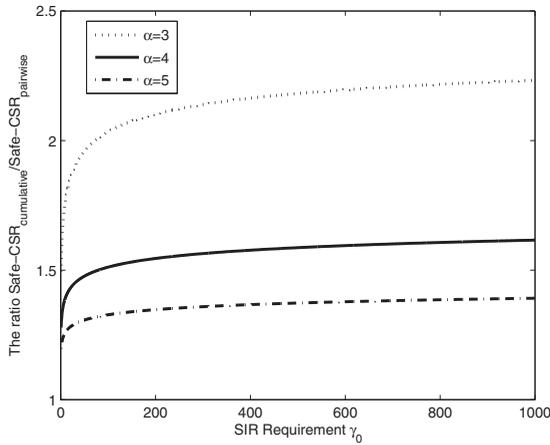


Fig. 5. The ratio of $\text{Safe-CSR}_{\text{cumulative}}$ to $\text{Safe-CSR}_{\text{pairwise}}$

4 A NEW CARRIER SENSING MECHANISM

We now discuss the implementation of $\text{Safe-CSR}_{\text{cumulative}}$. We first describe the difficulty of implementing the safe carrier-sensing range in (7) using the conventional physical carrier-sensing mechanism in 802.11. Then, we propose a new Incremental-Power Carrier-Sensing (IPCS) mechanism to resolve this implementation issue.

4.1 Limitation of Conventional Carrier-Sensing Mechanism

In the current 802.11 MAC protocol, given the safe carrier-sensing range $\text{Safe-CSR}_{\text{cumulative}}$, the carrier-sensing power threshold P_{th} can be set as

$$P_{th} = P_t G_0 (\text{Safe-CSR}_{\text{cumulative}})^{-\alpha}. \quad (13)$$

Before transmission, a transmitter T_i compares the power it senses, $P^{CS}(T_i)$, with the power threshold

P_{th} . A key disadvantage of this approach is that $P^{CS}(T_i)$ is a cumulative power from all the other nodes that are concurrently transmitting. The cumulative nature makes it impossible to tell whether $P^{CS}(T_i)$ is from one particular nearby transmitter or a group of far-off transmitters [23]. This reduces spatial reuse, as illustrated by the example in Fig. 6.

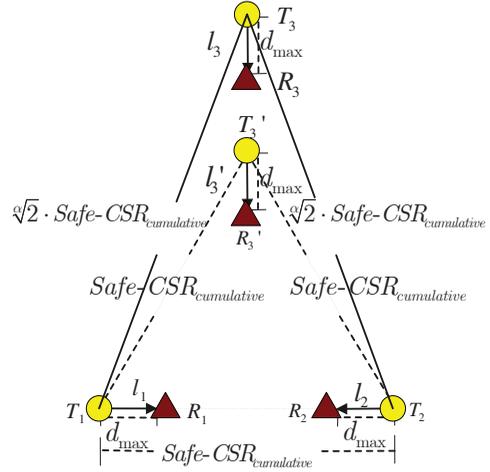


Fig. 6. Conventional carrier-sensing will reduce the spatial reuse in 802.11 networks (Link l_3 is placed based on the carrier-sensing mechanism in current 802.11, and link l'_3 is placed based on the IPCS mechanism)

There are four links in Fig. 6, with $\text{Safe-CSR}_{\text{cumulative}}$ set as in (7). In Fig. 6, the distance $d(T_1, T_2)$ is equal to $\text{Safe-CSR}_{\text{cumulative}}$. From (4), we find that T_1 and T_2 cannot carrier sense each other, thus they can transmit simultaneously.

First, consider the location of a third concurrent transmitting link l'_3 with both l_1 and l_2 , assuming that each transmitter can perfectly differentiate the distances from the other transmitters. Suppose that the third link is located on the middle line between l_1 and l_2 . Based on the carrier-sensing range analysis, the requirements are $d(T'_3, T_1) \geq \text{Safe-CSR}_{\text{cumulative}}$ and $d(T'_3, T_2) \geq \text{Safe-CSR}_{\text{cumulative}}$. So the third link can be located in the position of l'_3 , shown in Fig. 6. Furthermore, as the number of links increases, a tight packing of the concurrent transmitters will result in a regular equilateral triangle packing with side length $\text{Safe-CSR}_{\text{cumulative}}$. The “consumed area” of each transmitter is a constant given by $A = \frac{\sqrt{3}}{2} \text{Safe-CSR}_{\text{cumulative}}^2$.

Now, let us consider the location requirement of the third link l_3 under the carrier-sensing mechanism of the current 802.11 protocol. In order to have concurrent transmissions with both l_1 and l_2 , the cumulative power sensed by T_3 due to transmissions of both links l_1 and l_2 should be no larger than P_{th} , i.e.,

$$\begin{aligned} P^{CS}(T_3) &= P_t G_0 d(T_3, T_1)^{-\alpha} + P_t G_0 \cdot d(T_3, T_2)^{-\alpha} \\ &= 2 \cdot P_t G_0 d(T_3, T_1)^{-\alpha} \leq P_{th}, \end{aligned}$$

where P_{th} is given in equation (13). So the minimum distance requirement on $d(T_3, T_1)$ and $d(T_3, T_2)$ is

$$\begin{aligned} d(T_3, T_1) = d(T_3, T_2) &\geq \left(2 \frac{P_t}{P_{th}}\right)^{\frac{1}{\alpha}} \\ &= \sqrt[\alpha]{2} \cdot \text{Safe-CSR}_{cumulative}, \end{aligned}$$

as shown in Fig. 6. Since $\sqrt[\alpha]{2}$ is always greater than 1 for any choice of α , the requirement of the separation between transmitters is increased from $\text{Safe-CSR}_{cumulative}$ (i.e., $d(T_1, T_2)$) to $\sqrt[\alpha]{2}\text{Safe-CSR}_{cumulative}$ (i.e., $d(T_1, T_3)$ and $d(T_2, T_3)$). The requirement on the separation between transmitters will increase progressively as the number of concurrent links increases, and the corresponding packing of transmitters will be more and more sparse. As a result, spatial reuse is reduced as the number of links increases.

Another observation is that the transmissions order (i.e., which link transmits first and which link transmits next) also affects spatial reuse in the conventional carrier-sensing mechanism. Consider the three links, l_1 , l_2 and l_3 in Fig. 6 again. If transmissions order is $\{l_1, l_2, l_3\}$, as discussed above, T_1 , T_2 and T_3 sense a power no greater than P_{th} , and thus l_1 , l_2 and l_3 can be active simultaneously. If the sequence of transmissions on these links is $\{l_2, l_3, l_1\}$, however, both T_2 and T_3 sense a power no larger than P_{th} . But the cumulative power sensed by T_1 in this case is

$$\begin{aligned} P^{CS}(T_1) &= P_t G_0 d(T_3, T_1)^{-\alpha} + P_t G_0 d(T_2, T_1)^{-\alpha} \\ &= P_t G_0 \left(\left(\sqrt[\alpha]{2} \right)^{-\alpha} + 1 \right) \text{Safe-CSR}_{cumulative}^{-\alpha} \\ &= \frac{3}{2} P_{th} > P_{th}. \end{aligned}$$

Therefore, T_1 will sense the channel busy and will not initiate the transmission on l_1 . The spatial reuse is further reduced because there would have been no collisions had T_1 decided to transmit^{††}.

4.2 Incremental-Power Carrier-Sensing (IPCS) Mechanism

We propose a novel carrier-sensing mechanism called Incremental-Power Carrier-Sensing (IPCS) to solve the issues identified in Section 4.1. Specifically, the IPCS mechanism can implement the safe carrier-sensing range accurately by separating the detected powers from multiple concurrent transmitters.

Before explaining the details of IPCS, we want to emphasize that there are two fundamental causes for collisions in a CSMA network. Besides hidden nodes, collisions can also happen when the backoff mechanisms of two transmitters count down to zero simultaneously, causing them to transmit together. Note that for the latter, each of the two transmitters

is not aware that the other transmitter will begin transmission at the same time. Based on the power that it detects, it could perfectly be safe for it to transmit together with the existing active transmitters, only if the other transmitter did not decide to join in at the same time. There is no way for the carrier-sensing mechanism to prevent this kind of collisions. This paper addresses the hidden-node phenomenon only. To isolate the second kind of collisions, we will assume in the following discussion of IPCS that no two transmitters will transmit simultaneous due to simultaneous backoff countdown-to-zero. Conceptually, we could imagine the random variable associated with backoff countdown to be continuous rather than discrete, which means that the starting/ending of one link's transmission will coincide with the starting/ending of another link's transmission with zero probability. The case of discrete backoff time will be treated in Section 6.1. In particular, we argue that IPCS remains hidden-node-free with the same carrier-sensing power threshold in (13) when the backoff time is discrete.

Algorithm 1: Incremental-Power Carrier-Sensing (IPCS)

Input: $P_i^{CS}(t)$: the power sensed by T_i
Output: channel status decision

- 1 Monitor every increment $\Delta P_i^{CS}(t_k)$ during time window $[t - t_{packet}, t]$;
- 2 **if** $\Delta P_i^{CS}(t_k) \leq P_{th}, \forall t_k$ such that $t - t_{packet} \leq t_k \leq t$, **then**
- 3 | T_i decides that the channel is *idle* at time t ;
- 4 **else**
- 5 | T_i decides that the channel is *busy* at time t ;
- 6 **end**

The IPCS mechanism is described in Algorithm 1. The key idea of IPCS is to utilize the whole carrier-sensing power history, not just the carrier-sensing power at one particular time instance. In CSMA networks, each transmitter T_i carrier senses the channel except during its transmission of DATA or reception of ACK. The power being sensed increases if a new link starts to transmit, and decreases if an active link finishes its transmission. As a result, the power sensed by transmitter T_i , denoted by $P_i^{CS}(t)$, is a function of time t .

In IPCS, instead of checking the absolute power sensed at time t , the transmitter checks increments of power in the past up to time t . If the packet duration t_{packet} (including both DATA and ACK frames and the SIFS in between) is the same for all links, then it suffices to check the power increments during the time window $[t - t_{packet}, t]$. The same packet duration assumption is used to simplify explanation only. For the general case in which different packets have different packet length-

^{††}. This corresponds to the exposed-node phenomenon.

s, we could check a sufficiently large time window to cover the maximum packet size among all links[§]. Let $\{t_1, t_2, \dots, t_k, \dots\}$ denote the time instances when the power being sensed changes, and $\{\Delta P_i^{CS}(t_1), \Delta P_i^{CS}(t_2), \dots, \Delta P_i^{CS}(t_k), \dots\}$ denote the corresponding increments, respectively. In IPCS, transmitter T_i considers the channel to be *idle* at time t if the following conditions are met:

$$\Delta P_i^{CS}(t_k) \leq P_{th}, \quad \forall t_k \text{ such that } t - t_{packet} \leq t_k \leq t, \quad (14)$$

where P_{th} is the carrier-sensing power threshold determined according to CSR ; otherwise, the channel is considered to be *busy*. Since $\Delta P_i^{CS}(t_k)$ is negative if a link stops transmission at some time t_k , we only need to check the instances where the power increments are positive.

By checking every increment in the detected power over time, T_i can separate the powers from all concurrent transmitters, and can map the power profile to the required distance information. In this way, IPCS can ensure the separations between any two transmitters of all the transmitters are tight in accordance with Theorem 1.

Theorem 2: If the carrier-sensing range is set as equation (7), and the carrier-sensing power threshold P_{th} in the IPCS mechanism is set as equation (13), then it is sufficient to prevent hidden-node collisions under the cumulative interference model.

Proof: Consider any link l_i in set \mathcal{L} . Transmitter T_i will always do carrier sensing except when it transmits DATA frame or receives ACK frame. We show that condition (13) is sufficient to prevent hidden-node collisions in the following two situations, which cover all the possible transmission scenarios:

- 1) Link l_i has monitored the channel for at least t_{packet} length of time before its backoff counter reaches zero and it transmits.
- 2) Link l_i finishes a transmission; then monitors the channel for less than t_{packet} when its backoff counter reaches zero; then it transmits its next packet.

Let us first consider case 1):

We show that for the links that are allowed to transmit simultaneously, the separation between any pair of transmitters is no less than the safe carrier-sensing range $Safe-CSR_{cumulative}$. We prove this through induction. Suppose that before l_i starts to transmit, there are already M links transmitting and they are collectively denoted by the link set \mathcal{S}^{CS} . Without loss of generality, suppose that these M links begin to transmit one by one, according to the order l_1, l_2, \dots, l_M . For

§. For the case in which the packet lengths are different, setting the time window that to the maximum packet size may be overly conservative and not efficient for small packets. To improve efficiency, we further propose Incremental-and-Decremental-Power Carrier-Sensing (IDPCS), which monitors both increments and decrements to make carrier sensing decision. The details of IDPCS are in Section 6.2.

any link $l_j \in \mathcal{S}^{CS}$, let t_j and t'_j denote the times when link l_j starts to transmit the DATA frame and the ACK frame, respectively.

In our inductive proof, by assumption we have

$$d(T_j, T_k) \geq Safe-CSR_{cumulative}, \quad \forall j, k \in \{1, \dots, M\}, j \neq k. \quad (15)$$

We now show that condition (15) will still hold after link l_i starts its transmission.

Before link l_i starts its transmission, transmitter T_i monitors the channel for a time period of t_{packet} . So T_i at least senses M increments in the carrier-sensing power $P_i^{CS}(t)$ that happen at time t_1, t_2, \dots, t_M when the links in \mathcal{S}^{CS} start to transmit their DATA frames. There may also be some increments in the $P_i^{CS}(t)$ that happen at t'_1, t'_2, \dots, t'_M if the links in \mathcal{S}^{CS} start to transmit the ACK frames before link l_i starting its transmission. In the IPCS mechanism, at least the following M inequalities must be satisfied if T_i can start its transmission:

$$\Delta P_i^{CS}(t_j) \leq P_{th}, \quad \text{for } j = 1, \dots, M. \quad (16)$$

Because

$$\begin{aligned} \Delta P_i^{CS}(t_j) &= P_t G_0 d(T_i, T_j)^{-\alpha}, \\ P_{th} &= P_t G_0 (Safe-CSR_{cumulative})^{-\alpha}, \end{aligned} \quad (17)$$

we have

$$d(T_i, T_j) \geq Safe-CSR_{cumulative} \quad \text{for } j = 1, \dots, M. \quad (18)$$

Thus, we have shown that the separation between any pair of transmitters in the set $\mathcal{S}^{CS} \cup l_i$ is no less than $Safe-CSR_{cumulative}$ after link l_i starting transmission.

Now let us consider case 2):

Before starting the transmission of the $(m+1)$ th packet, link l_i first finishes the transmission of the m th packet (from time $t_i(m)$ to $t_i(m) + t_{packet}$), and waits for a DIFS plus a backoff time (from time $t_i(m) + t_{packet}$ to $t_i(m+1)$). Let \mathcal{S}^{CS} denote the set of links that are transmitting when l_i starts the $(m+1)$ th packet at time $t_i(m+1)$. Consider any link l_j in set \mathcal{S}^{CS} . Because the transmission time of every packet in the network is t_{packet} . We know that the start time t_j of the concurrent transmission on link l_j must range from $t_i(m)$ to $t_i(m+1)$, i.e., $t_i(m) < t_j < t_i(m+1)$.

If $t_i(m) + t_{packet} < t_j < t_i(m+1)$, this means t_j is in the DIFS or the backoff time of link l_i . During this period, transmitter T_i will do carrier sensing. The IPCS mechanism will make sure that the distance between T_i and T_j satisfies $d(T_i, T_j) \geq Safe-CSR_{cumulative}$.

If $t_i(m) < t_j < t_i(m) + t_{packet}$, this means t_j falls into the transmission time of the m th packet of link l_i . During the transmission time, T_i is not able to do carrier sensing because it is in the process of transmitting the DATA frame or receiving the ACK frame. However, the transmitter T_j will do carrier sensing before it starts to transmit at time t_j . The carrier sensing done

by T_j can make sure that the distance between T_i and T_j satisfies $d(T_i, T_j) \geq \text{Safe-CSR}_{\text{cumulative}}$.

So for any link l_j in \mathcal{S}^{CS} , we have $d(T_i, T_j) \geq \text{Safe-CSR}_{\text{cumulative}}$. \square

Let us use Fig. 6 again to show how IPCS can implement the safe carrier-sensing range successfully. We set the carrier-sensing power threshold P_{th} as in (13). We will show that the location requirement of the third link under IPCS is the same as indicated by the safe carrier-sensing range (location l'_3 in Fig. 6).

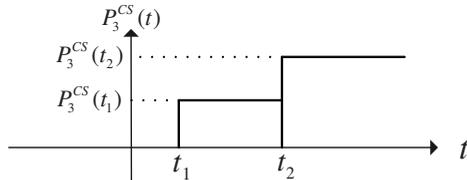


Fig. 7. The power sensed by transmitter T'_3 as a function of time

The transmitter of the third link will only initiate its transmission when it senses the channel to be idle. Its carrier-sensed power is shown in Fig. 7. Without loss of generality, suppose that link l_1 starts transmission before l_2 . The third transmitter detects two increments in its carrier-sensed power at time instances t_1 and t_2 which are due to the transmissions of T_1 and T_2 , respectively. In the IPCS mechanism, the third transmitter will believe that the channel is idle (i.e., it can start a new transmission) if the following is true:

$$\begin{cases} \Delta P_3^{\text{CS}}(t_1) = P_t G_0 d(T'_3, T_1)^{-\alpha} \leq P_{th}, \\ \Delta P_3^{\text{CS}}(t_2) = P_t G_0 d(T'_3, T_2)^{-\alpha} \leq P_{th}. \end{cases} \quad (19)$$

Substituting P_{th} in (13) to (19), we find that the requirements in (19) are equivalent to the following distance requirements:

$$\begin{cases} d(T'_3, T_1) \geq \text{Safe-CSR}_{\text{cumulative}}, \\ d(T'_3, T_2) \geq \text{Safe-CSR}_{\text{cumulative}}. \end{cases}$$

So the third link can be located at the position of l'_3 , as shown in Fig. 6, instead of far away at the location of l_3 as in the conventional carrier-sensing mechanism.

Compared with the conventional carrier-sensing mechanism, the advantages of IPCS are

- 1) IPCS is a pairwise carrier-sensing mechanism. In the IPCS mechanism, the power from each concurrent link is checked individually. This is equivalent to checking the separation between every pair of concurrent transmission links. With IPCS, all the analyses based on the concept of a carrier-sensing range remain valid.
- 2) IPCS improves spatial reuse and network throughput. In the conventional carrier-sensing mechanism, the link separation requirement increases as the number of concurrent links increases. In IPCS, however, the link separation

requirement remains the same. Furthermore, because IPCS is a pairwise mechanism, the order of the transmissions of links will not affect the spatial reuse.

5 SIMULATIONS RESULTS

We perform simulations to evaluate the throughput performance of IPCS compared to the conventional Carrier Sensing (CS). In our simulations, the nodes are located within a square area of $300m \times 300m$. The locations of the transmitters are generated according to a Poisson point process. The link length ranges from $10m$ to $20m$. More specifically, the receiver associated with a transmitter is randomly located between the two concentric circles of radii $10m$ and $20m$ centered on the transmitter. We study the system performance under different link densities and carrier-sensing power thresholds. For each given number of links, we investigate 100 random network topologies and present the averaged results.

The simulations are carried out based on the 802.11b protocol. The carrier frequency is $2.4GHz$. The bandwidth is $20MHz$. The reference channel gain G_0 at the reference distance $d_0 = 1m$ and the carrier frequency of $2.4GHz$ is $-24.9dB$ [24]. The common physical layer link rate is $11Mbps$. The packet size is 1460 Bytes. The minimum and maximum backoff windows and CW_{max} are 31 and 1023, respectively. The backoff time of each transmitter is uniformly distributed between CW_{min} and CW_{max} . The slot time length is $20\mu s$. The SIFS and DIFS are $10\mu s$ and $50\mu s$, respectively. The transmit power P_t is set as $100mW$. The noise power density is $-174dBm/Hz$. The path-loss exponent α is 4, the SINR requirement γ_0 is 20.

We first investigate the spatial reuse and network throughput performances under different link densities, by varying the number of links in the square from 1 to 200 in our simulations. The carrier-sensing range and the carrier-sensing power threshold are set according to (7) and (13), respectively. In particular, $\text{Safe-CSR}_{\text{cumulative}} = 117.6m$ and $P_{th} = 1.69 \times 10^{-9}mW$ with the system parameters assumed. Simulation results show that the network throughput is proportional to spatial reuse. So we plot these two results together in Fig. 8.

We define a "unit area" as the "consumed area" of each "active" transmitter under the tightest packing. Given $\text{Safe-CSR}_{\text{cumulative}} = 117.6m$, the "unit area" is $\frac{\sqrt{3}}{2} \text{Safe-CSR}_{\text{cumulative}}^2 = 1.2 \times 10^4 m^2$. The x-axis is the average number of links (i.e., all active and inactive links) per unit area as we vary the total number of links in the whole square. That is, the x-axis corresponds to the link density of the network. The left y-axis is the spatial reuse, or the average "active" link density in the network. The maximum value of the spatial reuse is 1, which is shown as a dashed line

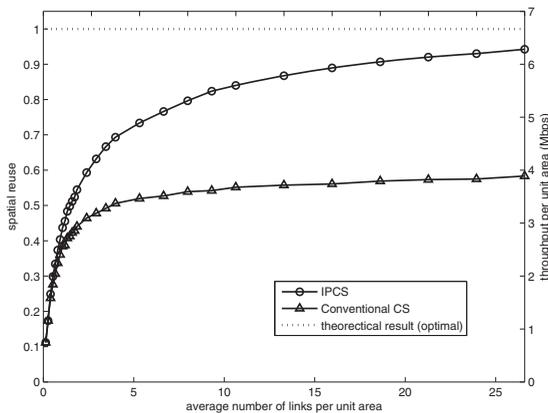


Fig. 8. Spatial reuse and network throughput under IPCS and the conventional CS mechanism as a function of network density

in Fig. 8. The right y-axis is the throughput per unit area.

It is clear from Fig. 8 that IPCS outperforms the conventional CS. The improvement becomes more significant when the network becomes denser. At the densest point in the figure, spatial reuses under IPCS and conventional CS are 0.9424 and 0.5834, respectively. The network throughputs per unit area are 6.66Mbps and 4.08Mbps, respectively. Using conventional CS as the base line, the IPCS improves spatial reuse and network throughput by up to 60%.

Under the conventional CS, in order to make sure the cumulative detected power is no larger than the power threshold P_{th} , the packing of concurrent transmission links will become more and more sparse as additional number of links attempt to transmit. Under IPCS, this does not occur. As a result, the improvement in spatial reuse is more significant as the network becomes denser. We also find that when the network becomes denser and denser, spatial reuse under IPCS becomes very close to the theoretical maximum result. The small gap is likely due to the fact that a link which could be active concurrently under IPCS does not exist in a given topology. The probability of this happening decreases as the network becomes denser.

Figure 9 shows the network throughput performance of IPCS and the conventional CS mechanism under different carrier-sensing power thresholds. The number of links in the square is fixed at 200 (and thus the average number of links per unit area is 26.67). At the initial point, the carrier-sensing power threshold P_{th} is set according to (13), which is $1.69 \times 10^{-9}mW$. Because the simulations are performed within a finite-size network, setting the carrier-sensing power according to (13) is sufficient but may also be too conservative to prevent collisions. Then we increase

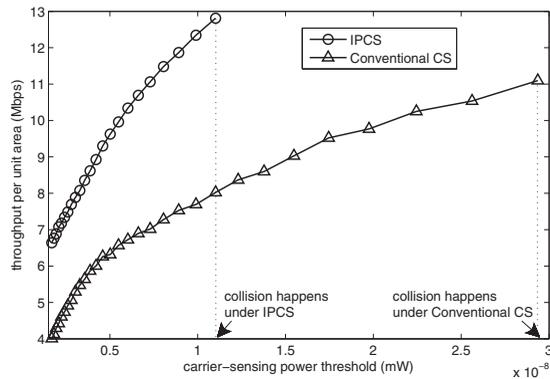


Fig. 9. Network throughput under IPCS and the conventional CS mechanism as a function of the carrier-sensing power threshold

P_{th} in each mechanism, until collisions just happen and the mechanism fails to prevent them. Therefore, this means that the transmissions are interference-safe for all values points we plotted in Fig. 9. Since IPCS monitors incremental power and the conventional CS monitors the total power, IPCS first incur collisions at a smaller P_{th} than the conventional CS (i.e., at the same P_{th} , IPCS allows more links to transmit simultaneously). It is clear from Fig. 9 that IPCS outperforms the conventional CS as we vary the carrier-sensing power threshold. Using the conventional CS as the base line, the throughput improvement of IPCS is more than 50% under the same carrier-sensing power thresholds. If we compare the maximum throughput obtained in IPCS to the maximum throughput obtained in the conventional CS in the interference-free regime, the throughput improvement of IPCS is still more than 15%.

6 FURTHER DISCUSSIONS

In this section, we will discuss two issues: the first one is the IPCS mechanism when the backoff time is a discrete random variable; the second one is how to improve the transmission efficiency of IPCS when the packet lengths are different.

6.1 IPCS With Discrete Backoff Time

For simplicity, we have assumed a continuous backoff time when discussing the main characteristic of the IPCS mechanism in this paper. In fact, Theorem 2 remains valid even if we remove the continuous backoff time assumption. In other words, IPCS can still prevent hidden-node collisions even when the backoff time is a discrete random variable. We remark, however, that with discrete backoff time, it is possible for multiple transmitters to count down to zero and transmit simultaneously. These collisions are not due to hidden nodes and will always be present so long

as the countdown process is discrete, and they are not the subject of focus of this paper.

Consider some time instance t , when the transmitter T_i senses an increment power composed of the sum of the powers from H , ($H \geq 2$) concurrent transmitters (denoted as $T_{j_h}, h = 1, \dots, H$), due to their discrete backoff counters reaching zero simultaneously. Then (16) and (17) in the proof of Theorem 2 become

$$\Delta P_i^{CS}(t) \leq P_{th}, \quad (20)$$

and

$$\Delta P_i^{CS}(t) = \sum_{h=1}^H P_t G_0 d(T_i, T_{j_h})^{-\alpha}. \quad (21)$$

The carrier-sensing power threshold P_{th} is $P_t G_0 (\text{Safe-CSR}_{cumulative})^{-\alpha}$. Then we have

$$\sum_{h=1}^H P_t G_0 d(T_i, T_{j_h})^{-\alpha} \leq P_t G_0 (\text{Safe-CSR}_{cumulative})^{-\alpha}.$$

Therefore,

$$d(T_i, T_{j_h}) \geq \text{Safe-CSR}_{cumulative} \quad \text{for } h = 1, \dots, H.$$

This means that the safe carrier-sensing range requirement (18) in the proof of Theorem 2 is still satisfied. If the carrier-sensing power threshold is set as (13), IPCS can prevent hidden-node collisions whether the backoff time is a continuous random variable or a discrete random variable.

We do note, however, that IPCS will be more conservative when the backoff time is discrete. When multiple transmitters count down to zero and transmit simultaneously, the sensing node treat their powers as the power coming from one single transmitter that is closer to the sensing node. Thus, the sensing node may withhold transmission even though it may be safe to transmit. However, under no circumstance will the sensing node transmit when it is not safe to do so.

6.2 IDPCS Mechanism

When the packet lengths are different, setting the time window to the maximum packet size may be overly-conservative. In IPCS, if an increment in the detected power is larger than the power threshold P_{th} , the transmitter T_i will freeze for a time duration which is equal to the maximum packet length. If this increment is caused by a small packet, such long freeze time is not necessary. In order to improve the transmission efficiency, we propose the IDPCS mechanism which monitors power decrements in addition to power increments. The IDPCS mechanism is given in Algorithm 2.

In IDPCS, T_i maintains a *counter*, which is the number of concurrent transmissions with the detected power increments larger than the power threshold P_{th} . Whenever T_i detects a power increment larger than P_{th} , the counter is increased by 1, because a new

Algorithm 2: Incremental-and-Decremental-Power Carrier-Sensing (IDPCS)

Input: $P_i^{CS}(t)$: the power sensed by T_i

Output: channel status decision

```

1 counter ← 0;
2 Monitor every change  $\Delta P_i^{CS}(t_k)$  in the detected
  power;
3 if  $\Delta P_i^{CS}(t_k) \geq P_{th}$ , then
4   | counter ++;
5 end
6 if  $\Delta P_i^{CS}(t_k) \leq -P_{th}$ , and counter > 0 then
7   | counter --;
8 end
9 if counter == 0 at time  $t$ , then
10  |  $T_i$  decides that the channel is idle at time  $t$ ;
11 else
12  |  $T_i$  decides that the channel is busy at time  $t$ ;
13 end
```

transmission (DATA frame or ACK frame) within the carrier-sensing range has begun. If T_i detects a power decrement which is greater than P_{th} , this means that a link within the carrier-sensing range has finished its transmission (DATA frame or ACK frame). In this case, the counter is decreased by 1. If the counter is zero, this means there is no link in the carrier-sensing range that is transmitting. Then the transmitter T_i decides the channel to be *idle*; otherwise, the channel is considered to be *busy*. By monitoring both increments and decrements, the transmitter can track both the start and the end of each transmission. A transmitter does not need to freeze for the maximum packet length once it detects an increment in the detected power that is larger than P_{th} . This will improve the transmission efficiency.

7 CONCLUSION

In this paper, we derive a threshold on the safe carrier-sensing range that is sufficient to prevent hidden-node collisions under the cumulative interference model. We then propose a novel carrier-sensing mechanism, called Incremental-Power Carrier-Sensing (IPCS), that can realize the safe carrier-sensing range concept in a simple way. The IPCS checks every increment in the detected power so that it can separate the detected power of every concurrent transmitter, and then maps the power profile to the required distance information. Our simulation results show that IPCS can boost spatial reuse and network throughput by up to 60% relative to the conventional carrier-sensing mechanism under the same carrier-sensing power thresholds. If we compare the maximum throughput in the interference-free regime, the throughput improvement of IPCS is still more than 15%. Last but not least, by providing an explicit implementation

of the concept of “carrier-sensing range”, IPCS also ties up a loose end in many other prior theoretical works that implicitly assume the use of a carrier-sensing range (interference-safe or otherwise) without an explicit design to realize it.

One future research direction is to study the interference-safe transmissions in CSMA networks while considering the fading and time-varying effects of the wireless channel. In this paper, we only consider the log-distance path model. Channel fading will influence both the detected powers by transmitters and the interference powers at the receivers. It requires a probabilistic analysis approach which is quite different from the deterministic approach used here. The carrier-sensing design to avoid severe interference under fast fading is an interesting topic for future study.

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