Effective Carrier Sensing in CSMA Networks under Cumulative Interference

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Abstract—This paper proposes and investigates the concept of a *safe carrier-sensing range* that can guarantee interference-safe (also termed hidden-node-free) transmissions in CSMA networks under the cumulative interference model. Compared with the safe carrier-sensing range under the commonly assumed but less realistic pairwise interference model, we show that the safe carrier-sensing range required under the cumulative interference model is larger by a constant multiplicative factor. For example, if the SINR requirement is $10dB$ and the path-loss exponent is 4, the factor is 1.4. 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 mechanism does not contain enough information for it to derive its distances from other concurrent transmitter nodes. We show that, fortunately, a 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 more than 60% relative to the conventional carrier-sensing mechanism. Last but not least, IPCS not only allows us to implement our safe carrier-sensing range, it also ties up a loose end in many other prior theoretical works that implicitly assume the use of a carrier-sensing range (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.

I. INTRODUCTION AND OVERVIEW

Due to the broadcast nature of wireless channels, signals transmitted over wireless links can mutually interfere with each other. How to optimize 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 [1]–[6]). 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 can guarantee interference-safe transmissions in CSMA networks under the *cumulative interference model*.
2) We show that the concept is implementable using a very simple Incremental-Power Carrier-Sensing (IPCS) mechanism.
3) We demonstrate that implementation of 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 model in [7]), in which the interference at a receiver node i consists of the cumulative power received from all the other nodes that are currently transmitting (except its own transmitter). This model is known to be more practical and much more difficult to analyze than the widely studied pairwise interference model (also termed the protocol interference model in [7]) 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 the receivers of all these links 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 $\mathcal{F} = \{\mathcal{S} \mid$ the SINR requirements of all links 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 $(\mathcal{S}_t)_{t=1}^{n}$ where each $\mathcal{S}_t \in \mathcal{F}$. 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 $\mathcal{F}^{CS} = \{\mathcal{S}^{CS} \mid$ simultaneous transmissions of links in $\mathcal{S}^{CS}$ 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 [8]. However, this issue was studied under the context of an idealized pairwise interference model [8] 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 a cumulative interference model. We believe that the safe carrier-sensing range established in this paper is a tight upperbound and achieves good spatial reuse. Another issue is how to implement the concept of safe carrier-sensing range in practice.

This brings us to 2) above. In traditional carrier sensing based on power threshold (e.g., that of the *basic mode* in IEEE 802.11), the absolute power received is being monitored. 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 leads to subpar spatial reuse. Fortunately, we show that a simple mechanism that monitors the incremental power changes over time, IPCS, will enable us to map the power profile to the required distance information. We believe that this contribution, although simple, is significant in that 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 (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. Without IPCS, and using only the conventional carrier-sensing mechanism, the results in these prior works would have been overly optimistic. Given the implementability of 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, in order 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* which is independent of the number of concurrent transmissions. Indeed, our simulation results indicate that compared to the conventional carrier-sensing mechanism, IPCS mechanism improves the spatial reuse and the network throughput by more than 60%.

A. Related Work

In the literature, most studies on carrier sensing (e.g., [8]–[13]) 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 the interference from each of the other links on the link concerned does not cause a collision, then it is assumed that there is no collision overall. Ref. [8] established the carrier-sensing range required to prevent hidden-node collisions in CSMA networks under the pairwise interference model. The resulting carrier-sensing range is too optimistic and can not eliminate hidden-node collisions if the more accurate cumulative interference model is adopted instead.

A number of recent papers studied the CSMA networks under the cumulative interference model (e.g., [14]–[17]). An earlier unpublished technical report of ours [17] 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. [14]–[16] address the implementation of a carrier-sensing range based on power detection. Ref. [14] studied the asymptotic capacity of large-scale CSMA networks with hidden-node-free designs. The focus of [14] is on "order" result rather than "tight" result. For example, if $\gamma_0 = 10 dB$ and $\alpha = 4$, the safe carrier-sensing range derived in [14] is $8.75 d_{\max}$. In this paper, we show that setting the safe carrier-sensing range to $5.27 d_{\max}$ is enough to prevent hidden-node collisions.

The authors in [15], [16] 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 [15], [16], spatial reuse and capacity are analyzed based on 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 can not be realized using the current 802.11 carrier-sensing mechanism. Therefore, the results in [15], [16] are overly optimistic without an appropriate carrier-sensing mechanism. IPCS fills this gap so that the theoretical results of [15], [16] remain valid. We summarize the key related models and results in the literature in Table I*.

The rest of this paper is organized as follows. Section II presents the cumulative interference model and the carrier sensing mechanism in the current 802.11 protocol. Section III derives the safe carrier-sensing range that successfully prevents

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*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.

TABLE I
SUMMARY OF THE RELATED WORK

Interference Models	Pairwise Interference Model	Cumulative Interference Model
Absolute power carrier sensing	many (e.g., [8], [10])	[15], [16]
Incremental power carrier sensing	**This paper**	**This paper**

the hidden-node collisions under the cumulative interference model. Section IV presents the IPCS mechanism. Section V evaluates the performance of IPCS in terms of spatial reuse and network throughput. Section VI concludes this paper.

II. SYSTEM MODEL

A. 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 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 path loss exponent $\alpha > 2$. The path gain $G(T_i, R_j)$ from transmitter T_i to receiver R_j follows a geometric model:

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

where $d(T_i, R_j)$ is the Euclidean distance between nodes T_i and R_j.

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 correct 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 $\mathcal{L}'$ or $\mathcal{L}''$, S_j represents the sender of link l_j, which can be either

T_j or R_j. This is because either DATA or ACK transmission on link l_j will cause interference to link l_i.

B. 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, this means there is collision in the network. In 802.11, carrier sensing is designed to prevent collision due to simultaneous transmissions that cause the violation of either (1) or (2). 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.

In most studies of 802.11 networks, the concept of a carrier-sensing range CSR is introduced. The carrier-sensing range CSR is mapped from the carrier-sensing power threshold P_{th}:

$$CSR = \left(\frac{P_t}{P_{th}} \right)^{\frac{1}{\alpha}}.$$

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

Setting an appropriate carrier-sensing range is crucial to the performance of 802.11 networks. If CSR is too large, spatial reuse will be unnecessarily limited. If CSR is not large enough, then hidden-node collisions may occur. The underlying cause of hidden-node collisions are as follows. A number of transmitters transmit simultaneously because condition (4) is satisfied by all pairs of the transmitters. However, there is at least one of the links does not satisfy either (1) or (2). As a result, collisions happen and the carrier sensing mechanism is said to have failed in preventing such collisions.

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

For analysis simplicity, we assume that the background noise power N is small compared with interference and thus can be ignored. We will consider Signal-to-Interference Ratio (SIR) instead of SINR.

III. SAFE CARRIER-SENSING RANGE UNDER CUMULATIVE INTERFERENCE MODEL

In this section, we derive a sufficient threshold for *Safe-$CSR_{cumulative}$*. When discussing the hidden-node free design [8], it is required that the receivers are operated with the "RS (Re-Start) mode" (see Appendix A for details). In the following discussion, we also make the same assumption.

Ref. [8] studied the safe carrier-sensing range under the *pairwise interference model*. The threshold is given as follows:

$$Safe\text{-}CSR_{pairwise} = \left(\gamma_0^{\frac{1}{\alpha}} + 2\right) d_{\max}, \qquad (5)$$

where $d_{\max} = \max_{l_i \in \mathcal{L}} d(T_i, R_i)$ 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 (5) is overly optimistic and not large enough to prevent hidden-node collisions under the *cumulative interference model*, as illustrated by the three-link example in Fig. 1.
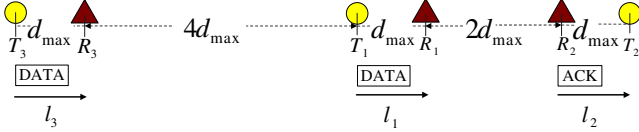

Fig. 1. Setting the carrier-sensing range as *Safe-$CSR_{pairwise}$* is insufficient to prevent hidden-node collisions under the cumulative interference model

In Fig. 1, suppose that the SIR requirement $\gamma_0 = 8$ and the path-loss exponent $\alpha = 3$. According to (5), 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 $P_{th} = P_t \left(4d_{\max}\right)^{-3} = 0.0156 P_t d_{\max}^{-3}$. In Fig. 1, 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 can not 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

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

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

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

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 (5) is not sufficient to prevent collisions under the cumulative interference model.

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

Theorem 1: The setting

$$Safe\text{-}CSR_{cumulative} = (K+2)d_{\max}, \qquad (6)$$

where

$$K = \left(6\gamma_0 \left(1 + \left(\frac{2}{\sqrt{3}}\right)^{\alpha} \frac{1}{\alpha - 2}\right)\right)^{\frac{1}{\alpha}}. \qquad (7)$$

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

Proof: The proof is given in Appendix B. ∎

Condition (6) 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 value given in (6).

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,

$$Safe\text{-}CSR_{pairwise} = 3.78 \cdot d_{\max},$$
$$Safe\text{-}CSR_{cumulative} = 5.27 \cdot d_{\max}.$$

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

$$Safe\text{-}CSR_{pairwise} = \left(2 + \gamma_0^{\frac{1}{4}}\right) d_{\max},$$

$$Safe\text{-}CSR_{cumulative} = \left(2 + \left(\frac{34}{3}\gamma_0\right)^{\frac{1}{4}}\right) d_{\max}.$$

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

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

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

$$\lim_{\gamma_0 \to \infty} \frac{Safe\text{-}CSR_{cumulative}}{Safe\text{-}CSR_{pairwise}} = \lim_{\gamma_0 \to \infty} \frac{2 + \left(\frac{34}{3}\gamma_0\right)^{\frac{1}{4}}}{2 + \gamma_0^{\frac{1}{4}}}$$
$$= \left(\frac{34}{3}\right)^{\frac{1}{4}} \approx 1.8348.$$

Fig. 2 shows the ratio $\frac{Safe\text{-}CSR_{cumulative}}{Safe\text{-}CSR_{pairwise}}$ as a function of the SIR requirements γ_0. Different curves represent different choices of the path-loss exponent α. The ratio $\frac{Safe\text{-}CSR_{cumulative}}{Safe\text{-}CSR_{pairwise}}$ increases when γ_0 increases or α decreases. For each choice of α, the

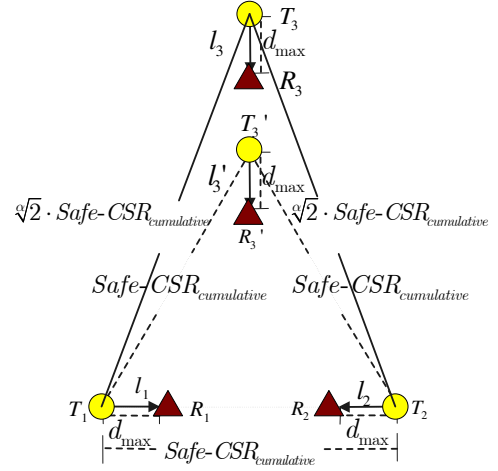Fig. 2. The ratio of *Safe-CSR*$_{cumulative}$ to *Safe-CSR*$_{pairwise}$

Fig. 3. Conventional carrier-sensing mechanism will reduce the spatial reuse in 802.11 networks. Link l_3 is placed based on the absolute power sensing mechanism in current 802.11, and link l'_3 is placed based on the *Safe-CSR*$_{cumulative}$ as enabled by our IPCS mechanism.
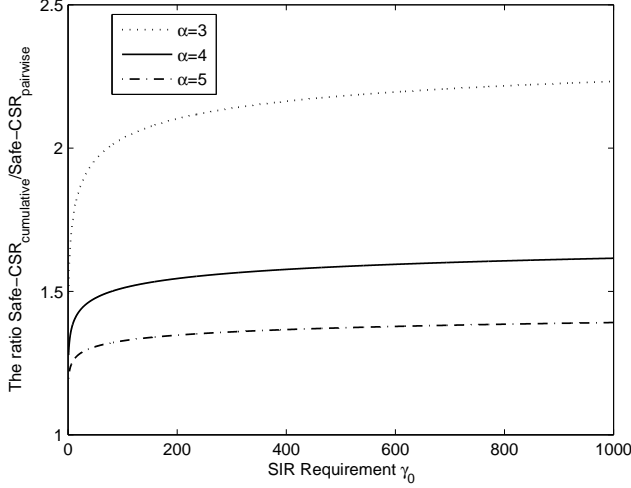
ratio converges to a constant as γ_0 goes to infinity. This shows that, compared with the pairwise interference model, the safe carrier-sensing range under the cumulative interference model will not increase arbitrarily.

IV. A NOVEL CARRIER SENSING MECHANISM

We now discuss the implementation of *Safe-CSR*$_{cumulative}$. We first describe the difficulty of implementing the safe carrier-sensing range in (6) using the existing physical carrier-sensing mechanism in the current 802.11 protocol. Then, we propose a new Incremental-Power Carrier-Sensing (IPCS) mechanism to resolve this implementation issue.

A. Limitation of Conventional Carrier-Sensing Mechanism

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

$$P_{th} = P_t \cdot \left(\textit{Safe-CSR}_{cumulative} \right)^{-\alpha}. \qquad (8)$$

Before transmitting, 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 [18]. This reduces spatial reuse, as illustrated by the example in Fig. 3.

There are four links in Fig. 3, with *Safe-CSR*$_{cumulative}$ set as in (6). In Fig. 3, the distance $d(T_1, T_2)$ is equal to *Safe-CSR*$_{cumulative}$. From (4), we find that T_1 and T_2 can not carrier sense each other, thus they can transmit simultaneously.

First, consider the location requirement of the third link l'_3 that can have a concurrent transmission 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 $d(T'_3, T_1) \geq$ *Safe-CSR*$_{cumulative}$ and $d(T'_3, T_2) \geq$ *Safe-CSR*$_{cumulative}$. So the third link can be located in the position of l'_3, shown in Fig. 3. 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 *Safe-CSR*$_{cumulative}$. The "consumed area" of each transmitter is a constant given by $A = \frac{\sqrt{3}}{2} \textit{Safe-CSR}^2_{cumulative}$.

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.,

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

where P_{th} is given in equation (8). So the minimum distance requirement on $d(T_3, T_1)$ and $d(T_3, T_2)$ is

$$d(T_3, T_1) = d(T_3, T_2) \geq \left(2 \frac{P_t}{P_{th}} \right)^{\frac{1}{\alpha}} = 2^{\frac{1}{\alpha}} \cdot \textit{Safe-CSR}_{cumulative},$$

as shown in Fig. 3. Since $2^{\frac{1}{\alpha}}$ is always greater than 1, the requirement of the separation between transmitters is increased from *Safe-CSR*$_{cumulative}$ (i.e., $d(T_1, T_2)$) to $2^{\frac{1}{\alpha}} \textit{Safe-CSR}_{cumulative}$ (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 thing to notice is that the order of the transmissions of links also affects spatial reuse in the conventional carrier-sensing mechanism. Consider the three links, l_1, l_2 and l_3 in Fig. 3 again. If the sequence of transmissions 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

$$P^{CS}(T_1) = P_t \cdot d(T_3, T_1)^{-\alpha} + P_t \cdot d(T_2, T_1)^{-\alpha}$$
$$= P_t \left(2^{\frac{1}{\alpha}} Safe\text{-}CSR_{cumulative}\right)^{-\alpha} + P_t \left(Safe\text{-}CSR_{cumulative}\right)^{-\alpha}$$
$$= \frac{3}{2} P_{th} > P_{th}.$$

Therefore, T_1 will sense the channel busy and will not initiate the transmission on l_1. The spatial reuse is unnecessarily reduced because there would have been no collisions had T_1 decide to transmit[††].

B. Incremental-Power Carrier-Sensing (IPCS) Mechanism

We propose an enhanced physical carrier-sensing mechanism called Incremental-Power Carrier-Sensing (IPCS) to solve the issues identified in section IV-A. Specifically, the IPCS mechanism can implement the safe carrier-sensing range accurately by separating the detected powers from multiple concurrent transmitters.

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 that the carrier-sensing mechanism can 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[‡]. 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 key idea of IPCS is to utilize the whole carrier-sensing power history, not just the carrier-sensing power at one particular time. In CSMA networks, each transmitter T_i carrier senses the channel except during the time when it transmits

DATA or receives ACK. The power being sensed increases if a link starts to transmit, and decreases if a link finishes transmission. As a result, the power sensed by transmitter T_i, denoted by $P_i^{CS}(t)$, is a continuous 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 a constant for all links, then it suffices to check the power increments during the time window $[t - t_{packet}, t]^{\S}$. Let $\{t_1, t_2, \cdots, t_k, \cdots\}$ denote the time instances when the power being sensed changes, and $\{\Delta P_i^{CS}(t_1), \Delta P_i^{CS}(t_2), \cdots, \Delta P_i^{CS}(t_k), \cdots\}$ denote the corresponding increments, respectively. In IPCS, transmitter T_i will decide the channel to be *idle* at time t if the following conditions are met:

$$\Delta P_i^{CS}(t_k) \leq P_{th}, \quad \forall t_k \text{ such that } t - t_{packet} \leq t_k \leq t, \quad (9)$$

where P_{th} is the carrier-sensing power threshold determined according to CSR; otherwise, the channel is deemed 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, 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 all transmitters are tight in accordance with Theorem 1.

Theorem 2: If the carrier-sensing power threshold P_{th} in the IPCS mechanism is set as:

$$P_{th} = P_t \left(Safe\text{-}CSR_{cumulative}\right)^{-\alpha}, \quad (10)$$

where $Safe\text{-}CSR_{cumulative}$ is the safe carrier-sensing range in (6), then it is sufficient to prevent hidden-node collisions under the cumulative interference model.
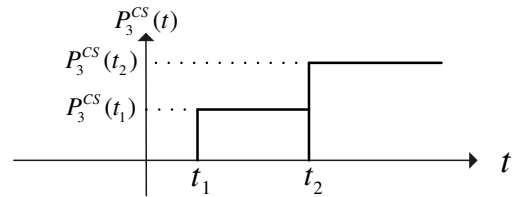
Proof: The proof is given in Appendix C. ∎

Fig. 4.   The power sensed by transmitter T_3' as a function of time

Let us use Fig. 3 again to show how IPCS can implement the safe carrier-sensing range successfully. We set the carrier-sensing power threshold P_{th} as in (10). 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. 3). The transmitter of the third link will only initiate its

[††]This corresponds to the exposed-node phenomenon.
[‡]Collisions due to simultaneous countdown-to-zero can be tackled by an exponential backoff mechanism in which the transmission probability of each node is adjusted in a dynamic way based on the busyness of the network. In WiFi, for example, the countdown window is doubled after each collision. The probability of this kind of collisions can be made small with a proper design of the backoff mechanism

[§]This assumption is used to simplify explanation only. In general, we could check a time window sufficiently large to cover the maximum packet size among all links.

transmission when it senses the channel to be idle. Its carrier-sensed power is shown in Fig. 4. 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:

$$\begin{cases} \Delta P_3^{CS}(t_1) = P_t d(T_3', T_1)^{-\alpha} \leq P_{th}, \\ \Delta P_3^{CS}(t_2) = P_t d(T_3', T_2)^{-\alpha} \leq P_{th}. \end{cases} \quad (11)$$

Substituting P_{th} in (10) to (11), we find that the requirements in (11) are equivalent to the following distance requirements:

$$\begin{cases} d(T_3', T_1) \geq \textit{Safe-CSR}_{cumulative}, \\ d(T_3', T_2) \geq \textit{Safe-CSR}_{cumulative}. \end{cases}$$

So the third link can be located at the position of l_3', as shown in Fig. 3, 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 and every 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.

V. SIMULATIONS RESULTS

We perform simulations to evaluate the relative performance of IPCS and conventional Carrier Sensing (CS). In our simulations, the nodes are located within in a square area of $300m \times 300m$. The locations of the transmitters are generated according to a Poisson point process. The length of a link is uniformly distributed between 10 and 20 meters. 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 by varying the number of links in the square from 1 to 200 in our simulations.

The simulations are carried out based on the 802.11b protocol. The common physical layer link rate is $11Mbps$. The packet size is 1460 Bytes. The minimum and maximum backoff window $CW_{\min}$ and $CW_{\max}$ are 31 and 1023, respectively. The slot time 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 path-loss exponent α is 4, the SIR requirement γ_0 is
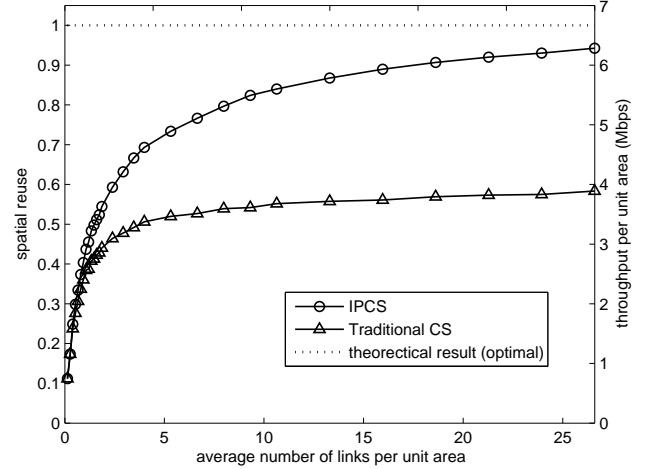

Fig. 5. Spatial reuse and network throughput under IPCS and the conventional CS mechanisms

20, and the corresponding $\textit{Safe-CSR}_{cumulative}$ equals $117.6m$ based on (6). That is, the carrier-sensing power threshold $P_{th} = P_t \left(\textit{Safe-CSR}_{cumulative}\right)^{-\alpha} = 5.23 \times 10^{-7} mW$.

In Fig. 5, we plot spatial reuse and network throughput under IPCS and the conventional CS mechanisms. Simulation results show that network throughput is proportional to spatial reuse. So we plot these two results in the same figure. We define a "unit area" as the "consumed area" of each "active" transmitter under the tightest packing. Given $\textit{Safe-CSR}_{cumulative} = 117.6m$, according to the carrier-sensing range analysis, the "unit area" is $\frac{\sqrt{3}}{2}\textit{Safe-CSR}_{cumulative}^2 = 1.197 \times 10^4 m^2$. The x-axis is the average number of links (i.e., all links, including 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 optimal value of the spatial reuse is 1, which is shown as a dashed line in Fig. 5. The right y-axis is the throughput per unit area.

It is clear from Fig. 5 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 more than 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 result. The small gap is likely due to the fact that a link which could be active concurrently under IPCS does not exist in the given topology. The probability of this happening decreases as the network becomes denser.

VI. 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 show that the safe carrier-sensing range required under the cumulative interference model is larger than that required under the pairwise interference model by a constant multiplicative factor.

We 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 more than 60% relative to the conventional carrier-sensing mechanism in the current 802.11 protocol.

One future research direction is to further tighten the safe carrier-sensing range according to the topology information. In this paper, we have assumed a common safe carrier-sensing range for all transmitters. Allowing the carrier-sensing range to vary from transmitter to transmitter according to the local network topological structures may improve spatial reuse further. In this paper, we have not considered virtual carrier sensing (i.e., the RTS/CTS mode in 802.11). Ensuring hidden-node free operation under virtual carrier sensing is rather complicated even under the pairwise interference model (see [11] for details.) The study of interference-safe transmissions for virtual carrier sensing under the cumulative interference model is a subject for further study.

APPENDIX A
THE NEED FOR RS(RE-START) MODE

It is shown in [8] that although the carrier-sensing range is sufficiently large for the SINR requirements of all nodes, transmission failures can still occur due to the "Receiver-Capture effect".
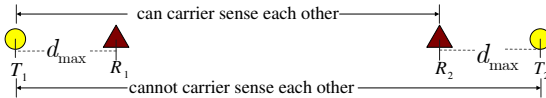

Fig. 6. Collision due to "Receiver-Capture effect"

Take a two-link case shown in Fig. 6 as an example. In Fig. 6, $d(T_1, T_2) > CSR$ and $d(T_1, R_2) < CSR$. So the transmitters T_1 and T_2 can not 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 will have sensed the signal of T_1 and 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 [8] that no matter how large the carrier-sensing range is, we can always come up with an example that gives rise 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". 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.

APPENDIX B
PROOF OF THEOREM 1

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 (6) is sufficient to guarantee the satisfaction of both the SIR 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. Consider any two links l_i and l_j in $\mathcal{S}^{CS}$, we have

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

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 based on the triangular inequality

$$d(T_j, R_i) \geq d(T_j, T_i) - d(T_i, R_i) \geq (K+1)d_{\max},$$
$$d(R_j, T_i) \geq d(T_i, T_j) - d(T_j, R_j) \geq (K+1)d_{\max},$$
$$d(R_j, R_i) \geq d(R_i, T_j) - d(T_j, R_j) \geq Kd_{\max}.$$

We take the most conservative distance $Kd_{\max}$ in our interference analysis (i.e., we will pack the interference links in a tightest manner given the *Safe-CSR_{cumulative}* in (6)). Consider any two links l_i and l_j in $\mathcal{S}^{CS}$. The following four inequalities are satisfied:

$$d(T_i, T_j) \geq Kd_{\max}, \quad d(T_i, R_j) \geq Kd_{\max},$$
$$d(T_j, R_i) \geq Kd_{\max}, \quad d(R_i, R_j) \geq Kd_{\max}.$$

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

$$SIR = \frac{P_t d^{-\alpha}(T_i, R_i)}{\sum\limits_{l_j \in \mathcal{S}^{CS}, j \neq i} P_t d^{-\alpha}(S_j, R_i)}$$

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

$$P_t d^{-\alpha}(T_i, R_i) \geq P_t \cdot d_{\max}^{-\alpha}. \qquad (12)$$

To calculate the cumulative interference power, we consider the worst case that all the other concurrent transmission links have the densest packing, in which the link lengths of all the other concurrent transmission links are equal to zero. In this case, the links degenerate to nodes. The minimum distance between any two links in $\mathcal{S}^{CS}$ is $Kd_{\max}$. The densest packing of nodes with the minimum distance requirement is the hexagon packing (as shown in Fig. 7).

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

$$P_t d^{-\alpha}(S_j, R_i) \leq P_t (Kd_{\max})^{-\alpha} = \frac{1}{K^\alpha} \cdot P_t d_{\max}^{-\alpha},$$

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

If link l_j is the second layer neighbor link of link l_i, we have $d(S_j, R_i) \geq \sqrt{3}Kd_{\max}$. Thus we have

$$P_t d^{-\alpha}(S_j, R_i) \leq P_t \left(\sqrt{3}Kd_{\max}\right)^{-\alpha} = \frac{1}{\left(\sqrt{3}K\right)^\alpha} P_t d_{\max}^{-\alpha},$$

and there are at most 12 neighbor links in the second layer.

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

$$P_t d^{-\alpha}(S_j, R_i) \leq P_t \left(\frac{\sqrt{3}}{2}nKd_{\max}\right)^{-\alpha} = \frac{1}{\left(\frac{\sqrt{3}}{2}nK\right)^\alpha} P_t d_{\max}^{-\alpha},$$

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

So the cumulative interference power satisfies:

$$\sum_{l_j \in \mathcal{S}^{CS}, j \neq i} P_t d^{-\alpha}(S_j, R_i)$$

$$\leq \left(6 \cdot \left(\frac{1}{K}\right)^\alpha + \sum_{n=2}^{\infty} 6n \left(\frac{2}{\sqrt{3}nK}\right)^\alpha\right) \cdot P_t d_{\max}^{-\alpha}$$

$$= 6 \cdot \left(\frac{1}{K}\right)^\alpha \left(1 + \sum_{n=2}^{\infty} n \left(\frac{2}{\sqrt{3}n}\right)^\alpha\right) \cdot P_t d_{\max}^{-\alpha}$$

$$= 6 \cdot \left(\frac{1}{K}\right)^\alpha \left(1 + \left(\frac{2}{\sqrt{3}}\right)^\alpha \sum_{n=2}^{\infty} n \left(\frac{1}{n}\right)^\alpha\right) \cdot P_t d_{\max}^{-\alpha}$$

$$= 6 \cdot \left(\frac{1}{K}\right)^\alpha \left(1 + \left(\frac{2}{\sqrt{3}}\right)^\alpha \sum_{n=2}^{\infty} \frac{1}{n^{\alpha-1}}\right) \cdot P_t d_{\max}^{-\alpha}$$

$$\leq 6 \cdot \left(\frac{1}{K}\right)^\alpha \left(1 + \left(\frac{2}{\sqrt{3}}\right)^\alpha \frac{1}{\alpha-2}\right) \cdot P_t d_{\max}^{-\alpha} \qquad (13)$$

$$= \frac{P_t d_{\max}^{-\alpha}}{\gamma_0}, \qquad (14)$$

where (13) follows from a bound on Riemann's zeta function and (14) follows from the definition of K in (7).

According to (12) and (14), we find that the SIR of the DATA frame of link l_i at the receiver R_i satisfies:

$$SIR = \frac{P_t d^{-\alpha}(T_i, R_i)}{\sum_{l_j \in \mathcal{S}^{CS}, j \neq i} P_t d^{-\alpha}(S_j, R_i)} \geq \frac{P_t \cdot d_{\max}^{-\alpha}}{\frac{P_t d_{\max}^{-\alpha}}{\gamma_0}} = \gamma_0.$$

This means that the SIR requirement of the successful transmission of the DATA frame on link l_i can be satisfied.
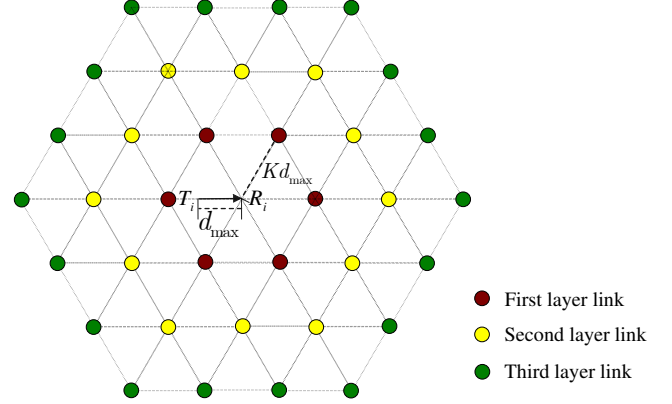

Fig. 7. The packing of the interfering links in the worst case

The proof that the SIR requirement of the ACK frame on link l_i can be satisfied follows a similar procedure as above. So for any link l_i in the concurrent transmission link set $\mathcal{S}^{CS}$, condition (6) is sufficient to satisfy the SIR requirements of the successful transmissions of both its DATA and ACK frames. This means that, together with the receiver's RS mode, condition (6) is sufficient for preventing hidden-node collisions in CSMA networks under the cumulative interference model. ∎

APPENDIX C
PROOF OF THEOREM 2

Proof: Consider any link l_i in the link 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 (10) 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} 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 $Safe\text{-}CSR_{cumulative}$. We use inductive proof method. 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 $l_1, l_2, \cdots, l_M$. For 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

$$d(T_j, T_k) \geq \textit{Safe-CSR}_{cumulative}, \forall j, k \in \{1, \cdots, M\}, j \neq k. \tag{15}$$

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 $t_1, t_2, \cdots, t_M$ 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 $t_1', t_2', \cdots, t_M'$ if the links in $\mathcal{S}^{CS}$ start to transmit the ACK frames before link l_i starting it transmission. In the IPCS mechanism, at least the following M inequalities must be satisfied if T_i can start its transmission:

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

Because

$$\Delta P_i^{CS}(t_j) = P_t d(T_i, T_j)^{-\alpha},$$
$$P_{th} = P_t \left(\textit{Safe-CSR}_{cumulative}\right)^{-\alpha},$$

we have

$$d(T_i, T_j) \geq \textit{Safe-CSR}_{cumulative} \quad \text{for} \quad j = 1, \cdots, M.$$

Thus, we have shown that the separation between any pair of transmitters in the link set $\mathcal{S}^{CS} \cup l_i$ is no less than $\textit{Safe-CSR}_{cumulative}$ 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 mth 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 $d(T_i, T_j) \geq \textit{Safe-CSR}_{cumulative}$.

If $t_i(m) < t_j < t_i(m) + t_{packet}$, this means t_j falls into the transmission time of the mth 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 $d(T_i, T_j) \geq \textit{Safe-CSR}_{cumulative}$.

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

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