Hidden-Node Removal and Its Application in Cellular WiFi Networks

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***Abstract*—This paper investigates the hidden-node phenomenon (HN) in IEEE 802.11 wireless networks. HN occurs when nodes outside the carrier-sensing range of each other are nevertheless close enough to interfere with each other. As a result, the carrier-sensing mechanism may fail to prevent packet collisions. HN can cause many performance problems, including throughput degradation, unfair throughput distribution among flows, and throughput instability. The contributions of this paper are threefold. 1) This is a first attempt to identify a set of conditions—which we called Hidden-node-Free Design (HFD)—that completely remove HN in 802.11 wireless networks. 2) We derive variations of HFD for large-scale cellular WiFi networks consisting of many wireless LAN cells. These HFDs are not only HN-free, but they also reduce exposed nodes at the same time so that the network capacity is improved. 3) We investigate the problem of frequency-channel assignment to adjacent cells. We find that with HFD, careful assignment in which adjacent cells use different frequency channels does not improve the overall network capacity (in unit of bits per second per frequency channel). Indeed, given f frequency channels, a simple scheme with f overlaid cellular WiFi networks in which each cell uses all f frequencies yields near-optimal performance.**

***Index Terms*—Hidden-node problem (HN), IEEE 802.11, modeling, performance evaluation, protocol design.**

I. INTRODUCTION

THIS PAPER investigates the hidden-node phenomenon (HN) in IEEE 802.11 wireless networks. HN occurs when nodes outside the carrier-sensing range of each other are nevertheless close enough to interfere with each other. As a result, the carrier-sensing mechanism may fail to prevent packet collisions. HN can cause many performance problems, including throughput degradation, unfair throughput distribution, and throughput instability [1].

The contributions of this paper are threefold.

1) As detailed in Section I-A1, most previous work considered HN in an isolated manner by focusing on specific examples in which it arises. In addition, most existing solutions aim to remove observed undesirable symptoms of HN rather than HN itself. With these piecemeal approaches, it is not clear whether all the negative effects of HN have been removed. Although some prior investigations gave the conditions under which HN does not occur, the conditions given are actually not sufficient to prevent HN in all cases (elaborated upon in Section I-A1). We believe our paper is a first attempt to identify a general set of sufficient conditions—which we called Hidden-node-Free Design (HFD)—that completely remove HN in 802.11 wireless networks (including *ad hoc* mode and infrastructure mode). Specifically, our conditions consist of two parts: a) a sufficiently large carrier-sensing range and b) a receiver mechanism called the "Restart Mode" (RS), in which the receiver will switch to receive another signal in the midst of receiving a signal if the new signal strength is sufficiently larger. Previous investigations did not identify requirement b), and their requirement for a) is not stringent enough to prevent HN.
2) Recent widespread adoption of 802.11 technologies has led to explosive deployment of wireless LAN (WLANs). In many instances, these WLANs are overlapping and may interfere with each other. How to minimize the interferences while achieving spectral reuse is therefore an interesting issue. We derive variations of HFD for such large-scale cellular WiFi networks. These HFDs are not only HN-free, but they also reduce exposed nodes (ENs) at the same time. They yield higher spectral reuse and higher overall network capacity.
3) We investigate the problem of frequency-channel assignment to adjacent cells in cellular WiFi networks. We find that with HFD, careful assignment in which adjacent cells use different frequency channels does not improve the overall network capacity (in unit of bits per second per frequency channel). Indeed, given f frequency channels, the simple scheme with f parallel overlaid cellular WiFi networks in which each cell uses all f frequencies yields near-optimal performance.

1) Related Work: In [1], two performance problems triggered by HN in multihop networks were identified: 1) unfair throughput distributions among contending TCP flows and 2) rerouting instability in a multihop flow. Reference [1] did not provide a solution to HN.

Reference [2] provided a "node-based" analysis of HN. It was argued that when the physical carrier-sensing (PCS)

Manuscript received August 20, 2005; revised March 3, 2006, July 19, 2006, January 12, 2007, and January 13, 2007. This work was supported in part by the Competitive Earmarked Research Grant under Project 414106, established under the University Grant Committee of the Hong Kong Special Administrative Region, China. The review of this paper was coordinated by Dr. Q. Zhang.

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Digital Object Identifier 10.1109/TVT.2007.900393

range[1] is larger than the link distance (transmitter–receiver distance) plus the interference range (IR),[2] HN can be removed, and RTS/CTS (which implements virtual carrier sensing) is no longer needed. A recent work [3] gives a similar result. According to our "link-based" analysis in this paper, however, this condition is not sufficient for the elimination of HN in general.

References [4]–[6] extended the investigation in [1]. In particular, the "self-HN interference" phenomenon of a single multihop traffic flow was studied. The successive packets of the same traffic flow may self-interfere among themselves as they hop from node to node. Detailed explanations on how self-HN interference causes throughput degradation as well as triggers the rerouting instability phenomenon were given in [5]–[8]. However, the studies in [4]–[8] only provided solutions to alleviate "symptoms" of HN, and these solutions do not remove the "root" of the problem: the HN itself. In contrast, this paper focuses on solutions that remove HN.

The rest of this paper is organized as follows. The general HFD that applies to all network topologies is presented in Section II and formally proved in Appendix A. Section III validates the general HFD by showing that it removes performance problems related to HN. Section IV systematically lays out the different possible channel-assignment schemes in cellular WiFi networks. Different flavors of HFDs that exploit the specific structure of the cellular-network topology to reduce the carrier-sensing range requirement (hence EN) are considered. Section V presents the performance results of the different schemes. Section VI discusses the tradeoff between HN and EN. In addition, Section VII concludes this paper.

II. HIDDEN-NODE-FREE DESIGN (HFD)

In this section, we first provide the definition of HN and, then, the sufficient conditions for removing HN. HN exists in 802.11 networks with either infrastructure mode or *ad hoc* mode. The following development is independent of the modes and is thus applicable to all 802.11 networks.

A. Definition and Examples

Define a "link" as a transmitter–receiver pair. Link i is also denoted by (T_i, R_i), where T_i and R_i are its transmitter and receiver.

1) Definition of HN: Link i is said to be hidden from link j if the following conditions are true. 1) T_j cannot carrier-sense the transmission on link i, and 2) link i may cause transmission failures on link j, or vice versa, so that transmission on at least one of the links will fail when both links transmit simultaneously (Note that by "simultaneous," we refer to the situation when the transmissions by different nodes overlap in time. Their transmissions may actually be initiated at different instances so that the start times of the transmissions are different).

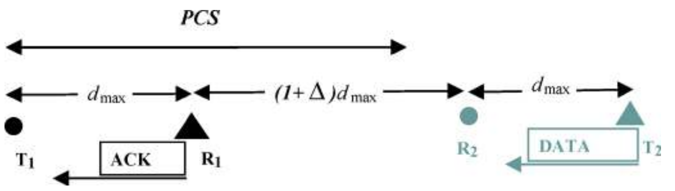

Fig. 1. PCS not sufficiently large leads to HN due to insufficient SIR.

There is HN between links i and j if either i is hidden from j or j is hidden from i. A network is said to suffer from HN if there is HN between any two links.

With respect to condition 1), for basic mode operation, T_j cannot carrier-sense the transmission on link i if T_j cannot carrier-sense T_i. For RTS/CTS mode, in addition to the above, if T_j can neither receive the RTS of T_i nor the CTS of R_i, the net result is that T_j may initiate a DATA transmission when T_i is already transmitting DATA.

With respect to condition 2), there are two situations that lead to "transmission failures:" 1) SIR[3] at a receiver is not sufficiently large and 2) "Receiver Capture" effect. When a transmitter tries to initiate a transmission (by sending a DATA or RTS packet), but the intended receiver cannot reply an ACK or CTS because of ongoing transmissions on other links, the transmission also fails even if SIR is high enough. This effect exists in both the basic and RTS/CTS modes. In the basic mode, it has to do with the normal receiver operation in many 802.11 products, which will be further explained later. Most previous work on HN (e.g., [2]) only considers the first situation 1). However, our definition of HN includes both situations since they both lead to transmission failures, after which, the transmitter must back off and retransmit the packet, without knowing whether the failure is due to insufficient SIR or "Receiver Capture" effect. We illustrate the two situations using a few examples in the following. For simplicity, we assume the basic mode (DATA–ACK handshake) in the examples. In addition, we assume that all nodes use the same transmit power.

2) Example 1—Simultaneous Transmissions But Insufficient SIR: The example in Fig. 1 shows a situation under which carrier sensing does not prevent simultaneous transmissions that result in collisions.

Before explaining this example, we need to first review the concept of IR. It has been shown in [2] that, with the power propagation function

$$P(P_t; d) = A\frac{P_t}{d^{\alpha}} \tag{1}$$

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[1] This is the range within which a transmitter triggers physical carrier detection. In IEEE 802.11 MAC, a transmitter can only start a transmission when it senses the media as idle.

[2] A node that is receiving a packet from its transmitter will be "interfered with" by another transmitter within the "Interference Range" of the node, resulting in the loss of the packet due to collision [2]. Detailed quantitative definitions of PCS and IR will be given later.

[3] SIR requirements can be different for DATA packets and ACK packets if they are transmitted at different bit rates. The SIR requirement for DATA is higher in cases where it is transmitted at a higher rate than ACK. Different commercial products may have different settings, but usually, ACK will not be transmitted at a higher rate than DATA. In this paper, we consider the "worst case," that is, we use the SIR requirement of DATA for both DATA and ACK. If this requirement is not met, then packet collision is possible; otherwise, collision is not possible because both SIR requirements for DATA and ACK are met. As we will see later, this simplifies our protocol design. We also note that many commercial APs actually use the same rate for DATA and ACK.

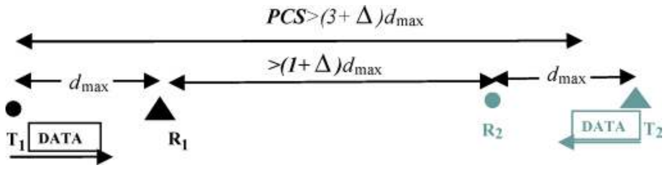

Fig. 2. Lack of receiver "RS mode" leads to HN no matter how large PCS and SIR are.

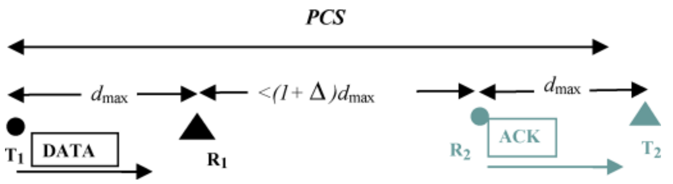

Fig. 3. With RS mode, PCS not sufficiently large still leads to HN due to insufficient SIR.

where $P(P_t; d)$ is the received power at a distance d from a transmitter that transmits at power P_t, A is a constant, and α is the pass-loss exponent. The IR of a link i (with link length d_i) is $IR_i = (1+\Delta)d_i$, where $1+\Delta = C_t^{1/\alpha}$, with C_t as the required SIR. The transmissions by any other node within IR_i of either the transmitter or receiver of link i will interfere with the transmission on link i by corrupting either its DATA frame or ACK frame.

In Fig. 1, there are two links (T_1, R_1) and (T_2, R_2), with the link length $d_{\max}$, which is the maximum link length allowed in the network. The distance $|R_1 - R_2|$ is equal to the IR of links 1 and 2, $(1+\Delta)d_{\max}$. In Fig. 1, the "PCS range" is less than $(2+\Delta)d_{\max} < |T_1 - T_2|$. Therefore, T_1 and T_2 can simultaneously initiate transmissions since they cannot carrier-sense each other. When they do so, R_1's ACK can corrupt T_2's DATA at R_2 (if T_1's DATA finishes earlier than T_2's DATA) due to the insufficient SIR at R_2. Therefore, HN can occur between the two interfering links. In fact, PCS larger than $(3+\Delta)d_{\max}$ is needed to prevent HN in this example. It turns out that this example represents the "worst case" situation requiring the largest PCS. We will prove later that PCS $\geq (3+\Delta)d_{\max}$ is one of the sufficiency conditions for prevention of HN in general.

3) Example 2—Simultaneous Transmissions, Sufficient SIR, But Inappropriate Receiver Carrier-Sensing Operation: Fig. 2 shows that no matter how large PCS is, HN can still occur without an appropriate receiver carrier-sensing operation. In Fig. 2, PCS $> (3+\Delta)d_{\max}$; $|R_2 - T_1| <$ PCS; however, $|T_2 - T_1| >$ PCS and $|R_1 - R_2| > (1+\Delta)d_{\max}$. Therefore, simultaneous transmissions can occur, and the SIR is sufficient. No "physical collisions" occur. However, HN can still happen, as described below.

Assume that T_1 starts first to transmit a DATA packet to R_1. According to the experimental results in [9] (as well as the assumption in NS2 [10]), after the physical-layer preamble of the packet is received by R_2 (since R_2 is within the PCS of T_1, R_2 can carrier-sense the physical-layer header even though it cannot decode the payload. The PHY header is typically transmitted at a lower data rate than the MAC payload), R_2 will "capture" the packet and will not attempt to receive another new packet while T_1's DATA is ongoing. If, at this time, T_2 starts to transmit a DATA to R_2, R_2 will not receive it and will not reply with an ACK, causing a transmission failure on link (T_2, R_2). This behavior is called "receiver capture." Note that no matter how large PCS is, we can always come up with an example like that in Fig. 2 that gives rise to HN.

This HN problem can be solved with a receiver "RS mode" which can be enabled in some 802.11 products (e.g., Atheros WiFi chips). With RS mode, a receiver will switch to receive the stronger packet as long as its power is C_t times [4] higher than the current packet. If the new packet is an 802.11 DATA targeted for it, the node will reply with an ACK after Short InterFrame Space (SIFS), whether the medium around this node is idle or not.

4) Example 3—Simultaneous Transmissions, Receiver RS Mode, and Insufficient SIR: One might wonder, given the example in Fig. 2, why the default receiver operations of all commercial products and the NS2 simulator do not assume RS mode. The reason is that, without a sufficiently large PCS, enabling RS mode may lead to HN collisions, as described below.

RS mode alone cannot prevent HN without a PCS $> (3+\Delta)d_{\max}$. To see this, consider the example in Fig. 3, where PCS $< (3+\Delta)d_{\max}$ and $|R_1 - R_2| < (1+\Delta)d_{\max}$. Assume that T_1 transmits a DATA to R_1 first. During the DATA's period, T_2 starts to send a shorter DATA packet to R_2. With RS mode, R_2 switches to receive T_2's DATA and sends an ACK after the reception. If T_1's DATA is still in progress, R_2's ACK will corrupt the DATA at R_1.

Therefore, it is not advisable to use RS mode if PCS is not large enough, which is the case in most commercial products. The NS2, which simulates operations in commercial products, for example, assumes PCS = 2.2 times the maximum transmission range (TxRange) of DATA. If $d_{\max}$, which is the maximum link length allowed in the network, is set to TxRange, then such HN collisions will inevitably occur. As a result, most commercial products do not use RS mode by default. However, without RS mode, HN collisions like that in Fig. 2 inevitably occur. Either way, HN occurs.

B. HFD for Basic Access Mode

From the above examples, we summarize the requirements for a HFD for basic mode in IEEE 802.11. It includes two requirements.

1) A range requirement

$$\text{PCS} \geq (3+\Delta)d_{\max}. \tag{2}$$

If $C_t = 10$, and $\alpha = 4$

$$\text{PCS} \geq 3.78 d_{\max} \tag{3}$$

2) and the receiver's RS mode.

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[4] Usually, the "restart threshold" is equal to C_t. If it is not, HFD needs only a minor modification.

Satisfaction of these two requirements is sufficient to prevent HN in any general network topology. The formal proof is given in Appendix A.

Similarly, we designed HFD for RTS/CTS mode. In that case, besides RS mode, a key requirement on the virtual carrier-sensing range (VCS) and $d_{\max}$ is VCS $\geq (2+\Delta)d_{\max}$. However, due to the limited space here, the details are given in [11]. We will only consider Basic Access Mode in the following sections.

Also, we have assumed that there are no significant physical obstructions for signal propagation. In Appendix B, we sketch how the HFD here can be augmented with additional features to deal with cases where there are physical obstructions.

1) Implications for Network Design and Implementation: Requirement 1) [Inequality (2)] may increase the EN problem, in which some legitimate noncolliding simultaneous transmissions may be disallowed because of the larger PCS required. This may reduce the network capacity. However, it is a price to pay if we want to remove HN entirely. In practice, we are more likely to fix PCS but reduce the maximum link length $d_{\max}$. In this case, for infrastructure-mode WiFi networks, the price of EN becomes the need for more access points (APs) (to cover the same area) in order to maintain the network connectivity and capacity. Since APs are rather inexpensive these days, this price may not be that significant from the practical standpoint. Nevertheless, for situations where APs cannot be deployed at will, and it is important for each AP to cover as much area as possible, it is interesting to investigate to what extent HN and EN can be traded off against each other and to what extent they can be reduced simultaneously. Section VI will discuss this issue and give a series of tradeoff points a designer can choose from (we also presented schemes based on the RTS/CTS mode to do so in [15]). This paper, however, mainly focuses on what needs to be done if we were to remove HN entirely.

For implementation, since PCS is usually limited by the actual receiver sensitivity, increasing PCS without changing $d_{\max}$ may be impractical. We could fix PCS (for example, 2.2* TxRange as in NS2 or other values in commercial products) and limit $d_{\max}$ to some value below TxRange instead. That is, although proper DATA decoding can be performed by a receiver up to a distance of TxRange from the transmitter, we will not establish links with link length larger than $d_{\max} <$ TxRange. For cellular WiFi networks, this means that more APs will be needed to cover the same area because the distance from the client stations to their associated APs will be limited by $d_{\max}$, not TxRange. Note that, although we will have fewer clients per AP, on an average basis, the bandwidth per client will not increase because PCS is kept constant. Each time a station transmits, it uses up the same spatial area within which no other stations can transmit. However, because of the elimination of HN, unfairness and other problems associated with HN can be solved.

To further elaborate on the implementation details, in practice, PCS and $d_{\max}$ are determined by the transmission power P_t and receiving thresholds. We can write

$$P(P_t; d_{\max}) = P_{\text{link}} \tag{4}$$

$$P(P_t; \text{PCS}) = P_{\text{PCS}} \tag{5}$$

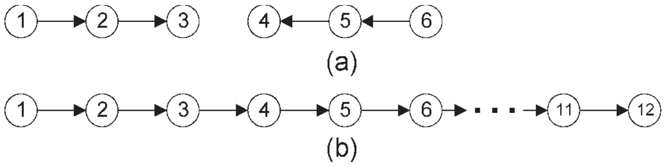


Fig. 4. Traffic flows that can give rise to HN.

where P_{link} is the received power threshold we impose for link establishment. A link will not be set up during the initial routing process if the received power falls below this threshold; P_{PCS} is the received power threshold we impose on PCS. Note that P_{link} and P_{PCS} are lower-bounded by the minimum power thresholds (receiver sensitivities) required to physically decode DATA/ACK or operate PCS, respectively. Reference [16] lists the minimum thresholds for some different data rates of DATA/ACK. That is, we will generally set them higher than the receiver sensitivities needed but not lower.

Therefore, if PCS is fixed, $d_{\max}$ can be adjusted by tuning P_{link} (if we keep P_t unchanged). For example, if we want PCS $= 3.78 d_{\max}$, with the assumption of two-ray ground model with the "path loss exponent" $\alpha = 4$, (4) and (5) become

$$A\frac{P_t}{d_{\max}^4} = P_{\text{link}} \tag{6}$$

$$A\frac{P_t}{\text{PCS}^4} = P_{\text{PCS}} \tag{7}$$

where A is a constant [12]. Therefore

$$P_{\text{link}} = 3.78^4 P_{\text{PCS}}$$

or

$$P_{\text{link}}(\text{dB}) \approx P_{\text{PCS}}(\text{dB}) + 23.10\ (\text{dB}). \tag{8}$$

III. REMOVAL OF HN PERFORMANCE PROBLEMS

"TCP unfairness" and "rerouting instability" are two performance problems triggered by HN that is identified previously [1]. This section validates by simulation that, by removing HN, HFD also eliminates such performance problems. As in [1], we consider topologies as shown in Fig. 4. Nodes in a straight line are equally spaced apart by 140 m.

The simulations were conducted using NS2 [10]. The data rate is set at 11 Mb/s. The two-ray ground propagation model is adopted with loss exponent $\alpha = 4$. C_t is set to 10 dB. The PCS range is 550 m. Thus, for HFD, the maximum link distance $d_{\max}$ according to (3) is $550/3.78 = 145$ m. The *Ad Hoc* On-Demand Distance Vector routing protocol is used. All data sources are UDP or TCP traffic streams with fixed packet size of 1460 B. AQ6

With HFD, receiver RS mode is turned on; for the case without HFD, receiver RS mode is turned off. The PCS range is 550 m in both cases.

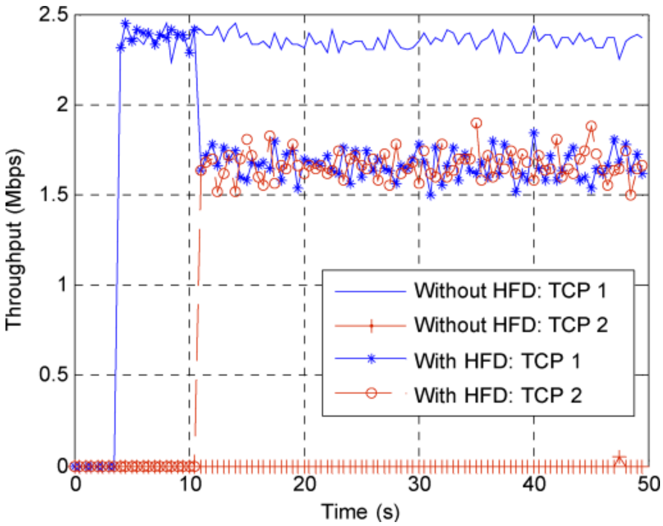


Fig. 5. TCP unfairness (fairness) without (with) HFD.

A. *TCP Unfairness*

We ran a TCP simulation experiment using the topology in Fig. 4(a). There are two TCP connections. TCP 1 is from node 1 to node 3, and TCP 2 is from node 6 to node 4. TCP 1 starts earlier than TCP 2 at time = 3.0 s, and TCP 2 starts at time = 10.0 s. Without HFD, node 1 is hidden from node 5, causing node 5's DATA packet to collide at node 4 with node 1's DATA packet. Likewise, node 2 is hidden from node 6, causing node 6's DATA packet to collide at node 5 with 2's DATA packet. Because TCP 1 starts earlier, TCP 2 virtually has no chance to obtain any throughput (see Fig. 5). Fig. 5 also shows that this severe "unfairness" problem is eliminated with HFD.

B. *Rerouting Instability*

Rerouting instability is triggered by excessive packet collisions that are introduced by hidden terminal nodes (which is mistaken for route unavailability). We performed a UDP simulation experiment using the chain topology [Fig. 4(b)]. There is a UDP flow from node 1 to node 12. Without HFD, node 5 is "hidden" from node 1, causing the DATA packets of node 1 to repetitively collide at node 2 with node 5's DATA packets. Likewise, nodes 2, 3, 4, 5, etc., face the same problems. It has been shown in [1], [7], and [8] that throughput instability can result from misinterpretation by the routing algorithm that links are down (because of repetitive packet transmission failures due to HN). Fig. 6 shows that the throughput instability is removed with HFD.

IV. CHANNEL ASSIGNMENT IN WiFi CELLULAR WITH HFD

There are three orthogonal channels for 802.11b/g and eight orthogonal channels for 802.11a. When multiple WLANs are deployed to form a large WiFi cellular network, there is the issue of how to assign these channels to the different WLANs while keeping the network free of HN. On one hand, channel assignment can separate cells with the same channel further apart so that intercell physical interference can be reduced or totally eliminated, relaxing the HFD's requirements on the carrier-sensing range. On the other hand, more spectrum resources (channels) will be used. Thus, an issue is whether a careful channel assignment can yield better spectrum efficiency or not while ensuring no HN in the network. We address this issue by examining possible channel assignment schemes systematically.

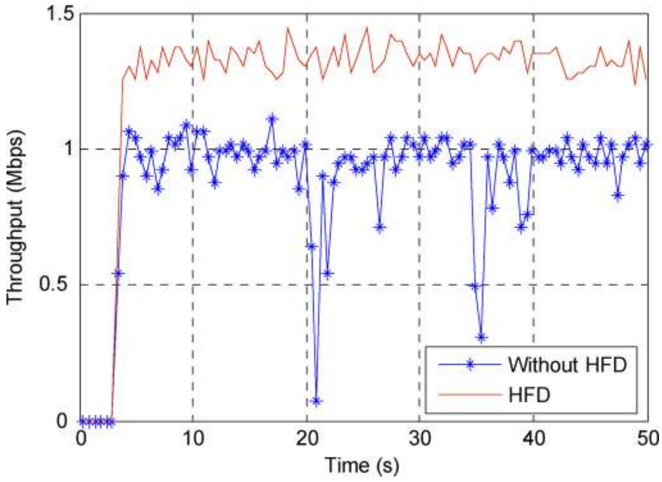


Fig. 6. Throughput instability (stability) of an 11-hop UDP flow without (with) HFD.

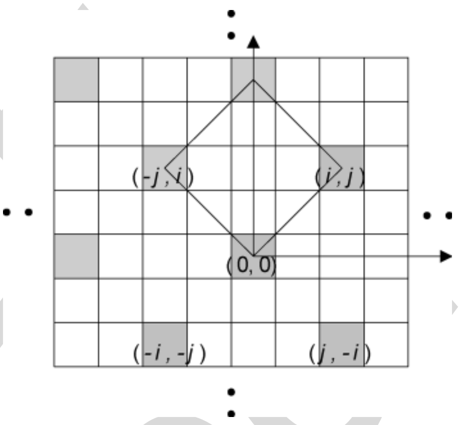


Fig. 7. Channel assignment $(N = 8)$ with square cells.

This section focuses on the square-cellular topology. In [11], we also studied channel assignment in hexagon-cellular topology and presented its performance results. In a square-cellular WiFi network, the APs are placed in a grid (see Fig. 7 in which each square corresponds to one WLAN). Clients are located randomly and are associated with the nearest APs. We assume that the AP is placed at the center of the square of its WLAN. The largest link length $d_{\max}$ is the distance from the AP to the corner of the square. We denote the distance between an AP and another AP on the same channel closest to it by D, and the total number of channels needed to cover the overall WiFi cellular network by N.

A. *Channel Assignment*

In a regular topology, we can assign the channels in a regular manner. Channel assignment for a hexagon-cellular topology

TABLE 1
NUMBER OF CHANNELS USED IN THE WiFi CELLULAR NETWORK FOR DIFFERENT OFFSET ASSIGNMENTS

(i, j)	(1, 0)	(1, 1)	(2, 0)	(2, 1)	(2, 2)	(3, 0)	(3, 2)
N	1	2	4	5	8	9	13

is well known [12]. If a cell is in the form of a square, by emulating the channel assignment for hexagon cells, we can assign a channel as in Fig. 7 (the gray cells use the same channel). We denote by $(i,\ j)$ the "offsets" (in two axes) of one of the four adjacent cells that use the same channel as cell (0, 0), where $i \geq 0$, and $j \geq 0$. As illustrated in Fig. 7, for cell (0, 0), the four adjacent cells are cells (i, j), $(-j, i)$, $(-i, -j)$, and $(j, -i)$.

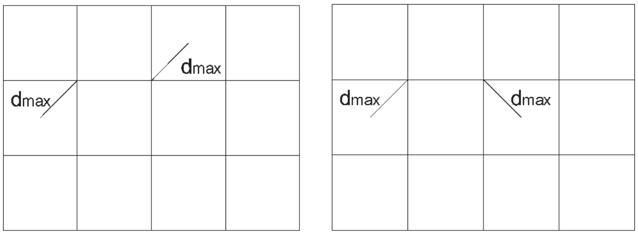
Note that, with this kind of "offset design," we can always form a square among four cells using the same channel. As illustrated in Fig. 7, cells (0,0), (i, j), $(i-j, j+i)$, and $(-j, i)$ form a square with length of each side $= D = \sqrt{i^2+j^2}$. Table I lists some possible offset assignments and the number of frequency channels used with each offset.

For an offset assignment (i, j), the number of frequency channels used to fill the whole WiFi cellular network is $N = i^2 + j^2$. To see this result, consider the square formed by the APs at cells (0,0), (i, j), $(i-j,\ j+i)$, and $(-j, i)$. With reference to Fig. 7, the area of the square is i^2+j^2. Within this square, an area of one unit is covered by the gray color. The whole plane can be divided by similar squares described above. If we omit the boundary effect (assume that the plane is infinitely large), one channel can cover $1/(i^2+j^2)$ of the whole plane. Therefore, $N = i^2+j^2$ channels are needed.

The different offsets and frequency channel requirements in Table I correspond to different "design alternatives." To systematically address all possible cases, we categorize them into three design alternatives, as listed below. In the following, we say that there is "physical interference" between two cells if it is possible that a link in one cell has physical interference with a link in the other cell (due to insufficient SIR at the latter), and there is "protocol interference" between two cells if it is possible that the transmission on a link in one cell can prevent a link in the other cell from transmitting through carrier sensing.

1) There is no protocol interference or physical interference between adjacent cells using the same channel. With this design, transmissions on cells are independent.
2) There is protocol interference, but no physical interference between adjacent cells using the same channel. In this case, the carrier-sensing mechanism may be overly aggressive so that legitimate simultaneous transmissions on different cells may be prevented by the protocol operation.
3) There is physical interference between adjacent cells using the same channel. With this design, some simultaneous transmissions on different cells need to be prevented. Therefore, to avoid HN (with HFD), there must be protocol interference.

The next few sections lay down the operating parameters of these design alternatives and elaborate on them.



(a) (b)

Fig. 8. Minimum distance between two cells. (a) $i > 0$, $j > 0$. (b) $i > 0$, $j = 0$.

B. Design Alternative 1 (DA1): No Physical Interference or Protocol Interference Among Adjacent Cells

For DA1, two transmissions on adjacent cells using the same channel must not physically interfere with each other. A certain minimum number of channels ($N_{\min}$) are required to guarantee this. Consider Fig. 8, $d_{\max}$ is the distance between the AP at the center of a cell and a client at the corner of the cell. The two cells in consideration use the same channel. Without loss of generality, we assume that $i \geq 1$, and $j \geq 0$ (since i, j cannot be both zero). In Fig. 8(a), where $i = 2$ and $j = 1$ (generally, when $i,\ j > 0$), the distance between the two corners (i.e., between the two clients) is $\sqrt{(i-1)^2+(j-1)^2}$; in Fig. 8(b), where $i = 2$ and $j = 0$ (generally, when $i > 0$, $j = 0$), the distance is $\sqrt{(i-1)^2+0^2}$. Combining the two cases, the distance between the two closest corners of two adjacent cells which use the same channel is $\sqrt{(i-1)^2+[\max(j-1, 0)]^2}$. Now, this distance must be larger than the IR. Therefore, we require

$$\sqrt{(i-1)^2+[\max(j-1,0)]^2} > (1+\Delta)d_{\max} \qquad i \geq 1,\ j \geq 0. \tag{9}$$

Now, $d_{\max} = 1/\sqrt{2}$. Assuming $\Delta = 0.78$ [as in (3)], the offsets (i, j) that satisfy this requirement are

$$(1,3), (1,4), \ldots,\ (2,2), (2,4), \ldots,\ (3,0), (3,1), \ldots .$$

Requirement (9) is the no-physical interference requirement. Given this requirement, carrier sensing still needs to work properly if simultaneous transmissions on adjacent cells are to be allowed. Specifically, we require

$$\sqrt{(i-1)^2+[\max(j-1,0)]^2} > \text{PCS} \geq 2d_{\max} \qquad \text{where} \quad i \geq 1,\ j \geq 0 \tag{10}$$

where PCS is the PCS range. The lower bound on PCS in (10) is to ensure that carrier sensing works properly to prevent simultaneous transmission within the same cell. The maximum distance between two wireless stations in the same cell is $2d_{\max}$. The upper bound on PCS in (10) ensures that a station does not sense other stations in adjacent cells. There is no need for sensing beyond a cell since (9) ensures that there is no interference beyond a cell.

Note that PCS can be adjusted by tuning the receiver sensitivity for carrier sensing while maintaining the same transmission power. Generally, the maximum PCS $\text{PCS}_{\max}$ is defined by the transmission power and the lowest received power required to decode the PHY header. If we want to make actual operating PCS smaller than $\text{PCS}_{\max}$, the following two requirements must both be satisfied before PCS is triggered.

1) The PHY header must be decodable.
2) In addition, the received power must be above a certain threshold [e.g., as dictated by the upper bound in (10) after translating it to a power relationship].

If 1) is satisfied but 2) is not, the transmission whose PHY header has been detected will be ignored.

With $\Delta = 0.78$, (10) is a more stringent requirement than (9), and satisfaction of (10) automatically implies the satisfaction of (9). The "offsets" that satisfy (10) and, therefore, correspond to DA1 are

$$(1,3),(1,4),\ldots,\ (2,4),\ldots,\ (3,0),(3,1),\ldots\ .$$

Note that (2, 2) just misses the requirement of (10) because of the strict inequality for the PCS upper bound. Among the above offsets, (3, 0) yields the smallest number of channels required

$$N_{\min} = i^2 + j^2 = 9. \tag{11}$$

C. Design Alternative 2 (DA2): No Physical Interference, But With Protocol Interference Among Adjacent Cells

Requirement (9) still applies for this case. Instead of (10), we have

$$\text{PCS} \geq 2d_{\max} \geq \sqrt{(i-1)^2 + [\max(j-1,0)]^2}. \tag{12}$$

That is, the PCS required for proper carrier sensing within a cell will also prevent some simultaneous transmissions among adjacent cells. For $\Delta = 0.78$, among the offsets that satisfy (9), there is only one that also meets (12), and that is (2, 2). The corresponding $N_{\min}$ is

$$N_{\min} = i^2 + j^2 = 8. \tag{13}$$

Note that with (2, 2), although, in principle, there could be interference between two links of two adjacent cells, in practice, this occurs with zero probability assuming random placement of nodes within cells. Specifically, there is protocol interference only if two stations of the two links are positioned right at the corners of their associated cells. Any small deviation from this will remove the protocol interference.

Therefore, from the probabilistic viewpoint, $N_{\min} = 8$ could be said to be a design that meets the requirement of DA1 with probability 1. Having said that, we concede that, in practice, one may have to include a certain margin of error or uncertainty in the design. That is, it is still possible for stations that are located near the corners of adjacent cells to interfere with each other. Furthermore, with different cell shapes, Δ values, and parameter settings, there could be nontrivial cases for DA2. For this reason, we group this design under a different category than DA1.

D. Design Alternative 3 (DA3): With Physical Interference Among Adjacent Cells

For DA3, adjacent cells using the same channel may physically interfere with each other. That is, (9) is not satisfied

$$\sqrt{(i-1)^2 + [\max(j-1,0)]^2} \leq (1+\Delta)d_{\max} \qquad i \geq 1,\ j \geq 0. \tag{14}$$

The offsets that satisfy (14) are

$$(1,0),\ (1,1),\ (1,2),\ (2,0),\ (2,1).$$

Therefore, we see that the channels used are

$$N = i^2 + j^2 = 1, 2, 4, \text{ or } 5.$$

Note that $N \leq 5$ is due to the particular regular (i,j) channel assignment strategy we assume. There could be other cell assignments that yield different results of N.

Design Alternatives 1 and 2 are HN-free if $\text{PCS} \geq 2d_{\max}$. The next few sections consider different ways of setting PCS for DA3 to make it HN-free.

1) General HFD: According to (2), the general HFD requires

$$\text{PCS} \geq (3+\Delta)d_{\max}. \tag{15}$$

Inequality (15) is independent of the network topology. In a given topology, however, it may be overkill because each node adopts the PCS range for "the worst case."

2) HFD With Nonuniform PCS: General HFD can remove HN, but without considering the actual topology. If we take the actual link layouts into consideration and allow the PCS range to vary from node to node [relaxing the requirement in (15)], EN can be reduced by allowing more noncolliding transmissions to proceed simultaneously.

Note that, in previous sections, "PCS" is defined from the perspective of a transmitter. That is, with respect to a transmitter, its transmission will prevent all the nodes within its PCS range from transmitting. In this section, however, we define "PCS" from the perspective of a receiver. That is, a node will be prevented from transmitting by the transmission from any node within its PCS range.

For clarity, we use "PCS^T" to denote PCS with respect to transmitters, and "PCS^R" to denote PCS with respect to receivers. If all nodes transmit at the same power (P_t), the PCS^R of a node a, $\text{PCS}^R(a)$, is only related to its receiver sensitivity for carrier-sensing purposes. Clearly, for uniform PCS in the previous section, $\text{PCS}^T = \text{PCS}^R$, since all the nodes have the same transmit power and carrier-sensing sensitivity.

In this section, we assume that all nodes use the same transmit power and data rate. In the following algorithm, each node computes the PCS^R it should assume in its receiver design.

3) HFD With Nonuniform PCS: For any node a

1) Denote the set of links whose sender is node A by $L(A) = \{a_1, a_2, a_3, \ldots, a_n\}$. Denote the set of links which has an "interference relationship" ("InR") with link k by $I(k)$ [links that are either physically

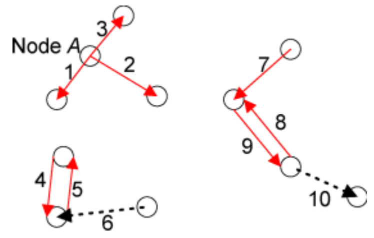


Fig. 9. Node A's interference link set $M(A) = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$.

interfered by link k or vice versa. As detailed in Appendix A, there is "InR" between links i and j if any inequality in (19) or (20) is NOT true]. Define node A's "interference link set," $M(A) = I(a_1) \cup I(a_2) \cup I(a_3) \cup, \ldots, \cup I(a_n)$.

a) For example, in Fig. 9, $L(A) = \{1, 2, 3\}$, $I(1) = \{2, 3, 4, 5\}$, $I(2) = \{1, 3, 7, 8, 9\}$, and $I(3) = \{1, 2\}$. Therefore, $M(A) = \{1, 2, 3, 4, 5, 7, 8, 9\}$. These links have been marked with red color.

b) For each node to find out the necessary information about InRs, a "Power-Exchange Algorithm" (PE) is used, which is explained in the Appendix C.

2) PCS of node A is computed as $\text{PCS}^R(A) = \max_{k \in M(A)}(|A - T_k|)$, where link k is a member of $M(A)$, and T_k is the sender of link k. Set the receiver carrier-sensing threshold of node A according to $\text{PCS}^R(A)$.[5]

Note that to obtain the distance $|A - T_k|$, A should be able to decode the PE packets (to be explained in Appendix C) from T_k and, thus, deduce the distance from the power of the received packet $P(T_k, A)$. Therefore, we set $\text{PERange} \geq (3 + \Delta)d_{\max}$ here.

Note also that, in actual situations, particularly for indoor environment, different node pairs may incur different path-loss exponents. In this case, the distance derived can be regarded as a "virtual distance" assuming a fixed path-loss exponent (corresponding to a fixed Δ). The virtual distances may not correspond to the actual distances. However, this does not pose any difficulty in the above operation because it is the virtual distances rather than the actual distances that define the InRs among nodes. Also, the operation of HFD is affected by setting the correct power threshold for carrier sensing, and the relationship among node pairs can be directly expressed in terms of powers rather than distances, so that even the virtual distances need not be computed.

V. NUMERICAL RESULTS

In this section, we give the NS2 simulation results of a square-cellular topology under different design alternatives (simulations of a hexagon-cellular topology yield very similar results [11]). The square-cellular network has $10 * 10 = 100$ APs (see Fig. 7). The size of each cell is 205 m $*$ 205 m.

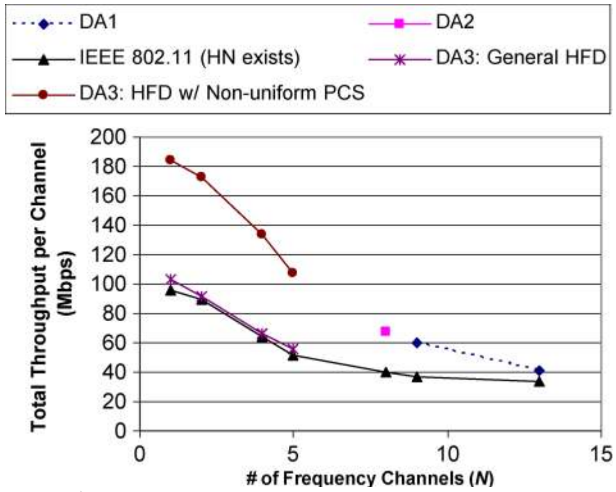


Fig. 10. Throughput per channel for different HFD Design Alternatives ("DA") in square-cellular networks.

Therefore, $d_{\max} = 205/\sqrt{2}$ m. We ensure that $d_{\max} \leq$ TxRange (i.e., the maximum transmission range). Around 400 clients are randomly placed in this area with a uniform distribution. Each client is associated with the nearest AP and sends a saturated traffic flow to the AP. The results are shown in Fig. 10.

In Fig. 10, for IEEE 802.11, PCS $= 550$ m, but "RS mode" is not enabled; therefore, it is not HN-free. For other cases, "RS mode" is enabled, and PCS is set in such a way as to ensure an HN-free property.

As discussed in Section IV, DA1 corresponds to $N > 8$, and DA2 corresponds to $N = 8$. In both cases, we set PCS $= 2d_{\max}$ (the minimum requirement). We obtained the throughput per channel C for different values of N. That is, C is the total throughput divided by N. As shown in Fig. 10, for $N \geq 8$, C decreases as N increases. In fact, the total throughput $(C^* N)$ is roughly constant for $N \geq 8$. This implies that DA1 and DA2 do not put extra frequency channels to good use, and it is not advisable to insist on having no physical interference among cells using the same channels.

DA3 is adopted when $N < 8$. In this case, simulations with two different HFDs—General HFD [with PCS $= 550$ m, slightly larger than $(3 + \Delta)d_{\max}$, so that General HFD and 802.11 in the simulations only differ by RS mode being enabled in General HFD] and HFD w/ nonuniform PCS—were carried out.

As shown in Fig. 10, for $N < 8$, "HFD w/ nonuniform PCS" significantly improves C compared to "General HFD." This is because "HFD w/ nonuniform PCS" takes into account the actual topology and InRs, while "General HFD" tries to remove HN for "the worst case." In an actual topology where clients are randomly located, the lengths of some links may be much smaller than $d_{\max}$, and "the worst case," as shown in Fig. 1, may not appear. This relaxes the requirement of PCS, and the nonuniform PCS design takes advantage of this to reduce ENs and increases the capacity.

The overall results in Fig. 10 also indicate that careful assignment of frequency channels for different cells usually cannot improve the capacity of such cellular WiFi networks. If there

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[5] With the algorithm, the transmitter of link i, T_i will be able to sense the transmitter of any link j which has an "InR" with link i. Similarly, T_j can also sense T_i, since link i also has "InR" with link j ["InR" is symmetric, according to inequalities (19) or (20)].

are f available channels, for an N-channel cell assignment, we could have f/N parallel overlaid cellular networks. The simple scheme with $N = 1$ and f overlaid cellular WiFi networks in which each cell uses all f frequencies yields the best performance.

VI. TRADEOFF BETWEEN HN AND EN

The primary objective of this paper up to now has been to investigate the properties of networks that are completely free of HN. In general, there is a fundamental tradeoff between HN and EN. If some degree of HN is allowed to exist, the unfairness problem, rerouting instability, and other HN-related performance problems may resurface somewhat. On the other hand, the overall network throughput may increase due to a lessened EN.

To illustrate this point, we first consider the Basic Access Mode. We simulate a square-cellular topology with $4 * 4 = 16$ APs (i.e., 16 cells). The size of each cell is 175 m $*$ 175 m, and $d_{\max} = 175/\sqrt{2}$ m ≈ 123.8 m. Around 64 clients are randomly placed with a uniform probability distribution. Each client is associated with the nearest AP and sends a saturated flow to the AP. Two settings are simulated: "RS mode w/ different PCSs" and "IEEE 802.11." The results are shown in Fig. 11. In the first set of curves, RS mode is enabled (as in HFD), but PCS may or may not meet the requirement of General HFD. When PCS $= 470$ m, the requirement of General HFD is met (470 m $> 3.78\ d_{\max}$). We progressively decrease PCS below the requirement of General HFD to see its effect on EN and HN. In the "IEEE 802.11" curves, there is no "RS mode." We use "total throughput" as an indication of EN—Lower EN leads to higher throughput (higher HN can also lead to throughput degradation, but it is secondary compared to EN) and uses MAC-layer "collision probability" as an indication of HN (since HNs lead to heavy packet collisions). Also, as discussed earlier, HN causes unfairness problem. Therefore, we compute the Jain's Fairness Index to quantify the fairness among individual throughputs of all the flows.

There are three key observations from Fig. 11.

1) As expected, when PCS decreases, EN decreases and HN increases (therefore fairness decreases too) in both curves ("RS mode w/ different PCSs" and "IEEE 802.11"). In other words, the EN–HN tradeoff exists in both curves [Fig. 11(a) and (b)].
2) With the same PCS setting, "RS mode w/ different PCSs" always gives a higher throughput and a lower collision probability than "IEEE 802.11" [Fig. 11(a)]. Although we started out to remove HN in this paper, in practice, one can relax the requirement of PCS to achieve a tradeoff between EN and HN. The overall performance of our proposed design, however, is always better than IEEE 802.11 with the same PCS setting.
3) The tradeoff between EN and HN is manifested as a tradeoff between throughput and fairness [see Fig. 11(b)].

There are also other minor observations. 1) Note that the "floor" collision probability in General HFD (when PCS $=$ 470 m in the "RS mode w/ different PCSs" curve) is about 7%. These MAC-layer collisions are due to the fact that backoff timers of different nodes may still choose the same random number in a contention window even if HN is removed. However, this kind of collisions will not cause trouble since consecutive collisions (as in HN) are not likely due to the random backoff algorithm in 802.11. 2) With "RS mode w/ different PCSs" in this particular simulation, PCS larger than 300 m seems to have eliminated HN considerably. This is because when the clients are randomly located (and not very dense), most link distances are smaller than $d_{\max}$.

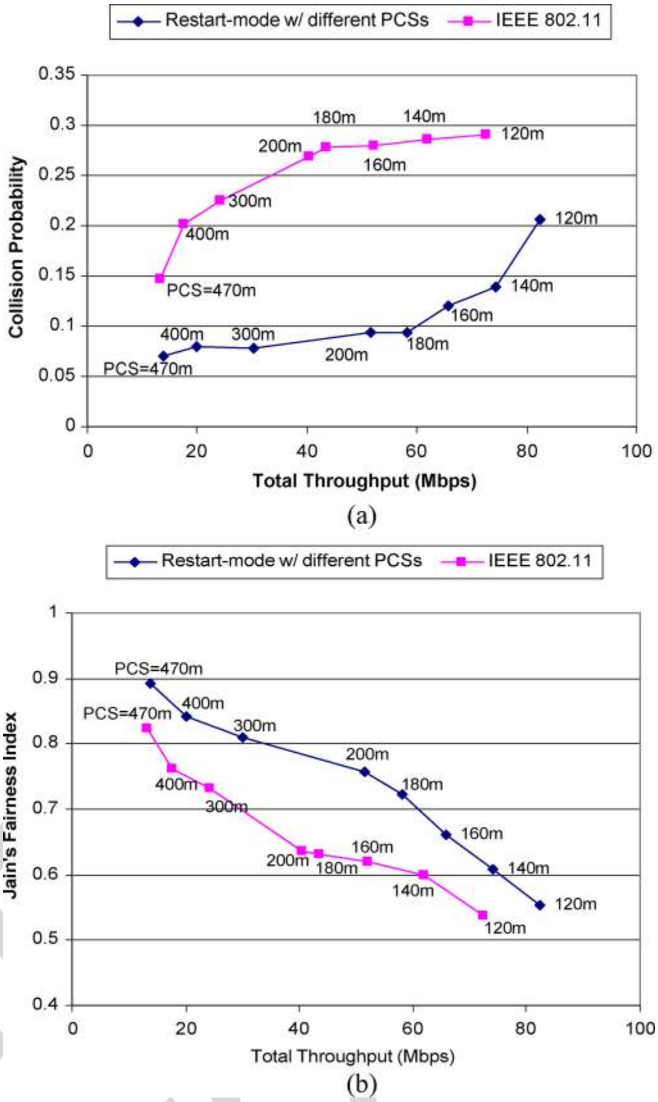

Fig. 11. Tradeoff between EN and HN. (a) Tradeoff between throughput and collision probability (the label beside each point shows the corresponding PCS value). (b) Tradeoff between throughput and fairness.

In RTS/CTS mode, our related research has shown that EN can be effectively reduced compared to the Basic Access Mode. That scheme combines HFD for RTS/CTS mode and an EN-reducing algorithm called "Selective Disregarding of NAVs (SDN)" [15]. SDN enables each node to selectively disregard "false-alarming" RTS/CTS from links that actually do not interfere with its transmissions. This cannot be achieved in the Basic Access Mode because without RTS/CTS, PHY header gives no address information. Interested readers are referred to

[15] for the scheme combining HFD and SDN. The tradeoff between EN and HN still exists in that scheme.

VII. CONCLUSION

This paper has provided a set of fundamental conditions called "General HFD," under which HN-free 802.11 networks can be designed. General HFD consists of as follows: 1) relationships between the carrier-sensing range and maximum link length $d_{\max}$ and 2) a receiver mechanism called the RS mode. We have shown that by adhering to the HFD conditions, performance problems related to HNs, including throughput degradation, unfair throughput distributions, and throughput instability [1], [5]–[8], can be removed.

For the Basic Access Mode, for example, 1) consists of just one relationship: PCS $> (3 + \Delta)\ d_{\max}$, where PCS is the PCS range, and $\Delta > 0$ is a quantity derived from the SIR requirement. This relationship provides a guideline as to how to dimension PCS and $d_{\max}$ to avoid HN in general, without the knowledge of the topology of the network beyond the fact that all link lengths are no more than $d_{\max}$. For a given network topology, less-restrictive relationships with smaller PCS can be found to improve throughput performance.

We have adapted the HFD principle for application in large-scale WiFi cellular networks consisting of many adjacent WLANs (a popular form of 802.11 deployments). We have designed variations of HFD beyond the General HFD. One version is "HFD with nonuniform PCS," in which the PCSs of different links are varied and minimized according to their surroundings. Such individual PCS minimization reduces ENs and increases spectrum spatial reuse. We have shown that the total throughput can be increased by about 100% with this design (see Fig. 10 for the case where number of channels $N = 1$).

Another approach to relax HFD's requirements on carrier-sensing range is to assign different frequency channels to adjacent cells so that intercell physical interference is either reduced or totally avoided. However, this approach also uses up more spectrum resources. Given f available frequency channels, an issue is whether it is better to assign different frequencies to adjacent cells or just have f parallel overlaid networks, with each cell having f APs: one on each frequency channel. We find that the latter has better throughput performance (in unit of bits per second per frequency channel). As indicated in Fig. 10 and using the General-HFD case in the figures as an example, the latter approach can achieve much higher throughput per channel $(N = 1)$ than the former approach ($N = 8$, wherein intercell physical interference is totally avoided).

Finally, we have discussed the fundamental tradeoff between HN and EN. We have shown the following: 1) The EN–HN tradeoff exists in both our scheme and IEEE 802.11. 2) Our scheme always outperforms IEEE 802.11 with the same PCS (PCS range) setting.

APPENDIX A

In the following, we prove that HFD for Basic Access Mode can remove HN in a network.

A. *Constraints for Simultaneous Transmissions in 802.11*

To understand the requirements of HFD, we need to first understand the fundamental causes of HN. There are two types of constraints concerning simultaneous transmissions in an 802.11 wireless network, as discussed below.

1) 802.11—Carrier-Sensing Constraints: In the Basic Access Mode, only PCS needs to be considered. For PCS, the PHY header is decoded. The length field in the PHY header informs the receiver of the duration of the payload that follows. Consider two links i and j with senders and receivers T_i, T_j, R_i, and R_j, respectively. For brevity, we will also use T_i, T_i, R_i, and R_j to denote their positions in the following discussion.

Simultaneous transmissions on the two links are allowed when

$$|T_i - T_j| > \text{PCS}. \tag{16}$$

However, the simultaneous transmissions will fail unless

$$|T_i - R_j| > \text{PCS} \tag{17}$$
$$|R_i - T_j| > \text{PCS}. \tag{18}$$

This is due to the "receiver capture" effect in most 802.11 products. If (17) is not true when T_i starts a DATA transmission first, followed by T_j, then R_j will not attempt to receive the DATA from T_j because it is in the process of receiving the ongoing signal from T_i. Transmission on link j therefore fails. Similar argument applies for (18).

2) Physical No-Collision Constraints: We now consider under what conditions will there be no physical collision between simultaneous transmissions over links i and j. Define $d_i = |T_i - R_i|$ and $d_j = |T_j - R_j|$. Since each "atomic information exchange" over an 802.11 link consists of two-way traffic, DATA followed ACK in the reverse direction, the conditions for the two transmissions not interfering with each other are as follows [14]:

$$\begin{cases} \frac{P(d_i)}{P(|S_j - R_i|)} > C_t \\ \frac{P(d_i)}{P(|S_j - S_i|)} > C_t \\ \frac{P(d_i)}{P(|R_j - R_i|)} > C_t \\ \frac{P(d_i)}{P(|R_j - S_i|)} > C_t \end{cases} \begin{cases} \frac{P(d_j)}{P(|S_j - R_i|)} > C_t \\ \frac{P(d_j)}{P(|S_j - S_i|)} > C_t \\ \frac{P(d_j)}{P(|R_j - R_i|)} > C_t \\ \frac{P(d_j)}{P(|R_j - S_i|)} > C_t \end{cases} \text{, i.e., } \frac{\text{Signal}}{\text{Interference}} > C_t \tag{19}$$

where $P(d)$ is the received power as a function of distance. It is a simplified form of $P(P_t; d)$ when we assume that all the nodes use the same transmission power P_t.

The first inequality on the left in (19) says that the DATA signal on link j should be sufficiently small when it reaches the receiver of link i compared with the DATA signal on link i; the second inequality on the left is for DATA on link j not interfering with ACK on link i; and so on [14]. As mentioned in Section II, assuming the power propagation function in (1), (19)

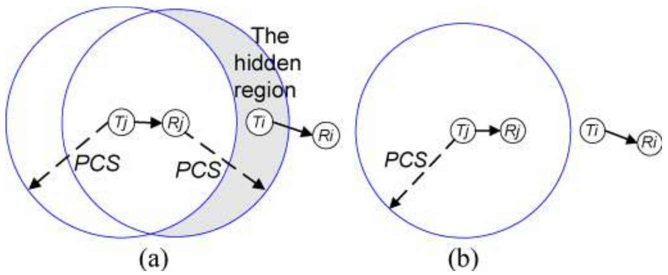

Fig. 12. (a) HN due to (17) and (18), and (b) RS mode removes the HN.

can be transformed into inequalities among distances instead of power levels.[6]

$$
\begin{aligned}
&|T_j - R_i| > (1+\Delta)d_i; |T_j - R_i| > (1+\Delta)d_j\\
&|T_j - T_i| > (1+\Delta)d_i; |T_j - T_i| > (1+\Delta)d_j\\
&|R_j - R_i| > (1+\Delta)d_i; |R_j - R_i| > (1+\Delta)d_j\\
&|R_j - T_i| > (1+\Delta)d_i; |R_j - T_i| > (1+\Delta)d_j. \qquad (20)
\end{aligned}
$$

3) Goal of HFD: Following the above discussion, HN can arise out of two situations—When (16) is satisfied, the following situations happen.

1) Equation (17) or (18) is not satisfied.
2) Equation (19) is not satisfied.

That is, the carrier-sensing mechanism allows simultaneous transmissions that will fail. The goal of HFD is to make sure that the above two situations will not happen.

B. Proof of HFD for IEEE 802.11 Basic Access Mode

1) Receiver RS Mode: We first argue that no matter how large the carrier-sensing range PCS is, (16) does not guarantee (17) and (18). This leads to the fundamental requirement that (17) and (18) must be removed if HN is to be eliminated, which can be achieved with the receiver RS mode.

To see why (16) is not sufficient for guaranteeing (17), consider the counter example in Fig. 12(a). The two circles define the regions that can be sensed by T_j and R_j. There is inevitably a "hidden" region which cannot be sensed by T_j and which can be sensed by R_j. If T_i is within this hidden region, then (16) holds, but (17) does not. When T_i and T_j transmit DATA packets in an overlapping manner with T_i transmitting first, T_j's DATA cannot be received by R_j due to the "receiver capture" effect. Note that this HN problem exists no matter how large PCS is—A naïve solution of increasing the PCS range alone is not viable.

RS mode can be used to remove constraints (17) and (18). Recall that with RS mode, when the power of a later-arriving packet is more than C_t times that of the earlier packet, the receiver switches to receive the stronger new packet. Thus, as long as the SIR is sufficient, the order of transmissions does not matter. Essentially, (17) and (18) will then be replaced by the same constraints as in (20), and consideration of (20) without (17) and (18) is sufficient for our HFDs.

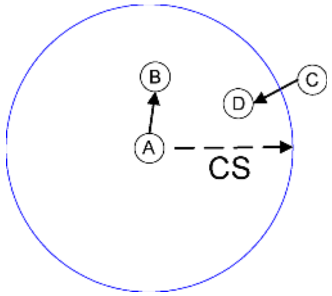

Fig. 13. Interaction of a pair of links.

2) Receive-Power Inequality: With RS mode, we now only need to make (16) sufficient for (20). Consider Fig. 13. Suppose that A is transmitting a DATA to B, and C intends to transmit a DATA to D. To avoid HN, the following must be true:

For any link (C, D) in the neighborhood of link (A, B) where nodes A and C cannot carrier-sense each other, constraint (20) must be satisfied. That is, there must not be any of the following:

1) DATA–DATA collisions at B or D;
2) ACK–ACK collisions at A or C;
3) DATA–ACK collisions at B or D.

Sufficient condition for satisfying constraints (20): Use of receiver RS mode plus PCS $\geq (3+\Delta)d_{\max}$.

Proof for 3): We only present the proof for 3). The proofs for 1) and 2) are similar. Suppose we assume the contrary: DATA–ACK collisions occur at B or D in spite of the use of RS mode and PCS $\geq (3+\Delta)d_{\max}$. With respect to Fig. 13, since A and C cannot sense each other, we have

$$|C - A| > \text{PCS}. \qquad (21)$$

First, suppose that DATA from A to B collides with D's ACK at B. With RS mode, the order of arrivals of the DATA and ACK at B does not matter. In order that there is collision, SIR at B must be insufficient. Equivalently

$$|D - B| \leq (1+\Delta)|A - B|. \qquad (22)$$

From (21), we have

$$|C - A| - |A - B| - |C - D| > \text{PCS} - |A - B| - |C - D|. \qquad (23)$$

Using triangular inequality

$$
\begin{aligned}
|D - A| &\leq |D - B| + |B - A|\\
|C - A| &\leq |D - A| + |C - D|.
\end{aligned}
$$

We have

$$|C - A| \leq |D - B| + |B - A| + |C - D|. \qquad (24)$$

From (23) and (24), we have

$$|D - B| > \text{PCS} - |A - B| - |C - D| \geq \text{PCS} - 2d_{\max}. \qquad (25)$$

---

[6] All the range requirements in this paper assume power propagation function (1). More general forms of power-budget requirements without this assumption can be derived without much difficulty. For example, (2) corresponds to $P(d_{\max}) \geq C_t P(\text{PCS} - 2d_{\max})$.

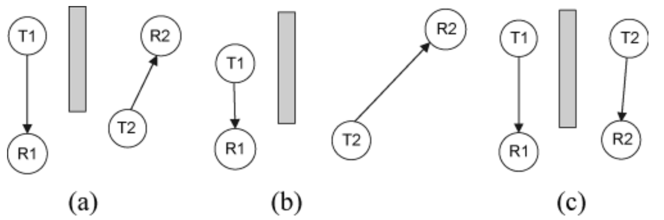

Fig. 14. HN induced by obstructions.

According to (22), we have

$$|D - B| \leq (1 + \Delta)d_{\max}. \tag{26}$$

From (25) and (26), we have

$$\mathrm{PCS} < (3 + \Delta)d_{\max}. \tag{27}$$

However, this contradicts with the condition $\mathrm{PCS} \geq (3 + \Delta)d_{\max}$.

Therefore, D's ACK cannot collide with A's DATA at B.

Similarly, B's ACK cannot collide with C's DATA at D.

APPENDIX B

A. *Discussion of HN Induced by Obstructions*

In some cases involving obstructions (instead of regular power propagation), the HN problem becomes more complicated, and we may need additional mechanisms to alleviate HN. Consider the scenario in Fig. 14(a). There is an obstruction between T1 and T2, but not between R1 and T2. The obstruction leads to a sharp drop of signal strength, and here, we assume that the "channel gain" between T1 and T2 is zero. Even with HFD for the Basic Mode, when T1 is transmitting a DATA packet to R1, T2 cannot sense it and may transmit packets and corrupt T1's packet at R1 (T2 is the HN). With the RTS/CTS mode, the situation is better since T2 can still hear R1's CTS. However, if T2 transmits an RTS first, T1 cannot receive it and may go ahead to send an RTS to R1, which may lead to a failure.

The problem here is that the transmitter (T1) is blind to the transmissions on an interfering link (link 2) due to the existence of obstructions. There is no easy solution unless we make significant modifications to 802.11 MAC. One idea is that, since only R1 knows the transmissions on link 2, it can relay the information to T1, so that T1 can be prevented from transmission when link 2 is busy. The protocol works as follows. By default, each node operates normally with the Basic Mode. If excessive collisions occur, the nodes then conjecture that there is HN caused by obstructions, and each node in the neighborhood then finds out the "local map" [i.e., the "channel gains" between every pair of nodes of the neighborhood, as in Fig. 14(a)] through a simple "PE" protocol similar to that in Appendix C. Once HN caused by obstructions is confirmed, instead of the normal operations, the nodes involved then change their operations as follows.

1) The HN (T2 in the above example) will send an RTS before transmitting DATA. The targeted receiver of the HN (R2) will wait for a period of SIFS + RTS + SIFS before replying a CTS.
2) The nontargeted receiver above (R1) will relay the RTS to its transmitter (T1). The transmitter will not send DATA to the receiver during the NAV.

The protocol may not completely avoid collisions since multiple nodes may try to relay the RTS, leading to relay-RTS collision. An algorithm is needed to elect a representative node to relay the RTS. The details are an interesting subject for future study.

There are also other scenarios to consider. In Fig. 14(b), assume that T2's transmission does not cause insufficient SIR at R1 (i.e., with "RS mode," R1 can always receive T1's transmissions), but R1's transmission causes insufficient SIR at T2 (i.e., R1's transmission can corrupt the ACK from R2). The relay scheme above still applies here, but it generates additional RTS/CTS packets. An alternative is to use "Delayed ACK" operated in the Basic Mode (no RTS/CTS is needed), which is described as follows.

Since T1 and T2 cannot sense each other, they may be transmitting DATA packets at the same time. After R1 finishes receiving, its ACK may interfere with link 2. The idea of "Delayed ACK" is to let R1 do carrier sensing before returning an ACK, instead of sending ACK immediately after SIFS. If R1 senses no transmission (after receiving DATA from T1), it delays its ACK by SIFS+ACK (in case R2 is returning an ACK to T2); if R1 senses a transmission, it waits until the transmission ends and delays its ACK for an additional SIFS+ACK. Meanwhile, T1 is not aware of the delay and may go into exponential backoff. However, immediately after it receives the delayed ACK from R1, T1 gets out of the backoff state so that it does not need to continue to count down. We note in passing that 802.11e has some sort of a delayed ACK feature. Delayed ACK, however, does not entirely avoid T1's retransmission if the ACK is delayed too much.

Another scenario is shown in Fig. 14(c) in which the ACK from either R1 or R2 may interfere with the other link. In addition, R1 and R2 cannot sense the transmissions of T2 and T1, respectively. "Delayed ACK" does not apply here, and we have to fall back to the Relay scheme—In this scenario, R1 relays the CTS from R2 to T1, and vice versa. In the Relay scheme, since either RTS or CTS needs to be relayed in different scenarios, we also call it "RTS/CTS Relay scheme."

A strategy is to combine the delayed-ACK scheme with the RTS/CTS Relay Scheme. Since the RTS/CTS Relay Scheme is more expensive (i.e., it requires RTS/CTS, which may be further duplicated and relayed), it should be used only as an alternative when "Delayed ACK" algorithm does not work. The above has only sketched a plausible solution for HN that is caused by obstructions. This subject certainly deserves more careful investigations in the future.

APPENDIX C

A. *PE Algorithm for Discovering InRs*

To construct the InRs, each node A periodically broadcasts special PE packets and receives PE packets from nearby nodes. The transmission power for PE packets is the same as that for regular packets, and we assume that all nodes use the same transmit power and receiver sensitivity.

1) Node A measures the powers of PE packets that are transmitted by other nodes that it can hear and keep the power information in a "power set," $P_A = \{[C, P(C, A)]\}$, where C is the node label of the sender of the PE packets.
2) Periodically, node A broadcasts its PE packets, which contain as follows: a) A list of active links (A, B) or (B, A) (B is any other node forming a link with A) and b) P_A.
3) Node A identifies its associated InRs based on the PE packets that it receives (more details will be given below).

A point to note about the PE algorithm is that they are not the same as RTS/CTS packets and are not used for carrier-sensing purposes. They are special packets used for distributed discovery of InRs. Also, the PE packets need to be transmitted only when the network topology or conditions have changed. The periodic transmissions of PE packets above are mainly for simplification and to make the algorithm more robust. When nodes are not highly mobile, PE packets introduce little overhead because the broadcast period can be long.

B. Condition for Correct Operation of PE

The following condition is sufficient to ensure that a node can discover all the InRs relevant to itself:

$$P(d_{\max}) > C_t P(\text{PERange} - d_{\max})$$

or

$$\text{PERange} \geq (2 + \Delta) d_{\max} \tag{28}$$

where PERange is the transmission range of the PE packets.

Note: To meet (28), PE packets must be transmitted at a sufficiently low rate, such as that used by RTS/CTS packets.

Proof: Consider three nodes: Nodes A and B form links (A, B) and (B, A); and node C forms links with other nodes. Without loss of generality, assume that $P(A, B) < C_t\, P(C, B)$ so that the transmission by C can interfere with reception at B. We want to show the following: 1) nodes A and B, and 2) node C and any other node D that forms link with C can find out the existence of this InR.

Proof of 1): By definition, we have $|A - B| \leq d_{\max}$. If (28) holds, we have

$$\begin{aligned} C_t P(C, B) &> P(A, B) \geq P(d_{\max}) \\ &> C_t P(\text{PERange} - d_{\max}). \end{aligned} \tag{29}$$

The above implies that PERange $- d_{\max} > |C - B|$, since $P(\cdot)$ is a decreasing function of distance. Therefore

$$\text{PERange} > |C - B|$$

and

$$\text{PERange} > |C - B| + d_{\max} \geq |C - B| + |A - B| \geq |C - A|. \tag{30}$$

This means that, if $P(A, B) < C_t\, P(C, B)$, then the PE packets of C can reach A and B. By measuring the received power of C's PE packets and checking their source address to identify the sender, B can derive C and $P(C, B)$. Similarly, B can derive A and $P(A, B)$ from A's PE packets. Therefore, B can find out that $P(A, B) < C_t\, P(C, B)$ and, hence, the existence of InR between link $(A, B)/(B, A)$ and any other link with C being the transmitter or receiver—Note that these links are contained in the active link list in C's PE packets received by B.

Now, the PE packets of B contain information on $[C, P(C, B)]$ and $[A, P(A, B)]$. Upon receiving B's PE packets, A can also find out that $P(A, B) < C_t\, P(C, B)$ and, hence, the existence of InR between link $(A, B)/(B, A)$ and any other link with C being the transmitter or receiver—Note that these links are contained in the active link list in C's PE packets received by A.

Proof of 2): From the proof of 1), we have PERange $-$ $d_{\max} > |C - B|$. Therefore

$$\text{PERange} > |B - C|$$

and

$$\text{PERange} > |B - C| + d_{\max} \geq |B - C| + |C - D| \geq |B - D|. \tag{31}$$

Thus, the PE packets of B, which contain $[C, P(C, B)]$, $[A, P(A, B)]$, and active links (A, B) and (B, A) can reach C and any node D that forms link with C, from which they can discover the associated InRs.

REFERENCES

[1] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?" *IEEE Commun. Mag.*, vol. 39, no. 6, pp. 130–137, Jun. 2001.

[2] K. Xu, M. Gerla, and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks?" *Proc. IEEE GLOBECOM*, Nov. 2002, vol. 1, pp. 17–21.

[3] A. Vasan, R. Ramjee, and T. Woo, "ECHOS—Enhanced capacity 802.11 hotspots," in *Proc. IEEE Infocom*, Mar. 2005, pp. 1562–1572.

[4] S. Ansari *et al.*, "Performance enhancement of TCP on multi-hop ad hoc wireless networks," in *Proc. IEEE ICPWC*, Dec. 2002, pp. 90–94.

[5] P. C. Ng and S. C. Liew, "Offered load control in IEEE 802.11 multi-hop ad-hoc networks," in *Proc. 1st IEEE Int. Conf. MASS*, Oct. 2004, pp. 80–89.

[6] P. C. Ng and S. C. Liew, "Throughput analysis of IEEE 802.11 multi-hop ad hoc networks," *IEEE/ACM Trans. Netw.*, 2007. submitted for publication. **AQ8**

[7] P. C. Ng and S. C. Liew, "Re-routing instability in IEEE 802.11 multi-hop ad-hoc networks," in *Proc. 4th IEEE Int. Workshop Wireless Local Netw.*, Nov. 2004, pp. 602–609.

[8] P. C. Ng and S. C. Liew, "Re-routing instability in IEEE 802.11 multi-hop ad-hoc networks," *Ad Hoc Sensor Wirel. Netw.*, vol. 2, no. 1, pp. 1–25, 2006.

[9] A. Kochut, A. Vasan, A. U. Shankar, and A. Agrawala, "Sniffing out the correct physical layer capture model in 802.11b," in *Proc. ICNP*, 2004, pp. 252–261.

[10] *The Network Simulator—NS2*. [Online]. Available: http://www.isi.edu/nsnam/ns

[11] L. B. Jiang and S. C. Liew, "Hidden-node removal and its application in cellular WiFi networks," Tech. Rep. [Online]. Available: http://www.eecs.berkeley.edu/~ljiang/HFD.pdf

[12] T. S. Rappaport, *Wireless Communications—Principles & Practice*. Englewood Cliffs, NJ: Prentice-Hall, 2002.

[13] P. C. Ng, S. C. Liew, and L. B. Jiang, “A performance evaluation framework for IEEE 802.11 ad-hoc networks,” in *Proc. ACM Workshop PE-WASUN*, 2004, pp. 123–124.

[14] P. Gupta and P. R. Kumar, “The capacity of wireless network,” *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[15] L. B. Jiang, “Improving capacity and fairness by elimination of exposed and hidden nodes in 802.11 networks,” M.S. M.Phil. thesis, Chinese Univ. Hong Kong, Hong Kong, Jun. 2005. http://www.eecs.berkeley.edu/~ljiang/Thesis.pdf

[16] H. Zhai and Y. Fang, “Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks,” in *Proc. IEEE Infocom*, Apr. 2006, pp. 1–12.

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AQ9

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AQ1 = A citation of Section 1.1.1 was inserted here as this sentence was reworded. Please check if appropriate.
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AQ3 = Please provide the expanded form of the acronyms “RTS/CTS”.
AQ4 = Please check the changes made to this sentence.
AQ5 = All occurrences of “NS-2” were changed to “NS2”. Please check if appropriate.
AQ6 = Please provide the expanded form of the acronyms “UDP”.
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Hidden-Node Removal and Its Application in Cellular WiFi Networks

Li Bin Jiang and Soung Chang Liew, *Senior Member, IEEE*

***Abstract*—This paper investigates the hidden-node phenomenon (HN) in IEEE 802.11 wireless networks. HN occurs when nodes outside the carrier-sensing range of each other are nevertheless close enough to interfere with each other. As a result, the carrier-sensing mechanism may fail to prevent packet collisions. HN can cause many performance problems, including throughput degradation, unfair throughput distribution among flows, and throughput instability. The contributions of this paper are threefold. 1) This is a first attempt to identify a set of conditions—which we called Hidden-node-Free Design (HFD)—that completely remove HN in 802.11 wireless networks. 2) We derive variations of HFD for large-scale cellular WiFi networks consisting of many wireless LAN cells. These HFDs are not only HN-free, but they also reduce exposed nodes at the same time so that the network capacity is improved. 3) We investigate the problem of frequency-channel assignment to adjacent cells. We find that with HFD, careful assignment in which adjacent cells use different frequency channels does not improve the overall network capacity (in unit of bits per second per frequency channel). Indeed, given f frequency channels, a simple scheme with f overlaid cellular WiFi networks in which each cell uses all f frequencies yields near-optimal performance.**

***Index Terms*—Hidden-node problem (HN), IEEE 802.11, modeling, performance evaluation, protocol design.**

I. INTRODUCTION

THIS PAPER investigates the hidden-node phenomenon (HN) in IEEE 802.11 wireless networks. HN occurs when nodes outside the carrier-sensing range of each other are nevertheless close enough to interfere with each other. As a result, the carrier-sensing mechanism may fail to prevent packet collisions. HN can cause many performance problems, including throughput degradation, unfair throughput distribution, and throughput instability [1].

The contributions of this paper are threefold.

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1) As detailed in Section I-A1, most previous work considered HN in an isolated manner by focusing on specific examples in which it arises. In addition, most existing solutions aim to remove observed undesirable symptoms of HN rather than HN itself. With these piecemeal approaches, it is not clear whether all the negative effects of HN have been removed. Although some prior investigations gave the conditions under which HN does not occur, the conditions given are actually not sufficient to prevent HN in all cases (elaborated upon in Section I-A1). We believe our paper is a first attempt to identify a general set of sufficient conditions—which we called Hidden-node-Free Design (HFD)—that completely remove HN in 802.11 wireless networks (including *ad hoc* mode and infrastructure mode). Specifically, our conditions consist of two parts: a) a sufficiently large carrier-sensing range and b) a receiver mechanism called the "Restart Mode" (RS), in which the receiver will switch to receive another signal in the midst of receiving a signal if the new signal strength is sufficiently larger. Previous investigations did not identify requirement b), and their requirement for a) is not stringent enough to prevent HN.
2) Recent widespread adoption of 802.11 technologies has led to explosive deployment of wireless LAN (WLANs). In many instances, these WLANs are overlapping and may interfere with each other. How to minimize the interferences while achieving spectral reuse is therefore an interesting issue. We derive variations of HFD for such large-scale cellular WiFi networks. These HFDs are not only HN-free, but they also reduce exposed nodes (ENs) at the same time. They yield higher spectral reuse and higher overall network capacity.
3) We investigate the problem of frequency-channel assignment to adjacent cells in cellular WiFi networks. We find that with HFD, careful assignment in which adjacent cells use different frequency channels does not improve the overall network capacity (in unit of bits per second per frequency channel). Indeed, given f frequency channels, the simple scheme with f parallel overlaid cellular WiFi networks in which each cell uses all f frequencies yields near-optimal performance.

1) Related Work: In [1], two performance problems triggered by HN in multihop networks were identified: 1) unfair throughput distributions among contending TCP flows and AQ2 2) rerouting instability in a multihop flow. Reference [1] did not provide a solution to HN.

Reference [2] provided a "node-based" analysis of HN. It was argued that when the physical carrier-sensing (PCS)

Manuscript received August 20, 2005; revised March 3, 2006, July 19, 2006, January 12, 2007, and January 13, 2007. This work was supported in part by the Competitive Earmarked Research Grant under Project 414106, established under the University Grant Committee of the Hong Kong Special Administrative Region, China. The review of this paper was coordinated by Dr. Q. Zhang.

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Digital Object Identifier 10.1109/TVT.2007.900393

range[1] is larger than the link distance (transmitter–receiver distance) plus the interference range (IR),[2] HN can be removed, and RTS/CTS (which implements virtual carrier sensing) is no longer needed. A recent work [3] gives a similar result. According to our "link-based" analysis in this paper, however, this condition is not sufficient for the elimination of HN in general.

References [4]–[6] extended the investigation in [1]. In particular, the "self-HN interference" phenomenon of a single multihop traffic flow was studied. The successive packets of the same traffic flow may self-interfere among themselves as they hop from node to node. Detailed explanations on how self-HN interference causes throughput degradation as well as triggers the rerouting instability phenomenon were given in [5]–[8]. However, the studies in [4]–[8] only provided solutions to alleviate "symptoms" of HN, and these solutions do not remove the "root" of the problem: the HN itself. In contrast, this paper focuses on solutions that remove HN.

The rest of this paper is organized as follows. The general HFD that applies to all network topologies is presented in Section II and formally proved in Appendix A. Section III validates the general HFD by showing that it removes performance problems related to HN. Section IV systematically lays out the different possible channel-assignment schemes in cellular WiFi networks. Different flavors of HFDs that exploit the specific structure of the cellular-network topology to reduce the carrier-sensing range requirement (hence EN) are considered. Section V presents the performance results of the different schemes. Section VI discusses the tradeoff between HN and EN. In addition, Section VII concludes this paper.

II. HIDDEN-NODE-FREE DESIGN (HFD)

In this section, we first provide the definition of HN and, then, the sufficient conditions for removing HN. HN exists in 802.11 networks with either infrastructure mode or *ad hoc* mode. The following development is independent of the modes and is thus applicable to all 802.11 networks.

A. Definition and Examples

Define a "link" as a transmitter–receiver pair. Link i is also denoted by (T_i, R_i), where T_i and R_i are its transmitter and receiver.

1) Definition of HN: Link i is said to be hidden from link j if the following conditions are true. 1) T_j cannot carrier-sense the transmission on link i, and 2) link i may cause transmission failures on link j, or vice versa, so that transmission on at least one of the links will fail when both links transmit simultaneously (Note that by "simultaneous," we refer to the situation when the transmissions by different nodes overlap in time. Their transmissions may actually be initiated at different instances so that the start times of the transmissions are different).

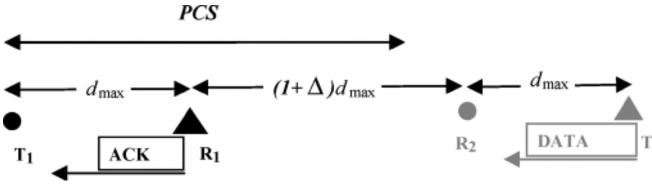

Fig. 1. PCS not sufficiently large leads to HN due to insufficient SIR.

There is HN between links i and j if either i is hidden from j or j is hidden from i. A network is said to suffer from HN if there is HN between any two links.

With respect to condition 1), for basic mode operation, T_j cannot carrier-sense the transmission on link i if T_j cannot carrier-sense T_i. For RTS/CTS mode, in addition to the above, if T_j can neither receive the RTS of T_i nor the CTS of R_i, the net result is that T_j may initiate a DATA transmission when T_i is already transmitting DATA.

With respect to condition 2), there are two situations that lead to "transmission failures:" 1) SIR[3] at a receiver is not sufficiently large and 2) "Receiver Capture" effect. When a transmitter tries to initiate a transmission (by sending a DATA or RTS packet), but the intended receiver cannot reply an ACK or CTS because of ongoing transmissions on other links, the transmission also fails even if SIR is high enough. This effect exists in both the basic and RTS/CTS modes. In the basic mode, it has to do with the normal receiver operation in many 802.11 products, which will be further explained later. Most previous work on HN (e.g., [2]) only considers the first situation 1). However, our definition of HN includes both situations since they both lead to transmission failures, after which, the transmitter must back off and retransmit the packet, without knowing whether the failure is due to insufficient SIR or "Receiver Capture" effect. We illustrate the two situations using a few examples in the following. For simplicity, we assume the basic mode (DATA–ACK handshake) in the examples. In addition, we assume that all nodes use the same transmit power.

2) Example 1—Simultaneous Transmissions But Insufficient SIR: The example in Fig. 1 shows a situation under which carrier sensing does not prevent simultaneous transmissions that result in collisions.

Before explaining this example, we need to first review the concept of IR. It has been shown in [2] that, with the power propagation function

$$P(P_t; d) = A\frac{P_t}{d^{\alpha}} \tag{1}$$

---

[1] This is the range within which a transmitter triggers physical carrier detection. In IEEE 802.11 MAC, a transmitter can only start a transmission when it senses the media as idle.

[2] A node that is receiving a packet from its transmitter will be "interfered with" by another transmitter within the "Interference Range" of the node, resulting in the loss of the packet due to collision [2]. Detailed quantitative definitions of PCS and IR will be given later.

[3] SIR requirements can be different for DATA packets and ACK packets if they are transmitted at different bit rates. The SIR requirement for DATA is higher in cases where it is transmitted at a higher rate than ACK. Different commercial products may have different settings, but usually, ACK will not be transmitted at a higher rate than DATA. In this paper, we consider the "worst case," that is, we use the SIR requirement of DATA for both DATA and ACK. If this requirement is not met, then packet collision is possible; otherwise, collision is not possible because both SIR requirements for DATA and ACK are met. As we will see later, this simplifies our protocol design. We also note that many commercial APs actually use the same rate for DATA and ACK.

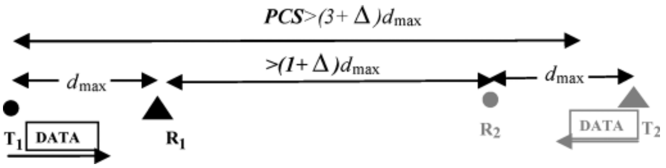

Fig. 2. Lack of receiver "RS mode" leads to HN no matter how large PCS and SIR are.

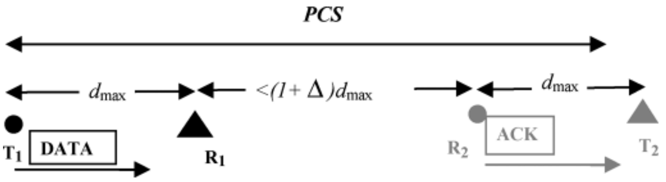

Fig. 3. With RS mode, PCS not sufficiently large still leads to HN due to insufficient SIR.

where $P(P_t; d)$ is the received power at a distance d from a transmitter that transmits at power P_t, A is a constant, and α is the pass-loss exponent. The IR of a link i (with link length d_i) is $IR_i = (1+\Delta)d_i$, where $1+\Delta = C_t^{1/\alpha}$, with C_t as the required SIR. The transmissions by any other node within IR_i of either the transmitter or receiver of link i will interfere with the transmission on link i by corrupting either its DATA frame or ACK frame.

In Fig. 1, there are two links (T_1, R_1) and (T_2, R_2), with the link length $d_{\max}$, which is the maximum link length allowed in the network. The distance $|R_1 - R_2|$ is equal to the IR of links 1 and 2, $(1+\Delta)d_{\max}$. In Fig. 1, the "PCS range" is less than $(2+\Delta)d_{\max} < |T_1 - T_2|$. Therefore, T_1 and T_2 can simultaneously initiate transmissions since they cannot carrier-sense each other. When they do so, R_1's ACK can corrupt T_2's DATA at R_2 (if T_1's DATA finishes earlier than T_2's DATA) due to the insufficient SIR at R_2. Therefore, HN can occur between the two interfering links. In fact, PCS larger than $(3+\Delta)d_{\max}$ is needed to prevent HN in this example. It turns out that this example represents the "worst case" situation requiring the largest PCS. We will prove later that PCS $\geq (3+\Delta)d_{\max}$ is one of the sufficiency conditions for prevention of HN in general.

3) Example 2—Simultaneous Transmissions, Sufficient SIR, But Inappropriate Receiver Carrier-Sensing Operation: Fig. 2 shows that no matter how large PCS is, HN can still occur without an appropriate receiver carrier-sensing operation. In Fig. 2, PCS $> (3+\Delta)d_{\max}$; $|R_2 - T_1| <$ PCS; however, $|T_2 - T_1| >$ PCS and $|R_1 - R_2| > (1+\Delta)d_{\max}$. Therefore, simultaneous transmissions can occur, and the SIR is sufficient. No "physical collisions" occur. However, HN can still happen, as described below.

Assume that T_1 starts first to transmit a DATA packet to R_1. According to the experimental results in [9] (as well as the assumption in NS2 [10]), after the physical-layer preamble of the packet is received by R_2 (since R_2 is within the PCS of T_1, R_2 can carrier-sense the physical-layer header even though it cannot decode the payload. The PHY header is typically transmitted at a lower data rate than the MAC payload), R_2 will "capture" the packet and will not attempt to receive another new packet while T_1's DATA is ongoing. If, at this time, T_2 starts to transmit a DATA to R_2, R_2 will not receive it and will not reply with an ACK, causing a transmission failure on link (T_2, R_2). This behavior is called "receiver capture." Note that no matter how large PCS is, we can always come up with an example like that in Fig. 2 that gives rise to HN.

This HN problem can be solved with a receiver "RS mode" which can be enabled in some 802.11 products (e.g., Atheros WiFi chips). With RS mode, a receiver will switch to receive the stronger packet as long as its power is C_t times [4] higher than the current packet. If the new packet is an 802.11 DATA targeted for it, the node will reply with an ACK after Short InterFrame Space (SIFS), whether the medium around this node is idle or not.

4) Example 3—Simultaneous Transmissions, Receiver RS Mode, and Insufficient SIR: One might wonder, given the example in Fig. 2, why the default receiver operations of all commercial products and the NS2 simulator do not assume RS mode. The reason is that, without a sufficiently large PCS, enabling RS mode may lead to HN collisions, as described below.

RS mode alone cannot prevent HN without a PCS $> (3+\Delta)d_{\max}$. To see this, consider the example in Fig. 3, where PCS $< (3+\Delta)d_{\max}$ and $|R_1 - R_2| < (1+\Delta)d_{\max}$. Assume that T_1 transmits a DATA to R_1 first. During the DATA's period, T_2 starts to send a shorter DATA packet to R_2. With RS mode, R_2 switches to receive T_2's DATA and sends an ACK after the reception. If T_1's DATA is still in progress, R_2's ACK will corrupt the DATA at R_1.

Therefore, it is not advisable to use RS mode if PCS is not large enough, which is the case in most commercial products. The NS2, which simulates operations in commercial products, for example, assumes PCS $= 2.2$ times the maximum transmission range (TxRange) of DATA. If $d_{\max}$, which is the maximum link length allowed in the network, is set to TxRange, then such HN collisions will inevitably occur. As a result, most commercial products do not use RS mode by default. However, without RS mode, HN collisions like that in Fig. 2 inevitably occur. Either way, HN occurs.

B. HFD for Basic Access Mode

From the above examples, we summarize the requirements for a HFD for basic mode in IEEE 802.11. It includes two requirements.

1) A range requirement

$$\text{PCS} \geq (3+\Delta)d_{\max}. \tag{2}$$

If $C_t = 10$, and $\alpha = 4$

$$\text{PCS} \geq 3.78 d_{\max} \tag{3}$$

2) and the receiver's RS mode.

---

[4] Usually, the "restart threshold" is equal to C_t. If it is not, HFD needs only a minor modification.

Satisfaction of these two requirements is sufficient to prevent HN in any general network topology. The formal proof is given in Appendix A.

Similarly, we designed HFD for RTS/CTS mode. In that case, besides RS mode, a key requirement on the virtual carrier-sensing range (VCS) and $d_{\max}$ is $\text{VCS} \geq (2+\Delta)d_{\max}$. However, due to the limited space here, the details are given in [11]. We will only consider Basic Access Mode in the following sections.

Also, we have assumed that there are no significant physical obstructions for signal propagation. In Appendix B, we sketch how the HFD here can be augmented with additional features to deal with cases where there are physical obstructions.

1) Implications for Network Design and Implementation: Requirement 1) [Inequality (2)] may increase the EN problem, in which some legitimate noncolliding simultaneous transmissions may be disallowed because of the larger PCS required. This may reduce the network capacity. However, it is a price to pay if we want to remove HN entirely. In practice, we are more likely to fix PCS but reduce the maximum link length $d_{\max}$. In this case, for infrastructure-mode WiFi networks, the price of EN becomes the need for more access points (APs) (to cover the same area) in order to maintain the network connectivity and capacity. Since APs are rather inexpensive these days, this price may not be that significant from the practical standpoint. Nevertheless, for situations where APs cannot be deployed at will, and it is important for each AP to cover as much area as possible, it is interesting to investigate to what extent HN and EN can be traded off against each other and to what extent they can be reduced simultaneously. Section VI will discuss this issue and give a series of tradeoff points a designer can choose from (we also presented schemes based on the RTS/CTS mode to do so in [15]). This paper, however, mainly focuses on what needs to be done if we were to remove HN entirely.

For implementation, since PCS is usually limited by the actual receiver sensitivity, increasing PCS without changing $d_{\max}$ may be impractical. We could fix PCS (for example, 2.2* TxRange as in NS2 or other values in commercial products) and limit $d_{\max}$ to some value below TxRange instead. That is, although proper DATA decoding can be performed by a receiver up to a distance of TxRange from the transmitter, we will not establish links with link length larger than $d_{\max} < \text{TxRange}$. For cellular WiFi networks, this means that more APs will be needed to cover the same area because the distance from the client stations to their associated APs will be limited by $d_{\max}$, not TxRange. Note that, although we will have fewer clients per AP, on an average basis, the bandwidth per client will not increase because PCS is kept constant. Each time a station transmits, it uses up the same spatial area within which no other stations can transmit. However, because of the elimination of HN, unfairness and other problems associated with HN can be solved.

To further elaborate on the implementation details, in practice, PCS and $d_{\max}$ are determined by the transmission power P_t and receiving thresholds. We can write

$$P(P_t; d_{\max}) = P_{\text{link}} \tag{4}$$

$$P(P_t; \text{PCS}) = P_{\text{PCS}} \tag{5}$$

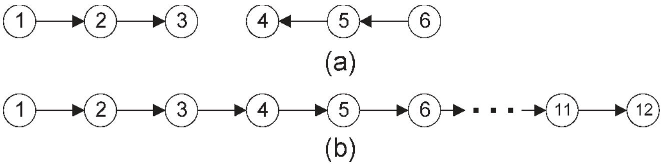

Fig. 4. Traffic flows that can give rise to HN.

where P_{link} is the received power threshold we impose for link establishment. A link will not be set up during the initial routing process if the received power falls below this threshold; P_{PCS} is the received power threshold we impose on PCS. Note that P_{link} and P_{PCS} are lower-bounded by the minimum power thresholds (receiver sensitivities) required to physically decode DATA/ACK or operate PCS, respectively. Reference [16] lists the minimum thresholds for some different data rates of DATA/ACK. That is, we will generally set them higher than the receiver sensitivities needed but not lower.

Therefore, if PCS is fixed, $d_{\max}$ can be adjusted by tuning P_{link} (if we keep P_t unchanged). For example, if we want $\text{PCS} = 3.78 d_{\max}$, with the assumption of two-ray ground model with the "path loss exponent" $\alpha = 4$, (4) and (5) become

$$A\frac{P_t}{d_{\max}^4} = P_{\text{link}} \tag{6}$$

$$A\frac{P_t}{\text{PCS}^4} = P_{\text{PCS}} \tag{7}$$

where A is a constant [12]. Therefore

$$P_{\text{link}} = 3.78^4 P_{\text{PCS}}$$

or

$$P_{\text{link}}(\text{dB}) \approx P_{\text{PCS}}(\text{dB}) + 23.10\ (\text{dB}). \tag{8}$$

III. REMOVAL OF HN PERFORMANCE PROBLEMS

"TCP unfairness" and "rerouting instability" are two performance problems triggered by HN that is identified previously [1]. This section validates by simulation that, by removing HN, HFD also eliminates such performance problems. As in [1], we consider topologies as shown in Fig. 4. Nodes in a straight line are equally spaced apart by 140 m.

The simulations were conducted using NS2 [10]. The data rate is set at 11 Mb/s. The two-ray ground propagation model is adopted with loss exponent $\alpha = 4$. C_t is set to 10 dB. The PCS range is 550 m. Thus, for HFD, the maximum link distance $d_{\max}$ according to (3) is $550/3.78 = 145$ m. The *Ad Hoc* On-Demand Distance Vector routing protocol is used. All data sources are UDP or TCP traffic streams with fixed packet size of 1460 B.

With HFD, receiver RS mode is turned on; for the case without HFD, receiver RS mode is turned off. The PCS range is 550 m in both cases.

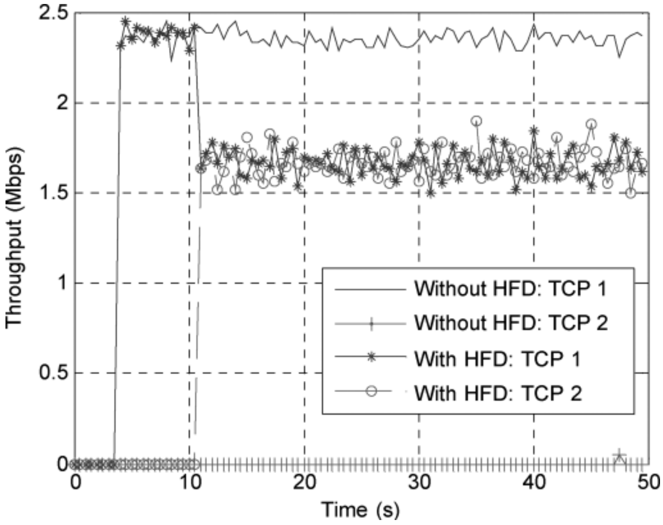

Fig. 5. TCP unfairness (fairness) without (with) HFD.

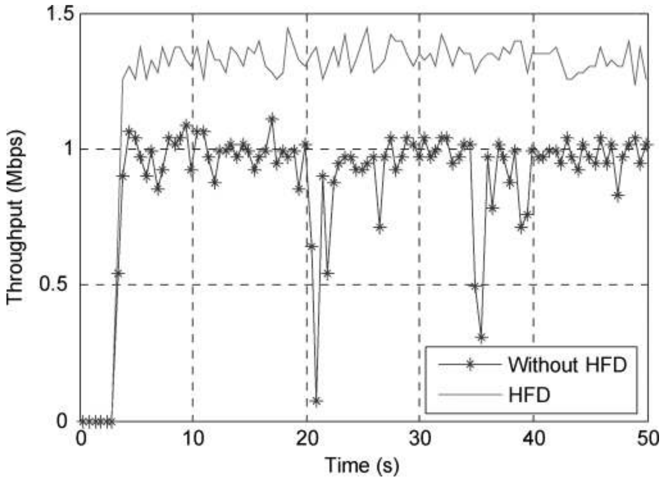

Fig. 6. Throughput instability (stability) of an 11-hop UDP flow without (with) HFD.

A. TCP Unfairness

We ran a TCP simulation experiment using the topology in Fig. 4(a). There are two TCP connections. TCP 1 is from node 1 to node 3, and TCP 2 is from node 6 to node 4. TCP 1 starts earlier than TCP 2 at time $= 3.0$ s, and TCP 2 starts at time $= 10.0$ s. Without HFD, node 1 is hidden from node 5, causing node 5's DATA packet to collide at node 4 with node 1's DATA packet. Likewise, node 2 is hidden from node 6, causing node 6's DATA packet to collide at node 5 with 2's DATA packet. Because TCP 1 starts earlier, TCP 2 virtually has no chance to obtain any throughput (see Fig. 5). Fig. 5 also shows that this severe "unfairness" problem is eliminated with HFD.

B. Rerouting Instability

Rerouting instability is triggered by excessive packet collisions that are introduced by hidden terminal nodes (which is mistaken for route unavailability). We performed a UDP simulation experiment using the chain topology [Fig. 4(b)]. There is a UDP flow from node 1 to node 12. Without HFD, node 5 is "hidden" from node 1, causing the DATA packets of node 1 to repetitively collide at node 2 with node 5's DATA packets. Likewise, nodes 2, 3, 4, 5, etc., face the same problems. It has been shown in [1], [7], and [8] that throughput instability can result from misinterpretation by the routing algorithm that links are down (because of repetitive packet transmission failures due to HN). Fig. 6 shows that the throughput instability is removed with HFD.

IV. CHANNEL ASSIGNMENT IN WIFI CELLULAR WITH HFD

There are three orthogonal channels for 802.11b/g and eight orthogonal channels for 802.11a. When multiple WLANs are deployed to form a large WiFi cellular network, there is the issue of how to assign these channels to the different WLANs while keeping the network free of HN. On one hand, channel assignment can separate cells with the same channel further apart so that intercell physical interference can be reduced or totally eliminated, relaxing the HFD's requirements on the carrier-sensing range. On the other hand, more spectrum resources (channels) will be used. Thus, an issue is whether a careful channel assignment can yield better spectrum efficiency or not while ensuring no HN in the network. We address this issue by examining possible channel assignment schemes systematically.

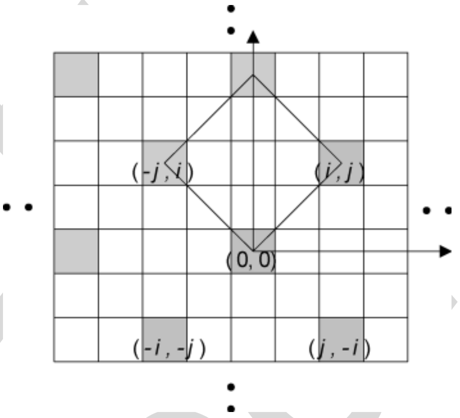

Fig. 7. Channel assignment ($N = 8$) with square cells.

This section focuses on the square-cellular topology. In [11], we also studied channel assignment in hexagon-cellular topology and presented its performance results. In a square-cellular WiFi network, the APs are placed in a grid (see Fig. 7 in which each square corresponds to one WLAN). Clients are located randomly and are associated with the nearest APs. We assume that the AP is placed at the center of the square of its WLAN. The largest link length $d_{\max}$ is the distance from the AP to the corner of the square. We denote the distance between an AP and another AP on the same channel closest to it by D, and the total number of channels needed to cover the overall WiFi cellular network by N.

A. Channel Assignment

In a regular topology, we can assign the channels in a regular manner. Channel assignment for a hexagon-cellular topology

TABLE I
NUMBER OF CHANNELS USED IN THE WiFi CELLULAR NETWORK FOR DIFFERENT OFFSET ASSIGNMENTS

(i,j)	(1, 0)	(1, 1)	(2, 0)	(2, 1)	(2, 2)	(3, 0)	(3, 2)
N	1	2	4	5	8	9	13

is well known [12]. If a cell is in the form of a square, by emulating the channel assignment for hexagon cells, we can assign a channel as in Fig. 7 (the gray cells use the same channel). We denote by $(i,\ j)$ the "offsets" (in two axes) of one of the four adjacent cells that use the same channel as cell (0, 0), where $i \geq 0$, and $j \geq 0$. As illustrated in Fig. 7, for cell (0, 0), the four adjacent cells are cells (i,j), $(-j,i)$, $(-i,-j)$, and $(j,-i)$.

Note that, with this kind of "offset design," we can always form a square among four cells using the same channel. As illustrated in Fig. 7, cells (0,0), (i,j), $(i-j, j+i)$, and $(-j,i)$ form a square with length of each side $= D = \sqrt{i^2+j^2}$. Table I lists some possible offset assignments and the number of frequency channels used with each offset.

For an offset assignment (i,j), the number of frequency channels used to fill the whole WiFi cellular network is $N = i^2 + j^2$. To see this result, consider the square formed by the APs at cells (0,0), (i,j), $(i-j,\ j+i)$, and $(-j,i)$. With reference to Fig. 7, the area of the square is $i^2 + j^2$. Within this square, an area of one unit is covered by the gray color. The whole plane can be divided by similar squares described above. If we omit the boundary effect (assume that the plane is infinitely large), one channel can cover $1/(i^2+j^2)$ of the whole plane. Therefore, $N = i^2 + j^2$ channels are needed.

The different offsets and frequency channel requirements in Table I correspond to different "design alternatives." To systematically address all possible cases, we categorize them into three design alternatives, as listed below. In the following, we say that there is "physical interference" between two cells if it is possible that a link in one cell has physical interference with a link in the other cell (due to insufficient SIR at the latter), and there is "protocol interference" between two cells if it is possible that the transmission on a link in one cell can prevent a link in the other cell from transmitting through carrier sensing.

1) There is no protocol interference or physical interference between adjacent cells using the same channel. With this design, transmissions on cells are independent.
2) There is protocol interference, but no physical interference between adjacent cells using the same channel. In this case, the carrier-sensing mechanism may be overly aggressive so that legitimate simultaneous transmissions on different cells may be prevented by the protocol operation.
3) There is physical interference between adjacent cells using the same channel. With this design, some simultaneous transmissions on different cells need to be prevented. Therefore, to avoid HN (with HFD), there must be protocol interference.

The next few sections lay down the operating parameters of these design alternatives and elaborate on them.

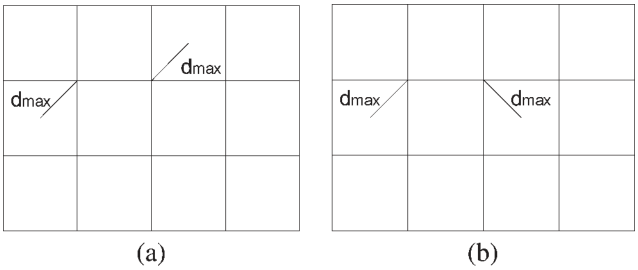

Fig. 8. Minimum distance between two cells. (a) $i > 0$, $j > 0$. (b) $i > 0$, $j = 0$.

B. Design Alternative 1 (DA1): No Physical Interference or Protocol Interference Among Adjacent Cells

For DA1, two transmissions on adjacent cells using the same channel must not physically interfere with each other. A certain minimum number of channels $(N_{\min})$ are required to guarantee this. Consider Fig. 8, $d_{\max}$ is the distance between the AP at the center of a cell and a client at the corner of the cell. The two cells in consideration use the same channel. Without loss of generality, we assume that $i \geq 1$, and $j \geq 0$ (since i, j cannot be both zero). In Fig. 8(a), where $i = 2$ and $j = 1$ (generally, when $i,\ j > 0$), the distance between the two corners (i.e., between the two clients) is $\sqrt{(i-1)^2 + (j-1)^2}$; in Fig. 8(b), where $i = 2$ and $j = 0$ (generally, when $i > 0,\ j = 0$), the distance is $\sqrt{(i-1)^2 + 0^2}$. Combining the two cases, the distance between the two closest corners of two adjacent cells which use the same channel is $\sqrt{(i-1)^2 + [\max(j-1,0)]^2}$. Now, this distance must be larger than the IR. Therefore, we require

$$\sqrt{(i-1)^2 + [\max(j-1,0)]^2} > (1+\Delta)d_{\max} \qquad i \geq 1,\ j \geq 0. \quad (9)$$

Now, $d_{\max} = 1/\sqrt{2}$. Assuming $\Delta = 0.78$ [as in (3)], the offsets (i,j) that satisfy this requirement are

$$(1,3), (1,4), \ldots,\ (2,2), (2,4), \ldots,\ (3,0), (3,1), \ldots .$$

Requirement (9) is the no-physical interference requirement. Given this requirement, carrier sensing still needs to work properly if simultaneous transmissions on adjacent cells are to be allowed. Specifically, we require

$$\sqrt{(i-1)^2 + [\max(j-1,0)]^2} > \text{PCS} \geq 2d_{\max} \qquad \text{where} \quad i \geq 1,\ j \geq 0 \quad (10)$$

where PCS is the PCS range. The lower bound on PCS in (10) is to ensure that carrier sensing works properly to prevent simultaneous transmission within the same cell. The maximum distance between two wireless stations in the same cell is $2d_{\max}$. The upper bound on PCS in (10) ensures that a station does not sense other stations in adjacent cells. There is no need for sensing beyond a cell since (9) ensures that there is no interference beyond a cell.

Note that PCS can be adjusted by tuning the receiver sensitivity for carrier sensing while maintaining the same transmission power. Generally, the maximum PCS $\mathrm{PCS}_{\max}$ is defined by the transmission power and the lowest received power required to decode the PHY header. If we want to make actual operating PCS smaller than $\mathrm{PCS}_{\max}$, the following two requirements must both be satisfied before PCS is triggered.

1) The PHY header must be decodable.
2) In addition, the received power must be above a certain threshold [e.g., as dictated by the upper bound in (10) after translating it to a power relationship].

If 1) is satisfied but 2) is not, the transmission whose PHY header has been detected will be ignored.

With $\Delta = 0.78$, (10) is a more stringent requirement than (9), and satisfaction of (10) automatically implies the satisfaction of (9). The "offsets" that satisfy (10) and, therefore, correspond to DA1 are

$$(1,3), (1,4), \ldots,\ (2,4), \ldots,\ (3,0), (3,1), \ldots\ .$$

Note that (2, 2) just misses the requirement of (10) because of the strict inequality for the PCS upper bound. Among the above offsets, (3, 0) yields the smallest number of channels required

$$N_{\min} = i^2 + j^2 = 9. \qquad (11)$$

C. Design Alternative 2 (DA2): No Physical Interference, But With Protocol Interference Among Adjacent Cells

Requirement (9) still applies for this case. Instead of (10), we have

$$\mathrm{PCS} \geq 2d_{\max} \geq \sqrt{(i-1)^2 + [\max(j-1,0)]^2}. \qquad (12)$$

That is, the PCS required for proper carrier sensing within a cell will also prevent some simultaneous transmissions among adjacent cells. For $\Delta = 0.78$, among the offsets that satisfy (9), there is only one that also meets (12), and that is (2, 2). The corresponding $N_{\min}$ is

$$N_{\min} = i^2 + j^2 = 8. \qquad (13)$$

Note that with (2, 2), although, in principle, there could be interference between two links of two adjacent cells, in practice, this occurs with zero probability assuming random placement of nodes within cells. Specifically, there is protocol interference only if two stations of the two links are positioned right at the corners of their associated cells. Any small deviation from this will remove the protocol interference.

Therefore, from the probabilistic viewpoint, $N_{\min} = 8$ could be said to be a design that meets the requirement of DA1 with probability 1. Having said that, we concede that, in practice, one may have to include a certain margin of error or uncertainty in the design. That is, it is still possible for stations that are located near the corners of adjacent cells to interfere with each other. Furthermore, with different cell shapes, Δ values, and parameter settings, there could be nontrivial cases for DA2. For this reason, we group this design under a different category than DA1.

D. Design Alternative 3 (DA3): With Physical Interference Among Adjacent Cells

For DA3, adjacent cells using the same channel may physically interfere with each other. That is, (9) is not satisfied

$$\sqrt{(i-1)^2 + [\max(j-1,0)]^2} \leq (1+\Delta)d_{\max} \qquad i \geq 1,\ j \geq 0. \qquad (14)$$

The offsets that satisfy (14) are

$$(1,0),\ (1,1),\ (1,2),\ (2,0),\ (2,1).$$

Therefore, we see that the channels used are

$$N = i^2 + j^2 = 1, 2, 4, \text{ or } 5.$$

Note that $N \leq 5$ is due to the particular regular (i,j) channel assignment strategy we assume. There could be other cell assignments that yield different results of N.

Design Alternatives 1 and 2 are HN-free if $\mathrm{PCS} \geq 2d_{\max}$. The next few sections consider different ways of setting PCS for DA3 to make it HN-free.

1) General HFD: According to (2), the general HFD requires

$$\mathrm{PCS} \geq (3+\Delta)d_{\max}. \qquad (15)$$

Inequality (15) is independent of the network topology. In a given topology, however, it may be overkill because each node adopts the PCS range for "the worst case."

2) HFD With Nonuniform PCS: General HFD can remove HN, but without considering the actual topology. If we take the actual link layouts into consideration and allow the PCS range to vary from node to node [relaxing the requirement in (15)], EN can be reduced by allowing more noncolliding transmissions to proceed simultaneously.

Note that, in previous sections, "PCS" is defined from the perspective of a transmitter. That is, with respect to a transmitter, its transmission will prevent all the nodes within its PCS range from transmitting. In this section, however, we define "PCS" from the perspective of a receiver. That is, a node will be prevented from transmitting by the transmission from any node within its PCS range.

For clarity, we use "PCS^T" to denote PCS with respect to transmitters, and "PCS^R" to denote PCS with respect to receivers. If all nodes transmit at the same power (P_t), the PCS^R of a node a, $\mathrm{PCS}^R(a)$, is only related to its receiver sensitivity for carrier-sensing purposes. Clearly, for uniform PCS in the previous section, $\mathrm{PCS}^T = \mathrm{PCS}^R$, since all the nodes have the same transmit power and carrier-sensing sensitivity.

In this section, we assume that all nodes use the same transmit power and data rate. In the following algorithm, each node computes the PCS^R it should assume in its receiver design.

3) HFD With Nonuniform PCS: For any node a

1) Denote the set of links whose sender is node A by $L(A) = \{a_1, a_2, a_3, \ldots, a_n\}$. Denote the set of links which has an "interference relationship" ("InR") with link k by $I(k)$ [links that are either physically

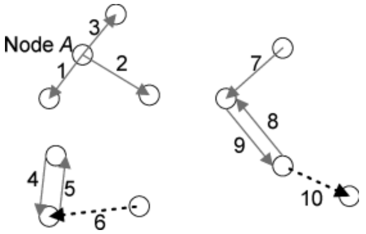

Fig. 9. Node A's interference link set $M(A) = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$.

interfered by link k or vice versa. As detailed in Appendix A, there is "InR" between links i and j if any inequality in (19) or (20) is NOT true]. Define node A's "interference link set," $M(A) = I(a_1) \cup I(a_2) \cup I(a_3) \cup, \ldots, \cup I(a_n)$.

  a) For example, in Fig. 9, $L(A) = \{1, 2, 3\}$, $I(1) = \{2, 3, 4, 5\}$, $I(2) = \{1, 3, 7, 8, 9\}$, and $I(3) = \{1, 2\}$. Therefore, $M(A) = \{1, 2, 3, 4, 5, 7, 8, 9\}$. These links have been marked with red color.
  b) For each node to find out the necessary information about InRs, a "Power-Exchange Algorithm" (PE) is used, which is explained in the Appendix C.

2) PCS of node A is computed as $\text{PCS}^R\ (A) = \max_{k \in M(A)}(|A - T_k|)$, where link k is a member of $M(A)$, and T_k is the sender of link k. Set the receiver carrier-sensing threshold of node A according to $\text{PCS}^R(A)$.[5]

Note that to obtain the distance $|A - T_k|$, A should be able to decode the PE packets (to be explained in Appendix C) from T_k and, thus, deduce the distance from the power of the received packet $P(T_k, A)$. Therefore, we set PERange $\geq (3 + \Delta)d_{\max}$ here.

Note also that, in actual situations, particularly for indoor environment, different node pairs may incur different path-loss exponents. In this case, the distance derived can be regarded as a "virtual distance" assuming a fixed path-loss exponent (corresponding to a fixed Δ). The virtual distances may not correspond to the actual distances. However, this does not pose any difficulty in the above operation because it is the virtual distances rather than the actual distances that define the InRs among nodes. Also, the operation of HFD is affected by setting the correct power threshold for carrier sensing, and the relationship among node pairs can be directly expressed in terms of powers rather than distances, so that even the virtual distances need not be computed.

V. NUMERICAL RESULTS

In this section, we give the NS2 simulation results of a square-cellular topology under different design alternatives (simulations of a hexagon-cellular topology yield very similar results [11]). The square-cellular network has $10 * 10 = 100$ APs (see Fig. 7). The size of each cell is 205 m $*$ 205 m. Therefore, $d_{\max} = 205/\sqrt{2}$ m. We ensure that $d_{\max} \leq$ TxRange (i.e., the maximum transmission range). Around 400 clients are randomly placed in this area with a uniform distribution. Each client is associated with the nearest AP and sends a saturated traffic flow to the AP. The results are shown in Fig. 10.

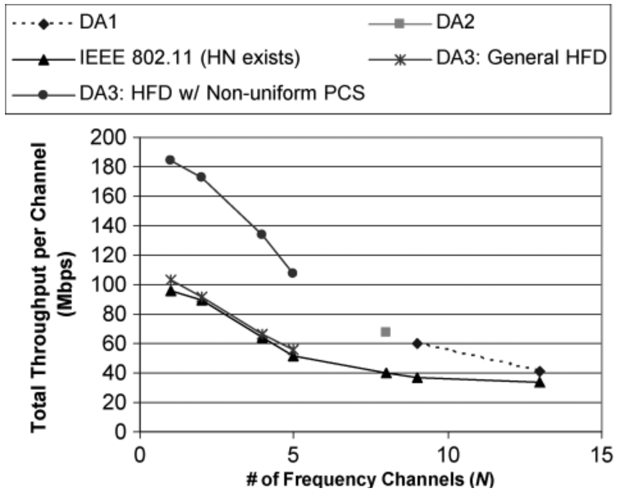

Fig. 10. Throughput per channel for different HFD Design Alternatives ("DA") in square-cellular networks.

In Fig. 10, for IEEE 802.11, PCS $= 550$ m, but "RS mode" is not enabled; therefore, it is not HN-free. For other cases, "RS mode" is enabled, and PCS is set in such a way as to ensure an HN-free property.

As discussed in Section IV, DA1 corresponds to $N > 8$, and DA2 corresponds to $N = 8$. In both cases, we set PCS $= 2d_{\max}$ (the minimum requirement). We obtained the throughput per channel C for different values of N. That is, C is the total throughput divided by N. As shown in Fig. 10, for $N \geq 8$, C decreases as N increases. In fact, the total throughput $(C^* N)$ is roughly constant for $N \geq 8$. This implies that DA1 and DA2 do not put extra frequency channels to good use, and it is not advisable to insist on having no physical interference among cells using the same channels.

DA3 is adopted when $N < 8$. In this case, simulations with two different HFDs—General HFD [with PCS $= 550$ m, slightly larger than $(3 + \Delta)d_{\max}$, so that General HFD and 802.11 in the simulations only differ by RS mode being enabled in General HFD] and HFD w/ nonuniform PCS—were carried out.

As shown in Fig. 10, for $N < 8$, "HFD w/ nonuniform PCS" significantly improves C compared to "General HFD." This is because "HFD w/ nonuniform PCS" takes into account the actual topology and InRs, while "General HFD" tries to remove HN for "the worst case." In an actual topology where clients are randomly located, the lengths of some links may be much smaller than $d_{\max}$, and "the worst case," as shown in Fig. 1, may not appear. This relaxes the requirement of PCS, and the nonuniform PCS design takes advantage of this to reduce ENs and increases the capacity.

The overall results in Fig. 10 also indicate that careful assignment of frequency channels for different cells usually cannot improve the capacity of such cellular WiFi networks. If there

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[5] With the algorithm, the transmitter of link i, T_i will be able to sense the transmitter of any link j which has an "InR" with link i. Similarly, T_j can also sense T_i, since link i also has "InR" with link j ["InR" is symmetric, according to inequalities (19) or (20)].

are f available channels, for an N-channel cell assignment, we could have f/N parallel overlaid cellular networks. The simple scheme with $N = 1$ and f overlaid cellular WiFi networks in which each cell uses all f frequencies yields the best performance.

VI. TRADEOFF BETWEEN HN AND EN

The primary objective of this paper up to now has been to investigate the properties of networks that are completely free of HN. In general, there is a fundamental tradeoff between HN and EN. If some degree of HN is allowed to exist, the unfairness problem, rerouting instability, and other HN-related performance problems may resurface somewhat. On the other hand, the overall network throughput may increase due to a lessened EN.

To illustrate this point, we first consider the Basic Access Mode. We simulate a square-cellular topology with $4 * 4 = 16$ APs (i.e., 16 cells). The size of each cell is 175 m $*$ 175 m, and $d_{\max} = 175/\sqrt{2}$ m ≈ 123.8 m. Around 64 clients are randomly placed with a uniform probability distribution. Each client is associated with the nearest AP and sends a saturated flow to the AP. Two settings are simulated: "RS mode w/ different PCSs" and "IEEE 802.11." The results are shown in Fig. 11. In the first set of curves, RS mode is enabled (as in HFD), but PCS may or may not meet the requirement of General HFD. When PCS $= 470$ m, the requirement of General HFD is met (470 m $> 3.78\ d_{\max}$). We progressively decrease PCS below the requirement of General HFD to see its effect on EN and HN. In the "IEEE 802.11" curves, there is no "RS mode." We use "total throughput" as an indication of EN—Lower EN leads to higher throughput (higher HN can also lead to throughput degradation, but it is secondary compared to EN) and uses MAC-layer "collision probability" as an indication of HN (since HNs lead to heavy packet collisions). Also, as discussed earlier, HN causes unfairness problem. Therefore, we compute the Jain's Fairness Index to quantify the fairness among individual throughputs of all the flows.

There are three key observations from Fig. 11.

1) As expected, when PCS decreases, EN decreases and HN increases (therefore fairness decreases too) in both curves ("RS mode w/ different PCSs" and "IEEE 802.11"). In other words, the EN–HN tradeoff exists in both curves [Fig. 11(a) and (b)].
2) With the same PCS setting, "RS mode w/ different PCSs" always gives a higher throughput and a lower collision probability than "IEEE 802.11" [Fig. 11(a)]. Although we started out to remove HN in this paper, in practice, one can relax the requirement of PCS to achieve a tradeoff between EN and HN. The overall performance of our proposed design, however, is always better than IEEE 802.11 with the same PCS setting.
3) The tradeoff between EN and HN is manifested as a tradeoff between throughput and fairness [see Fig. 11(b)].

There are also other minor observations. 1) Note that the "floor" collision probability in General HFD (when PCS $=$ 470 m in the "RS mode w/ different PCSs" curve) is about 7%. These MAC-layer collisions are due to the fact that backoff timers of different nodes may still choose the same random number in a contention window even if HN is removed. However, this kind of collisions will not cause trouble since consecutive collisions (as in HN) are not likely due to the random backoff algorithm in 802.11. 2) With "RS mode w/ different PCSs" in this particular simulation, PCS larger than 300 m seems to have eliminated HN considerably. This is because when the clients are randomly located (and not very dense), most link distances are smaller than $d_{\max}$.

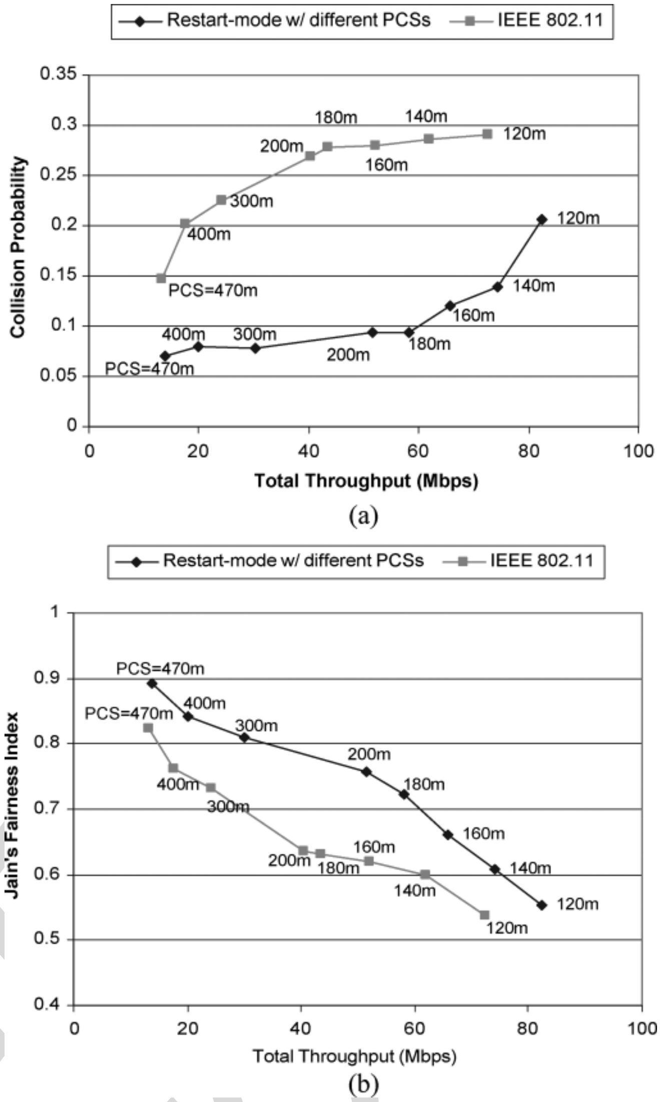

Fig. 11. Tradeoff between EN and HN. (a) Tradeoff between throughput and collision probability (the label beside each point shows the corresponding PCS value). (b) Tradeoff between throughput and fairness.

In RTS/CTS mode, our related research has shown that EN can be effectively reduced compared to the Basic Access Mode. That scheme combines HFD for RTS/CTS mode and an EN-reducing algorithm called "Selective Disregarding of NAVs (SDN)" [15]. SDN enables each node to selectively disregard "false-alarming" RTS/CTS from links that actually do not interfere with its transmissions. This cannot be achieved in the Basic Access Mode because without RTS/CTS, PHY header gives no address information. Interested readers are referred to

[15] for the scheme combining HFD and SDN. The tradeoff between EN and HN still exists in that scheme.

VII. CONCLUSION

This paper has provided a set of fundamental conditions called "General HFD," under which HN-free 802.11 networks can be designed. General HFD consists of as follows: 1) relationships between the carrier-sensing range and maximum link length $d_{\max}$ and 2) a receiver mechanism called the RS mode. We have shown that by adhering to the HFD conditions, performance problems related to HNs, including throughput degradation, unfair throughput distributions, and throughput instability [1], [5]–[8], can be removed.

For the Basic Access Mode, for example, 1) consists of just one relationship: PCS $> (3 + \Delta)\ d_{\max}$, where PCS is the PCS range, and $\Delta > 0$ is a quantity derived from the SIR requirement. This relationship provides a guideline as to how to dimension PCS and $d_{\max}$ to avoid HN in general, without the knowledge of the topology of the network beyond the fact that all link lengths are no more than $d_{\max}$. For a given network topology, less-restrictive relationships with smaller PCS can be found to improve throughput performance.

We have adapted the HFD principle for application in large-scale WiFi cellular networks consisting of many adjacent WLANs (a popular form of 802.11 deployments). We have designed variations of HFD beyond the General HFD. One version is "HFD with nonuniform PCS," in which the PCSs of different links are varied and minimized according to their surroundings. Such individual PCS minimization reduces ENs and increases spectrum spatial reuse. We have shown that the total throughput can be increased by about 100% with this design (see Fig. 10 for the case where number of channels $N = 1$).

Another approach to relax HFD's requirements on carrier-sensing range is to assign different frequency channels to adjacent cells so that intercell physical interference is either reduced or totally avoided. However, this approach also uses up more spectrum resources. Given f available frequency channels, an issue is whether it is better to assign different frequencies to adjacent cells or just have f parallel overlaid networks, with each cell having f APs: one on each frequency channel. We find that the latter has better throughput performance (in unit of bits per second per frequency channel). As indicated in Fig. 10 and using the General-HFD case in the figures as an example, the latter approach can achieve much higher throughput per channel $(N = 1)$ than the former approach ($N = 8$, wherein intercell physical interference is totally avoided).

Finally, we have discussed the fundamental tradeoff between HN and EN. We have shown the following: 1) The EN–HN tradeoff exists in both our scheme and IEEE 802.11. 2) Our scheme always outperforms IEEE 802.11 with the same PCS (PCS range) setting.

APPENDIX A

In the following, we prove that HFD for Basic Access Mode can remove HN in a network.

A. *Constraints for Simultaneous Transmissions in 802.11*

To understand the requirements of HFD, we need to first understand the fundamental causes of HN. There are two types of constraints concerning simultaneous transmissions in an 802.11 wireless network, as discussed below.

1) 802.11—Carrier-Sensing Constraints: In the Basic Access Mode, only PCS needs to be considered. For PCS, the PHY header is decoded. The length field in the PHY header informs the receiver of the duration of the payload that follows. Consider two links i and j with senders and receivers T_i, T_j, R_i, and R_j, respectively. For brevity, we will also use T_i, T_i, R_i, and R_j to denote their positions in the following discussion.

Simultaneous transmissions on the two links are allowed when

$$|T_i - T_j| > \text{PCS}. \tag{16}$$

However, the simultaneous transmissions will fail unless

$$|T_i - R_j| > \text{PCS} \tag{17}$$

$$|R_i - T_j| > \text{PCS}. \tag{18}$$

This is due to the "receiver capture" effect in most 802.11 products. If (17) is not true when T_i starts a DATA transmission first, followed by T_j, then R_j will not attempt to receive the DATA from T_j because it is in the process of receiving the ongoing signal from T_i. Transmission on link j therefore fails. Similar argument applies for (18).

2) Physical No-Collision Constraints: We now consider under what conditions will there be no physical collision between simultaneous transmissions over links i and j. Define $d_i = |T_i - R_i|$ and $d_j = |T_j - R_j|$. Since each "atomic information exchange" over an 802.11 link consists of two-way traffic, DATA followed ACK in the reverse direction, the conditions for the two transmissions not interfering with each other are as follows [14]:

$$\begin{cases} \frac{P(d_i)}{P(|S_j - R_i|)} > C_t \\ \frac{P(d_i)}{P(|S_j - S_i|)} > C_t \\ \frac{P(d_i)}{P(|R_j - R_i|)} > C_t \\ \frac{P(d_i)}{P(|R_j - S_i|)} > C_t \end{cases} \begin{cases} \frac{P(d_j)}{P(|S_j - R_i|)} > C_t \\ \frac{P(d_j)}{P(|S_j - S_i|)} > C_t \\ \frac{P(d_j)}{P(|R_j - R_i|)} > C_t \\ \frac{P(d_j)}{P(|R_j - S_i|)} > C_t \end{cases} \text{, i.e., } \frac{\text{Signal}}{\text{Interference}} > C_t \tag{19}$$

where $P(d)$ is the received power as a function of distance. It is a simplified form of $P(P_t; d)$ when we assume that all the nodes use the same transmission power P_t.

The first inequality on the left in (19) says that the DATA signal on link j should be sufficiently small when it reaches the receiver of link i compared with the DATA signal on link i; the second inequality on the left is for DATA on link j not interfering with ACK on link i; and so on [14]. As mentioned in Section II, assuming the power propagation function in (1), (19)

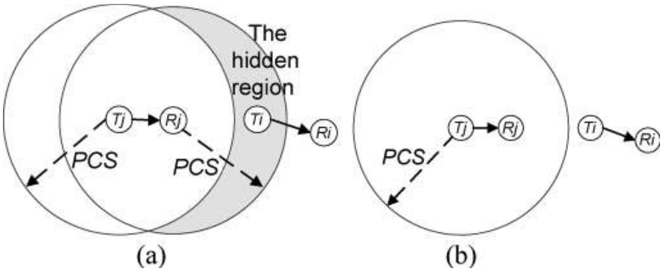

Fig. 12. (a) HN due to (17) and (18), and (b) RS mode removes the HN.

can be transformed into inequalities among distances instead of power levels.[6]

$$\begin{aligned} &|T_j - R_i| > (1+\Delta)d_i; |T_j - R_i| > (1+\Delta)d_j \\ &|T_j - T_i| > (1+\Delta)d_i; |T_j - T_i| > (1+\Delta)d_j \\ &|R_j - R_i| > (1+\Delta)d_i; |R_j - R_i| > (1+\Delta)d_j \\ &|R_j - T_i| > (1+\Delta)d_i; |R_j - T_i| > (1+\Delta)d_j. \qquad (20) \end{aligned}$$

3) Goal of HFD: Following the above discussion, HN can arise out of two situations—When (16) is satisfied, the following situations happen.

1) Equation (17) or (18) is not satisfied.
2) Equation (19) is not satisfied.

That is, the carrier-sensing mechanism allows simultaneous transmissions that will fail. The goal of HFD is to make sure that the above two situations will not happen.

B. Proof of HFD for IEEE 802.11 Basic Access Mode

1) Receiver RS Mode: We first argue that no matter how large the carrier-sensing range PCS is, (16) does not guarantee (17) and (18). This leads to the fundamental requirement that (17) and (18) must be removed if HN is to be eliminated, which can be achieved with the receiver RS mode.

To see why (16) is not sufficient for guaranteeing (17), consider the counter example in Fig. 12(a). The two circles define the regions that can be sensed by T_j and R_j. There is inevitably a "hidden" region which cannot be sensed by T_j and which can be sensed by R_j. If T_i is within this hidden region, then (16) holds, but (17) does not. When T_i and T_j transmit DATA packets in an overlapping manner with T_i transmitting first, T_j's DATA cannot be received by R_j due to the "receiver capture" effect. Note that this HN problem exists no matter how large PCS is—A naïve solution of increasing the PCS range alone is not viable.

RS mode can be used to remove constraints (17) and (18). Recall that with RS mode, when the power of a later-arriving packet is more than C_t times that of the earlier packet, the receiver switches to receive the stronger new packet. Thus, as long as the SIR is sufficient, the order of transmissions does not matter. Essentially, (17) and (18) will then be replaced by the same constraints as in (20), and consideration of (20) without (17) and (18) is sufficient for our HFDs.

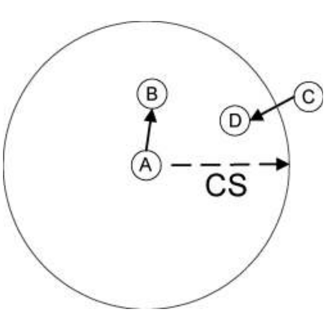

Fig. 13. Interaction of a pair of links.

2) Receive-Power Inequality: With RS mode, we now only need to make (16) sufficient for (20). Consider Fig. 13. Suppose that A is transmitting a DATA to B, and C intends to transmit a DATA to D. To avoid HN, the following must be true:

For any link (C, D) in the neighborhood of link (A, B) where nodes A and C cannot carrier-sense each other, constraint (20) must be satisfied. That is, there must not be any of the following:

1) DATA–DATA collisions at B or D;
2) ACK–ACK collisions at A or C;
3) DATA–ACK collisions at B or D.

Sufficient condition for satisfying constraints (20): Use of receiver RS mode plus PCS $\geq (3+\Delta)d_{\max}$.

Proof for 3): We only present the proof for 3). The proofs for 1) and 2) are similar. Suppose we assume the contrary: DATA–ACK collisions occur at B or D in spite of the use of RS mode and PCS $\geq (3+\Delta)d_{\max}$. With respect to Fig. 13, since A and C cannot sense each other, we have

$$|C - A| > \text{PCS}. \qquad (21)$$

First, suppose that DATA from A to B collides with D's ACK at B. With RS mode, the order of arrivals of the DATA and ACK at B does not matter. In order that there is collision, SIR at B must be insufficient. Equivalently

$$|D - B| \leq (1+\Delta)|A - B|. \qquad (22)$$

From (21), we have

$$|C - A| - |A - B| - |C - D| > \text{PCS} - |A - B| - |C - D|. \qquad (23)$$

Using triangular inequality

$$\begin{aligned} |D - A| &\leq |D - B| + |B - A| \\ |C - A| &\leq |D - A| + |C - D|. \end{aligned}$$

We have

$$|C - A| \leq |D - B| + |B - A| + |C - D|. \qquad (24)$$

From (23) and (24), we have

$$|D - B| > \mathrm{PC}S - |A - B| - |C - D| \geq \text{PCS} - 2d_{\max}. \qquad (25)$$

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[6] All the range requirements in this paper assume power propagation function (1). More general forms of power-budget requirements without this assumption can be derived without much difficulty. For example, (2) corresponds to $P(d_{\max}) \geq C_t P(\text{PCS} - 2d_{\max})$.

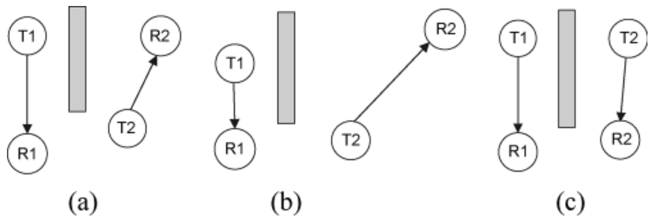

Fig. 14. HN induced by obstructions.

According to (22), we have

$$|D - B| \leq (1 + \Delta)d_{\max}. \tag{26}$$

From (25) and (26), we have

$$\text{PCS} < (3 + \Delta)d_{\max}. \tag{27}$$

However, this contradicts with the condition $\text{PCS} \geq (3 + \Delta)d_{\max}$.

Therefore, D's ACK cannot collide with A's DATA at B.

Similarly, B's ACK cannot collide with C's DATA at D.

APPENDIX B

A. Discussion of HN Induced by Obstructions

In some cases involving obstructions (instead of regular power propagation), the HN problem becomes more complicated, and we may need additional mechanisms to alleviate HN. Consider the scenario in Fig. 14(a). There is an obstruction between T1 and T2, but not between R1 and T2. The obstruction leads to a sharp drop of signal strength, and here, we assume that the "channel gain" between T1 and T2 is zero. Even with HFD for the Basic Mode, when T1 is transmitting a DATA packet to R1, T2 cannot sense it and may transmit packets and corrupt T1's packet at R1 (T2 is the HN). With the RTS/CTS mode, the situation is better since T2 can still hear R1's CTS. However, if T2 transmits an RTS first, T1 cannot receive it and may go ahead to send an RTS to R1, which may lead to a failure.

The problem here is that the transmitter (T1) is blind to the transmissions on an interfering link (link 2) due to the existence of obstructions. There is no easy solution unless we make significant modifications to 802.11 MAC. One idea is that, since only R1 knows the transmissions on link 2, it can relay the information to T1, so that T1 can be prevented from transmission when link 2 is busy. The protocol works as follows. By default, each node operates normally with the Basic Mode. If excessive collisions occur, the nodes then conjecture that there is HN caused by obstructions, and each node in the neighborhood then finds out the "local map" [i.e., the "channel gains" between every pair of nodes of the neighborhood, as in Fig. 14(a)] through a simple "PE" protocol similar to that in Appendix C. Once HN caused by obstructions is confirmed, instead of the normal operations, the nodes involved then change their operations as follows.

1) The HN (T2 in the above example) will send an RTS before transmitting DATA. The targeted receiver of the HN (R2) will wait for a period of SIFS + RTS + SIFS before replying a CTS.
2) The nontargeted receiver above (R1) will relay the RTS to its transmitter (T1). The transmitter will not send DATA to the receiver during the NAV.

The protocol may not completely avoid collisions since multiple nodes may try to relay the RTS, leading to relay-RTS collision. An algorithm is needed to elect a representative node to relay the RTS. The details are an interesting subject for future study.

There are also other scenarios to consider. In Fig. 14(b), assume that T2's transmission does not cause insufficient SIR at R1 (i.e., with "RS mode," R1 can always receive T1's transmissions), but R1's transmission causes insufficient SIR at T2 (i.e., R1's transmission can corrupt the ACK from R2). The relay scheme above still applies here, but it generates additional RTS/CTS packets. An alternative is to use "Delayed ACK" operated in the Basic Mode (no RTS/CTS is needed), which is described as follows.

Since T1 and T2 cannot sense each other, they may be transmitting DATA packets at the same time. After R1 finishes receiving, its ACK may interfere with link 2. The idea of "Delayed ACK" is to let R1 do carrier sensing before returning an ACK, instead of sending ACK immediately after SIFS. If R1 senses no transmission (after receiving DATA from T1), it delays its ACK by SIFS+ACK (in case R2 is returning an ACK to T2); if R1 senses a transmission, it waits until the transmission ends and delays its ACK for an additional SIFS+ACK. Meanwhile, T1 is not aware of the delay and may go into exponential backoff. However, immediately after it receives the delayed ACK from R1, T1 gets out of the backoff state so that it does not need to continue to count down. We note in passing that 802.11e has some sort of a delayed ACK feature. Delayed ACK, however, does not entirely avoid T1's retransmission if the ACK is delayed too much.

Another scenario is shown in Fig. 14(c) in which the ACK from either R1 or R2 may interfere with the other link. In addition, R1 and R2 cannot sense the transmissions of T2 and T1, respectively. "Delayed ACK" does not apply here, and we have to fall back to the Relay scheme—In this scenario, R1 relays the CTS from R2 to T1, and vice versa. In the Relay scheme, since either RTS or CTS needs to be relayed in different scenarios, we also call it "RTS/CTS Relay scheme."

A strategy is to combine the delayed-ACK scheme with the RTS/CTS Relay Scheme. Since the RTS/CTS Relay Scheme is more expensive (i.e., it requires RTS/CTS, which may be further duplicated and relayed), it should be used only as an alternative when "Delayed ACK" algorithm does not work. The above has only sketched a plausible solution for HN that is caused by obstructions. This subject certainly deserves more careful investigations in the future.

APPENDIX C

A. PE Algorithm for Discovering InRs

To construct the InRs, each node A periodically broadcasts special PE packets and receives PE packets from nearby nodes. The transmission power for PE packets is the same as that for regular packets, and we assume that all nodes use the same transmit power and receiver sensitivity.

1) Node A measures the powers of PE packets that are transmitted by other nodes that it can hear and keep the power information in a "power set," $P_A = \{[C, P(C, A)]\}$, where C is the node label of the sender of the PE packets.
2) Periodically, node A broadcasts its PE packets, which contain as follows: a) A list of active links (A, B) or (B, A) (B is any other node forming a link with A) and b) P_A.
3) Node A identifies its associated InRs based on the PE packets that it receives (more details will be given below).

A point to note about the PE algorithm is that they are not the same as RTS/CTS packets and are not used for carrier-sensing purposes. They are special packets used for distributed discovery of InRs. Also, the PE packets need to be transmitted only when the network topology or conditions have changed. The periodic transmissions of PE packets above are mainly for simplification and to make the algorithm more robust. When nodes are not highly mobile, PE packets introduce little overhead because the broadcast period can be long.

B. Condition for Correct Operation of PE

The following condition is sufficient to ensure that a node can discover all the InRs relevant to itself:

$$P(d_{\max}) > C_t P(\text{PERange} - d_{\max})$$

or

$$\text{PERange} \geq (2 + \Delta) d_{\max} \tag{28}$$

where PERange is the transmission range of the PE packets.

Note: To meet (28), PE packets must be transmitted at a sufficiently low rate, such as that used by RTS/CTS packets.

Proof: Consider three nodes: Nodes A and B form links (A, B) and (B, A); and node C forms links with other nodes. Without loss of generality, assume that $P(A, B) < C_t\, P(C, B)$ so that the transmission by C can interfere with reception at B. We want to show the following: 1) nodes A and B, and 2) node C and any other node D that forms link with C can find out the existence of this InR.

Proof of 1): By definition, we have $|A - B| \leq d_{\max}$. If (28) holds, we have

$$\begin{aligned} C_t P(C, B) &> P(A, B) \geq P(d_{\max}) \\ &> C_t P(\text{PERange} - d_{\max}). \end{aligned} \tag{29}$$

The above implies that $\text{PERange} - d_{\max} > |C - B|$, since $P(\cdot)$ is a decreasing function of distance. Therefore

$$\text{PERange} > |C - B|$$

and

$$\text{PERange} > |C - B| + d_{\max} \geq |C - B| + |A - B| \geq |C - A|. \tag{30}$$

This means that, if $P(A, B) < C_t\ P(C, B)$, then the PE packets of C can reach A and B. By measuring the received power of C's PE packets and checking their source address to identify the sender, B can derive C and $P(C, B)$. Similarly, B can derive A and $P(A, B)$ from A's PE packets. Therefore, B can find out that $P(A, B) < C_t\ P(C, B)$ and, hence, the existence of InR between link $(A, B)/(B, A)$ and any other link with C being the transmitter or receiver—Note that these links are contained in the active link list in C's PE packets received by B.

Now, the PE packets of B contain information on $[C, P(C, B)]$ and $[A, P(A, B)]$. Upon receiving B's PE packets, A can also find out that $P(A, B) < C_t\ P(C, B)$ and, hence, the existence of InR between link $(A, B)/(B, A)$ and any other link with C being the transmitter or receiver—Note that these links are contained in the active link list in C's PE packets received by A.

Proof of 2): From the proof of 1), we have $\text{PERange} - d_{\max} > |C - B|$. Therefore

$$\text{PERange} > |B - C|$$

and

$$\text{PERange} > |B - C| + d_{\max} \geq |B - C| + |C - D| \geq |B - D|. \tag{31}$$

Thus, the PE packets of B, which contain $[C, P(C, B)]$, $[A, P(A, B)]$, and active links (A, B) and (B, A) can reach C and any node D that forms link with C, from which they can discover the associated InRs.

REFERENCES

[1] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?" *IEEE Commun. Mag.*, vol. 39, no. 6, pp. 130–137, Jun. 2001.

[2] K. Xu, M. Gerla, and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks?" *Proc. IEEE GLOBECOM*, Nov. 2002, vol. 1, pp. 17–21.

[3] A. Vasan, R. Ramjee, and T. Woo, "ECHOS—Enhanced capacity 802.11 hotspots," in *Proc. IEEE Infocom*, Mar. 2005, pp. 1562–1572.

[4] S. Ansari *et al.*, "Performance enhancement of TCP on multi-hop ad hoc wireless networks," in *Proc. IEEE ICPWC*, Dec. 2002, pp. 90–94.

[5] P. C. Ng and S. C. Liew, "Offered load control in IEEE 802.11 multi-hop ad-hoc networks," in *Proc. 1st IEEE Int. Conf. MASS*, Oct. 2004, pp. 80–89.

[6] P. C. Ng and S. C. Liew, "Throughput analysis of IEEE 802.11 multi-hop ad hoc networks," *IEEE/ACM Trans. Netw.*, 2007. submitted for publication. AQ8

[7] P. C. Ng and S. C. Liew, "Re-routing instability in IEEE 802.11 multi-hop ad-hoc networks," in *Proc. 4th IEEE Int. Workshop Wireless Local Netw.*, Nov. 2004, pp. 602–609.

[8] P. C. Ng and S. C. Liew, "Re-routing instability in IEEE 802.11 multi-hop ad-hoc networks," *Ad Hoc Sensor Wirel. Netw.*, vol. 2, no. 1, pp. 1–25, 2006.

[9] A. Kochut, A. Vasan, A. U. Shankar, and A. Agrawala, "Sniffing out the correct physical layer capture model in 802.11b," in *Proc. ICNP*, 2004, pp. 252–261.

[10] *The Network Simulator—NS2*. [Online]. Available: http://www.isi.edu/nsnam/ns

[11] L. B. Jiang and S. C. Liew, "Hidden-node removal and its application in cellular WiFi networks," Tech. Rep. [Online]. Available: http://www.eecs.berkeley.edu/~ljiang/HFD.pdf

[12] T. S. Rappaport, *Wireless Communications—Principles & Practice*. Englewood Cliffs, NJ: Prentice-Hall, 2002.

[13] P. C. Ng, S. C. Liew, and L. B. Jiang, “A performance evaluation framework for IEEE 802.11 ad-hoc networks,” in *Proc. ACM Workshop PE-WASUN*, 2004, pp. 123–124.

[14] P. Gupta and P. R. Kumar, “The capacity of wireless network,” *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[15] L. B. Jiang, “Improving capacity and fairness by elimination of exposed and hidden nodes in 802.11 networks,” M.S. M.Phil. thesis, Chinese Univ. Hong Kong, Hong Kong, Jun. 2005. http://www.eecs.berkeley.edu/~ljiang/Thesis.pdf

[16] H. Zhai and Y. Fang, “Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks,” in *Proc. IEEE Infocom*, Apr. 2006, pp. 1–12.

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Dr. Liew is a Fellow of the IEE and the HKIE. He is listed in *Marquis Who’s Who in Science and Engineering*. He was the recipient of the first Vice-Chancellor Exemplary Teaching Award at the Chinese University of Hong Kong. Recently, he and his student won the Best Paper Awards at the First IEEE International Conference on Mobile *Ad hoc* and Sensor Systems (IEEE MASS 2004) and the Fourth IEEE International Workshop on Wireless Local Network (IEEE WLN 2004). Separately, TCP Veno, which is a version of TCP to improve its performance over wireless networks proposed by him and his student, has been incorporated into a recent release of Linux OS.

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = A citation of Section 1.1.1 was inserted here as this sentence was reworded. Please check if appropriate.
AQ2 = Please provide the expanded form of the acronym “TCP”.
AQ3 = Please provide the expanded form of the acronyms “RTS/CTS”.
AQ4 = Please check the changes made to this sentence.
AQ5 = All occurrences of “NS-2” were changed to “NS2”. Please check if appropriate.
AQ6 = Please provide the expanded form of the acronyms “UDP”.
AQ7 = Please check this sentence. It is being reworded.
AQ8 = Please provide additional information in Ref. [6].
AQ9 = The author’s current affiliation provided in the footnote did not correspond to the current affiliation provided in the curriculum vitae. Please check.
Note: Reference [5] and [6] were split into two. Consequently, the reference list as well as the bibliographic citations in the body was renumbered. Please check.

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