

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 LANs (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)

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87 range¹ is larger than the link distance (transmitter–receiver
88 distance) plus the interference range (IR),² HN can be removed,
89 and RTS/CTS (which implements virtual carrier sensing) is
90 no longer needed. A recent work [3] gives a similar result.
91 According to our “link-based” analysis in this paper, however,
92 this condition is not sufficient for the elimination of HN in
93 general.

94 References [4]–[6] extended the investigation in [1]. In par-
95 ticular, the “self-HN interference” phenomenon of a single
96 multihop traffic flow was studied. The successive packets of
97 the same traffic flow may self-interfere among themselves as
98 they hop from node to node. Detailed explanations on how
99 self-HN interference causes throughput degradation as well as
100 triggers the rerouting instability phenomenon were given in
101 [5]–[8]. However, the studies in [4]–[8] only provided solutions
102 to alleviate “symptoms” of HN, and these solutions do not
103 remove the “root” of the problem: the HN itself. In contrast,
104 this paper focuses on solutions that remove HN.

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

117 II. HIDDEN-NODE-FREE DESIGN (HFD)

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

123 A. Definition and Examples

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

127 1) *Definition of HN*: Link i is said to be hidden from link j if
128 the following conditions are true. 1) T_j cannot carrier-sense the
129 transmission on link i , and 2) link i may cause transmission fail-
130 ures on link j , or vice versa, so that transmission on at least one
131 of the links will fail when both links transmit simultaneously
132 (Note that by “simultaneous,” we refer to the situation when
133 the transmissions by different nodes overlap in time. Their

¹This 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.

²A 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.

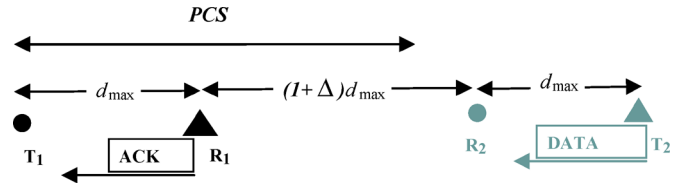


Fig. 1. PCS not sufficiently large leads to HN due to insufficient SIR.

transmissions may actually be initiated at different instances so
that the start times of the transmissions are different).

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) SIR³ 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 trans-
mitter 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

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

³SIR 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.

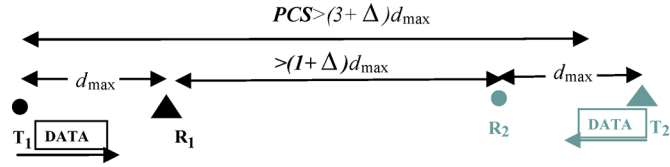


Fig. 2. Lack of receiver “RS mode” leads to HN no matter how large PCS and SIR are.

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

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

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

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

217 This HN problem can be solved with a receiver “RS mode”
 218 which can be enabled in some 802.11 products (e.g., Atheros
 219 WiFi chips). With RS mode, a receiver will switch to receive the

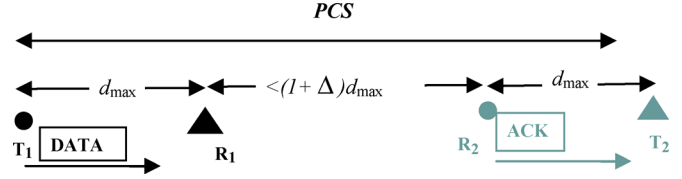


Fig. 3. With RS mode, PCS not sufficiently large still leads to HN due to insufficient SIR.

stronger packet as long as its power is C_t times⁴ higher than the
 220 current packet. If the new packet is an 802.11 DATA targeted
 221 for it, the node will reply with an ACK after Short InterFrame
 222 Space (SIFS), whether the medium around this node is idle
 223 or not. 224

4) *Example 3—Simultaneous Transmissions, Receiver RS*
 225 *Mode, and Insufficient SIR:* One might wonder, given the
 226 example in Fig. 2, why the default receiver operations of all
 227 commercial products and the NS2 simulator do not assume
 228 RS mode. The reason is that, without a sufficiently large PCS,
 229 enabling RS mode may lead to HN collisions, as described
 230 below. 231

RS mode alone cannot prevent HN without a $PCS > (3 + 222$
 $\Delta)d_{\max}$. To see this, consider the example in Fig. 3, where
 233 $PCS < (3 + \Delta)d_{\max}$ and $|R_1 - R_2| < (1 + \Delta)d_{\max}$. Assume
 234 that T_1 transmits a DATA to R_1 first. During the DATA’s period,
 235 T_2 starts to send a shorter DATA packet to R_2 . With RS mode,
 236 R_2 switches to receive T_2 ’s DATA and sends an ACK after
 237 the reception. If T_1 ’s DATA is still in progress, R_2 ’s ACK will
 238 corrupt the DATA at R_1 . 239

Therefore, it is not advisable to use RS mode if PCS is not
 240 large enough, which is the case in most commercial products.
 241 The NS2, which simulates operations in commercial products,
 242 for example, assumes $PCS = 2.2$ times the maximum transmis-
 243 sion range (TxRange) of DATA. If d_{\max} , which is the maximum
 244 link length allowed in the network, is set to TxRange, then
 245 such HN collisions will inevitably occur. As a result, most
 246 commercial products do not use RS mode by default. However,
 247 without RS mode, HN collisions like that in Fig. 2 inevitably
 248 occur. Either way, HN occurs. 249

B. HFD for Basic Access Mode 250

From the above examples, we summarize the requirements
 251 for a HFD for basic mode in IEEE 802.11. It includes two
 252 requirements. 253

- 1) A range requirement 254

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

If $C_t = 10$, and $\alpha = 4$ 255

$$PCS \geq 3.78d_{\max} \quad (3)$$

- 2) and the receiver’s RS mode. 256

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

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

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

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

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

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

309 To further elaborate on the implementation details, in prac-
 310 tice, PCS and d_{\max} are determined by the transmission power
 311 P_t and receiving thresholds. We can write

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

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

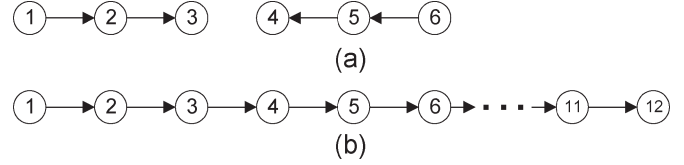


Fig. 4. Traffic flows that can give rise to HN.

where P_{link} is the received power threshold we impose for
 link establishment. A link will not be set up during the ini-
 tial 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 dif-
 ferent 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 tun-
 ing P_{link} (if we keep P_t unchanged). For example, if we
 want $\text{PCS} = 3.78d_{\max}$, with the assumption of two-ray ground
 model with the “path loss exponent” $\alpha = 4$, (4) and (5) become

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

$$A \frac{P_t}{\text{PCS}^4} = P_{\text{PCS}} \quad (7)$$

where A is a constant [12]. Therefore

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

or

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

III. REMOVAL OF HN PERFORMANCE PROBLEMS

“TCP unfairness” and “rerouting instability” are two perfor-
 mance 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.

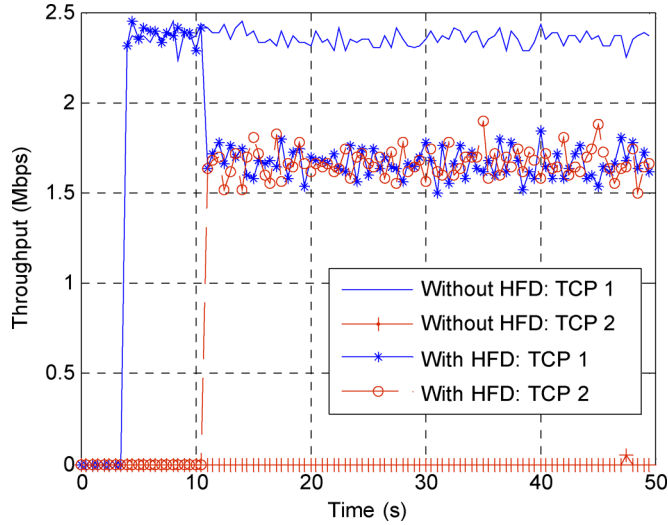


Fig. 5. TCP unfairness (fairness) without (with) HFD.

347 A. TCP Unfairness

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

359 B. Rerouting Instability

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

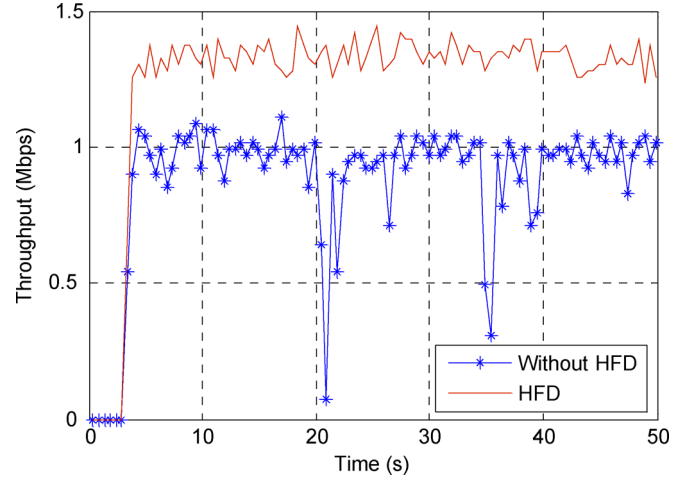


Fig. 6. Throughput instability (stability) of an 11-hop UDP flow without (with) HFD.

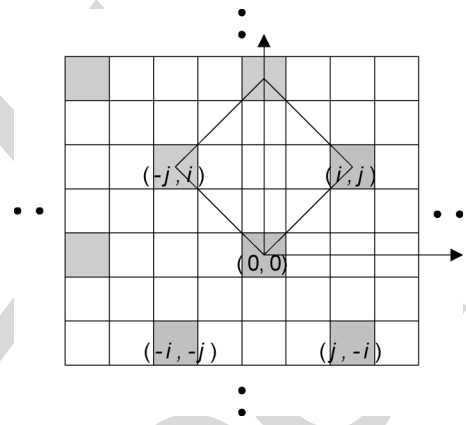


Fig. 7. Channel assignment ($N = 8$) with square cells.

or totally eliminated, relaxing the HFD's requirements on the
 382 carrier-sensing range. On the other hand, more spectrum re- 383
 384 sources (channels) will be used. Thus, an issue is whether a 384
 385 careful channel assignment can yield better spectrum efficiency 385
 386 or not while ensuring no HN in the network. We address 386
 387 this issue by examining possible channel assignment schemes 387
 388 systematically.

This section focuses on the square-cellular topology. In [11],
 389 we also studied channel assignment in hexagon-cellular topol- 390
 391 ogy and presented its performance results. In a square-cellular 391
 392 WiFi network, the APs are placed in a grid (see Fig. 7 in which 392
 393 each square corresponds to one WLAN). Clients are located 393
 394 randomly and are associated with the nearest APs. We assume 394
 395 that the AP is placed at the center of the square of its WLAN. 395
 396 The largest link length d_{\max} is the distance from the AP to the 396
 397 corner of the square. We denote the distance between an AP and 397
 398 another AP on the same channel closest to it by D , and the total 398
 399 number of channels needed to cover the overall WiFi cellular 399
 400 network by N .

401 A. Channel Assignment

In a regular topology, we can assign the channels in a regular
 402 manner. Channel assignment for a hexagon-cellular topology 403

373 IV. CHANNEL ASSIGNMENT IN WiFi

374 CELLULAR WITH HFD

375 There are three orthogonal channels for 802.11b/g and eight
 376 orthogonal channels for 802.11a. When multiple WLANs are
 377 deployed to form a large WiFi cellular network, there is the
 378 issue of how to assign these channels to the different WLANs
 379 while keeping the network free of HN. On one hand, channel
 380 assignment can separate cells with the same channel further
 381 apart so that intercell physical interference can be reduced

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

404 is well known [12]. If a cell is in the form of a square, by
405 emulating the channel assignment for hexagon cells, we can
406 assign a channel as in Fig. 7 (the gray cells use the same
407 channel). We denote by (i, j) the “offsets” (in two axes) of
408 one of the four adjacent cells that use the same channel as cell
409 $(0, 0)$, where $i \geq 0$, and $j \geq 0$. As illustrated in Fig. 7, for cell
410 $(0, 0)$, the four adjacent cells are cells (i, j) , $(-j, i)$, $(-i, -j)$,
411 and $(j, -i)$.

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

418 For an offset assignment (i, j) , the number of frequency
419 channels used to fill the whole WiFi cellular network is $N =$
420 $i^2 + j^2$. To see this result, consider the square formed by
421 the APs at cells $(0,0)$, (i, j) , $(i - j, j + i)$, and $(-j, i)$. With
422 reference to Fig. 7, the area of the square is $i^2 + j^2$. Within
423 this square, an area of one unit is covered by the gray color.
424 The whole plane can be divided by similar squares described
425 above. If we omit the boundary effect (assume that the plane
426 is infinitely large), one channel can cover $1/(i^2 + j^2)$ of the
427 whole plane. Therefore, $N = i^2 + j^2$ channels are needed.

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

- 438 1) There is no protocol interference or physical interference
439 between adjacent cells using the same channel. With this
440 design, transmissions on cells are independent.
- 441 2) There is protocol interference, but no physical interfer-
442 ence between adjacent cells using the same channel. In
443 this case, the carrier-sensing mechanism may be overly
444 aggressive so that legitimate simultaneous transmissions
445 on different cells may be prevented by the protocol
446 operation.
- 447 3) There is physical interference between adjacent cells
448 using the same channel. With this design, some simul-
449 taneous transmissions on different cells need to be pre-
450 vented. Therefore, to avoid HN (with HFD), there must
451 be protocol interference.

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

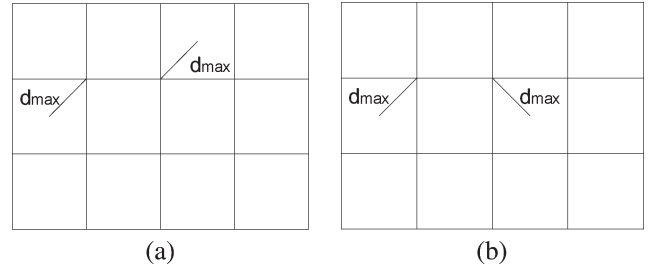


Fig. 8. Minimum distance between two cells. (a) $i > 0$, $j > 0$. (b) $i > 0$, $j = 0$.

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

454 For DA1, two transmissions on adjacent cells using the same
455 channel must not physically interfere with each other. A certain
456 minimum number of channels (N_{\min}) are required to guarantee
457 this. Consider Fig. 8, d_{\max} is the distance between the AP at
458 the center of a cell and a client at the corner of the cell. The
459 two cells in consideration use the same channel. Without loss of
460 generality, we assume that $i \geq 1$, and $j \geq 0$ (since i, j cannot be
461 both zero). In Fig. 8(a), where $i = 2$ and $j = 1$ (generally, when
462 $i, j > 0$), the distance between the two corners (i.e., between
463 the two clients) is $\sqrt{(i-1)^2 + (j-1)^2}$; in Fig. 8(b), where
464 $i = 2$ and $j = 0$ (generally, when $i > 0, j = 0$), the distance
465 is $\sqrt{(i-1)^2 + 0^2}$. Combining the two cases, the distance
466 between the two closest corners of two adjacent cells which use
467 the same channel is $\sqrt{(i-1)^2 + [\max(j-1, 0)]^2}$. Now, this
468 distance must be larger than the IR. Therefore, we require
469

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

470 Now, $d_{\max} = 1/\sqrt{2}$. Assuming $\Delta = 0.78$ [as in (3)], the
471 offsets (i, j) that satisfy this requirement are
472

$$(1, 3), (1, 4), \dots, (2, 2), (2, 4), \dots, (3, 0), (3, 1), \dots$$

473 Requirement (9) is the no-physical interference requirement.
474 Given this requirement, carrier sensing still needs to work
475 properly if simultaneous transmissions on adjacent cells are to
476 be allowed. Specifically, we require
477

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

478 where PCS is the PCS range. The lower bound on PCS in
479 (10) is to ensure that carrier sensing works properly to prevent
480 simultaneous transmission within the same cell. The maximum
481 distance between two wireless stations in the same cell is
482 $2d_{\max}$. The upper bound on PCS in (10) ensures that a station
483 does not sense other stations in adjacent cells. There is no need
484 for sensing beyond a cell since (9) ensures that there is no
485 interference beyond a cell.

486 Note that PCS can be adjusted by tuning the receiver sensitiv-
ity for carrier sensing while maintaining the same transmission

487 power. Generally, the maximum PCS PCS_{\max} is defined by the
488 transmission power and the lowest received power required to
489 decode the PHY header. If we want to make actual operating
490 PCS smaller than PCS_{\max} , the following two requirements
491 must both be satisfied before PCS is triggered.

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

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

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

$$(1, 3), (1, 4), \dots, (2, 4), \dots, (3, 0), (3, 1), \dots$$

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

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

505 C. Design Alternative 2 (DA2): No Physical Interference, But 506 With Protocol Interference Among Adjacent Cells

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

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

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

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

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

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

D. Design Alternative 3 (DA3): With Physical Interference Among Adjacent Cells 531 532

For DA3, adjacent cells using the same channel may physi- 533
cally interfere with each other. That is, (9) is not satisfied 534

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

The offsets that satisfy (14) are 535

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

Therefore, we see that the channels used are 536

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

Note that $N \leq 5$ is due to the particular regular (i, j) channel 537
assignment strategy we assume. There could be other cell 538
assignments that yield different results of N . 539

Design Alternatives 1 and 2 are HN-free if $PCS \geq 2d_{\max}$. 540
The next few sections consider different ways of setting PCS 541
for DA3 to make it HN-free. 542

1) *General HFD*: According to (2), the general HFD 543
requires 544

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

Inequality (15) is independent of the network topology. In a 545
given topology, however, it may be overkill because each node 546
adopts the PCS range for “the worst case.” 547

2) *HFD With Nonuniform PCS*: General HFD can remove 548
HN, but without considering the actual topology. If we take 549
the actual link layouts into consideration and allow the PCS 550
range to vary from node to node [relaxing the requirement 551
in (15)], EN can be reduced by allowing more noncolliding 552
transmissions to proceed simultaneously. 553

Note that, in previous sections, “PCS” is defined from the 554
perspective of a transmitter. That is, with respect to a transmit- 555
ter, its transmission will prevent all the nodes within its PCS 556
range from transmitting. In this section, however, we define 557
“PCS” from the perspective of a receiver. That is, a node will be 558
prevented from transmitting by the transmission from any node 559
within its PCS range. 560

For clarity, we use “ PCS^T ” to denote PCS with respect 561
to transmitters, and “ PCS^R ” to denote PCS with respect to 562
receivers. If all nodes transmit at the same power (P_t), the 563
 PCS^R of a node a , $PCS^R(a)$, is only related to its receiver 564
sensitivity for carrier-sensing purposes. Clearly, for uniform 565
PCS in the previous section, $PCS^T = PCS^R$, since all the nodes 566
have the same transmit power and carrier-sensing sensitivity. 567

In this section, we assume that all nodes use the same trans- 568
mit power and data rate. In the following algorithm, each node 569
computes the PCS^R it should assume in its receiver design. 570

3) *HFD With Nonuniform PCS*: For any node a 571

- 1) Denote the set of links whose sender is node A 572
by $L(A) = \{a_1, a_2, a_3, \dots, a_n\}$. Denote the set of 573
links which has an “interference relationship” (“InR”) 574
with link k by $I(k)$ [links that are either physically 575

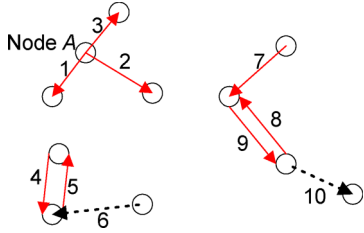


Fig. 9. Node A 's interference link set $M(A) = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$.

576 interfered by link k or vice versa. As detailed in
 577 Appendix A, there is “InR” between links i and j if
 578 any inequality in (19) or (20) is NOT true]. Define
 579 node A 's “interference link set,” $M(A) = I(a_1) \cup$
 580 $I(a_2) \cup I(a_3) \cup \dots \cup I(a_n)$.

581 a) For example, in Fig. 9, $L(A) = \{1, 2, 3\}$, $I(1) =$
 582 $\{2, 3, 4, 5\}$, $I(2) = \{1, 3, 7, 8, 9\}$, and $I(3) =$
 583 $\{1, 2\}$. Therefore, $M(A) = \{1, 2, 3, 4, 5, 7, 8, 9\}$.
 584 These links have been marked with red color.

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

588 2) PCS of node A is computed as $PCS^R(A) =$
 589 $\max_{k \in M(A)} (|A - T_k|)$, where link k is a member
 590 of $M(A)$, and T_k is the sender of link k . Set the
 591 receiver carrier-sensing threshold of node A according
 592 to $PCS^R(A)$.⁵

593 Note that to obtain the distance $|A - T_k|$, A should be able
 594 to decode the PE packets (to be explained in Appendix C)
 595 from T_k and, thus, deduce the distance from the power of
 596 the received packet $P(T_k, A)$. Therefore, we set $PERange \geq$
 597 $(3 + \Delta)d_{max}$ here.

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

611 V. NUMERICAL RESULTS

612 In this section, we give the NS2 simulation results of a
 613 square-cellular topology under different design alternatives
 614 (simulations of a hexagon-cellular topology yield very sim-
 615 ilar results [11]). The square-cellular network has $10 * 10 =$
 616 100 APs (see Fig. 7). The size of each cell is $205 \text{ m} * 205 \text{ m}$.

⁵With 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)].

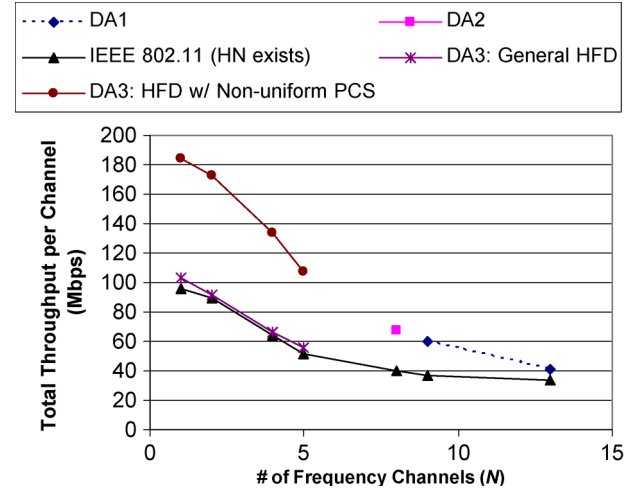


Fig. 10. Throughput per channel for different HFD Design Alternatives (“DA”) in square-cellular networks.

Therefore, $d_{max} = 205/\sqrt{2}$ m. We ensure that $d_{max} \leq 617$
 TxRange (i.e., the maximum transmission range). Around 400
 618 clients are randomly placed in this area with a uniform distrib-
 619 ution. Each client is associated with the nearest AP and sends a
 620 saturated traffic flow to the AP. The results are shown in Fig. 10.
 621

In Fig. 10, for IEEE 802.11, $PCS = 550$ m, but “RS mode”
 622 is not enabled; therefore, it is not HN-free. For other cases, “RS
 623 mode” is enabled, and PCS is set in such a way as to ensure an
 624 HN-free property.
 625

As discussed in Section IV, DA1 corresponds to $N > 8$, and
 626 DA2 corresponds to $N = 8$. In both cases, we set $PCS = 2d_{max}$
 627 (the minimum requirement). We obtained the throughput per
 628 channel C for different values of N . That is, C is the total
 629 throughput divided by N . As shown in Fig. 10, for $N \geq 8$, C
 630 decreases as N increases. In fact, the total throughput ($C * N$)
 631 is roughly constant for $N \geq 8$. This implies that DA1 and DA2
 632 do not put extra frequency channels to good use, and it is not
 633 advisable to insist on having no physical interference among
 634 cells using the same channels.
 635

DA3 is adopted when $N < 8$. In this case, simulations
 636 with two different HFDs—General HFD [with $PCS = 550$ m,
 637 slightly larger than $(3 + \Delta)d_{max}$, so that General HFD and
 638 802.11 in the simulations only differ by RS mode being en-
 639 abled in General HFD] and HFD w/ nonuniform PCS—were
 640 carried out.
 641

As shown in Fig. 10, for $N < 8$, “HFD w/ nonuniform PCS”
 642 significantly improves C compared to “General HFD.” This
 643 is because “HFD w/ nonuniform PCS” takes into account the
 644 actual topology and InRs, while “General HFD” tries to remove
 645 HN for “the worst case.” In an actual topology where clients
 646 are randomly located, the lengths of some links may be much
 647 smaller than d_{max} , and “the worst case,” as shown in Fig. 1,
 648 may not appear. This relaxes the requirement of PCS, and the
 649 nonuniform PCS design takes advantage of this to reduce ENs
 650 and increases the capacity.
 651

The overall results in Fig. 10 also indicate that careful assign-
 652 ment of frequency channels for different cells usually cannot
 653 improve the capacity of such cellular WiFi networks. If there
 654

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

660 VI. TRADEOFF BETWEEN HN AND EN

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

669 To illustrate this point, we first consider the Basic Access
 670 Mode. We simulate a square-cellular topology with $4 * 4 =$
 671 16 APs (i.e., 16 cells). The size of each cell is $175 \text{ m} * 175 \text{ m}$,
 672 and $d_{\max} = 175/\sqrt{2} \text{ m} \approx 123.8 \text{ m}$. Around 64 clients are
 673 randomly placed with a uniform probability distribution. Each
 674 client is associated with the nearest AP and sends a saturated
 675 flow to the AP. Two settings are simulated: “RS mode w/ differ-
 676 ent PCSs” and “IEEE 802.11.” The results are shown in Fig. 11.
 677 In the first set of curves, RS mode is enabled (as in HFD), but
 678 PCS may or may not meet the requirement of General HFD.
 679 When PCS = 470 m, the requirement of General HFD is met
 680 ($470 \text{ m} > 3.78 d_{\max}$). We progressively decrease PCS below
 681 the requirement of General HFD to see its effect on EN and
 682 HN. In the “IEEE 802.11” curves, there is no “RS mode.”
 683 We use “total throughput” as an indication of EN—Lower
 684 EN leads to higher throughput (higher HN can also lead to
 685 throughput degradation, but it is secondary compared to EN)
 686 and uses MAC-layer “collision probability” as an indication
 687 of HN (since HNs lead to heavy packet collisions). Also, as
 688 discussed earlier, HN causes unfairness problem. Therefore,
 689 we compute the Jain’s Fairness Index to quantify the fairness
 690 among individual throughputs of all the flows.

691 There are three key observations from Fig. 11.

- 692 1) As expected, when PCS decreases, EN decreases and HN
 693 increases (therefore fairness decreases too) in both curves
 694 (“RS mode w/ different PCSs” and “IEEE 802.11”). In
 695 other words, the EN–HN tradeoff exists in both curves
 696 [Fig. 11(a) and (b)].
- 697 2) With the same PCS setting, “RS mode w/ different PCSs”
 698 always gives a higher throughput and a lower collision
 699 probability than “IEEE 802.11” [Fig. 11(a)]. Although we
 700 started out to remove HN in this paper, in practice, one
 701 can relax the requirement of PCS to achieve a tradeoff
 702 between EN and HN. The overall performance of our
 703 proposed design, however, is always better than IEEE
 704 802.11 with the same PCS setting.
- 705 3) The tradeoff between EN and HN is manifested as a
 706 tradeoff between throughput and fairness [see Fig. 11(b)].
 707 There are also other minor observations. 1) Note that the
 708 “floor” collision probability in General HFD (when PCS =
 709 470 m in the “RS mode w/ different PCSs” curve) is about
 710 7%. These MAC-layer collisions are due to the fact that

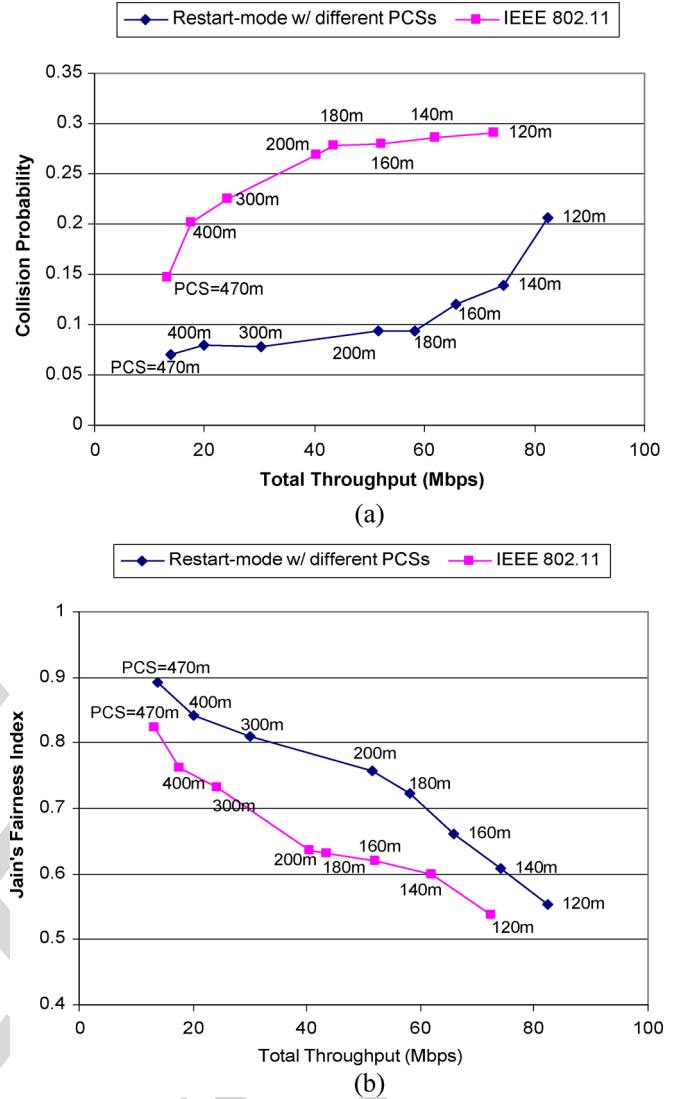


Fig. 11. Tradeoff between EN and HN. (a) Tradeoff between throughput and collision probability (the label beside each point shows the corresponding PCS value). (b) Tradeoff between throughput and fairness.

backoff timers of different nodes may still choose the same
 711 random number in a contention window even if HN is removed.
 712 However, this kind of collisions will not cause trouble since
 713 consecutive collisions (as in HN) are not likely due to the
 714 random backoff algorithm in 802.11. 2) With “RS mode w/
 715 different PCSs” in this particular simulation, PCS larger than
 716 300 m seems to have eliminated HN considerably. This is
 717 because when the clients are randomly located (and not very
 718 dense), most link distances are smaller than d_{\max} .
 719

In RTS/CTS mode, our related research has shown that
 720 EN can be effectively reduced compared to the Basic Access
 721 Mode. That scheme combines HFD for RTS/CTS mode and
 722 an EN-reducing algorithm called “Selective Disregarding of
 723 NAVs (SDN)” [15]. SDN enables each node to selectively
 724 disregard “false-alarming” RTS/CTS from links that actually do
 725 not interfere with its transmissions. This cannot be achieved in
 726 the Basic Access Mode because without RTS/CTS, PHY header
 727 gives no address information. Interested readers are referred to 728

729 [15] for the scheme combining HFD and SDN. The tradeoff
730 between EN and HN still exists in that scheme.

731

VII. CONCLUSION

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

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

750 We have adapted the HFD principle for application in large-
751 scale WiFi cellular networks consisting of many adjacent
752 WLANs (a popular form of 802.11 deployments). We have
753 designed variations of HFD beyond the General HFD. One
754 version is “HFD with nonuniform PCS,” in which the PCSs
755 of different links are varied and minimized according to their
756 surroundings. Such individual PCS minimization reduces ENs
757 and increases spectrum spatial reuse. We have shown that the
758 total throughput can be increased by about 100% with this
759 design (see Fig. 10 for the case where number of channels
760 $N = 1$).

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

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

780

APPENDIX A

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

A. Constraints for Simultaneous Transmissions in 802.11

783

To understand the requirements of HFD, we need to first
784 understand the fundamental causes of HN. There are two types
785 of constraints concerning simultaneous transmissions in an
786 802.11 wireless network, as discussed below. 787

1) *802.11—Carrier-Sensing Constraints:* In the Basic Ac-
788 cess Mode, only PCS needs to be considered. For PCS, the
789 PHY header is decoded. The length field in the PHY header
790 informs the receiver of the duration of the payload that follows.
791 Consider two links i and j with senders and receivers T_i ,
792 T_j , R_i , and R_j , respectively. For brevity, we will also use
793 T_i , T_j , R_i , and R_j to denote their positions in the following
794 discussion. 795

Simultaneous transmissions on the two links are allowed
796 when 797

$$|T_i - T_j| > \text{PCS}. \quad (16)$$

However, the simultaneous transmissions will fail unless 798

$$|T_i - R_j| > \text{PCS} \quad (17)$$

$$|R_i - T_j| > \text{PCS}. \quad (18)$$

This is due to the “receiver capture” effect in most 802.11
799 products. If (17) is not true when T_i starts a DATA transmission
800 first, followed by T_j , then R_j will not attempt to receive the
801 DATA from T_j because it is in the process of receiving the
802 ongoing signal from T_i . Transmission on link j therefore fails.
803 Similar argument applies for (18). 804

2) *Physical No-Collision Constraints:* We now consider un-
805 der what conditions will there be no physical collision between
806 simultaneous transmissions over links i and j . Define $d_i =$
807 $|T_i - R_i|$ and $d_j = |T_j - R_j|$. Since each “atomic information
808 exchange” over an 802.11 link consists of two-way traffic,
809 DATA followed ACK in the reverse direction, the conditions
810 for the two transmissions not interfering with each other are as
811 follows [14]: 812

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

where $P(d)$ is the received power as a function of dis-
813 tance. It is a simplified form of $P(P_t; d)$ when we
814 assume that all the nodes use the same transmission
815 power P_t . 816

The first inequality on the left in (19) says that the DATA
817 signal on link j should be sufficiently small when it reaches the
818 receiver of link i compared with the DATA signal on link i ;
819 the second inequality on the left is for DATA on link j not
820 interfering with ACK on link i ; and so on [14]. As mentioned in
821 Section II, assuming the power propagation function in (1), (19)
822

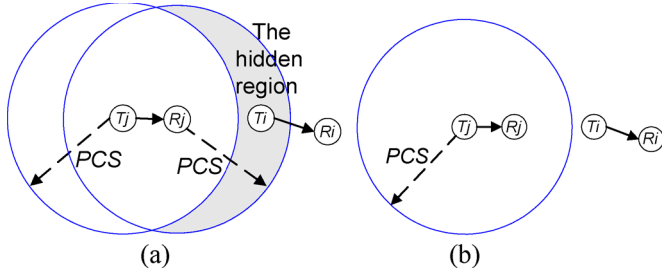


Fig. 12. (a) HN due to (17) and (18), and (b) RS mode removes the HN.

823 can be transformed into inequalities among distances instead of
824 power levels.⁶

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

825 3) *Goal of HFD*: Following the above discussion, HN can
826 arise out of two situations—When (16) is satisfied, the follow-
827 ing situations happen.

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

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

833 B. Proof of HFD for IEEE 802.11 Basic Access Mode

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

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

850 RS mode can be used to remove constraints (17) and (18).
851 Recall that with RS mode, when the power of a later-arriving
852 packet is more than C_t times that of the earlier packet, the
853 receiver switches to receive the stronger new packet. Thus, as
854 long as the SIR is sufficient, the order of transmissions does not
855 matter. Essentially, (17) and (18) will then be replaced by the

⁶All 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 $P(d_{\max}) \geq C_t P(\text{PCS} - 2d_{\max})$.

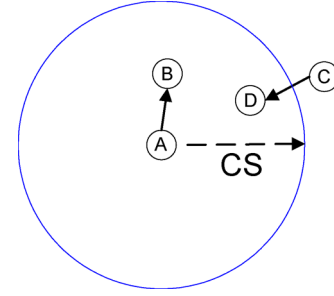


Fig. 13. Interaction of a pair of links.

same constraints as in (20), and consideration of (20) without
856 (17) and (18) is sufficient for our HFDs. 857

858 2) *Receive-Power Inequality*: With RS mode, we now only
859 need to make (16) sufficient for (20). Consider Fig. 13. Suppose
860 that A is transmitting a DATA to B, and C intends to transmit a
861 DATA to D. To avoid HN, the following must be true: 861

862 For any link (C, D) in the neighborhood of link (A, B) where
863 nodes A and C cannot carrier-sense each other, constraint (20)
864 must be satisfied. That is, there must not be any of the
865 following: 865

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

869 *Sufficient condition for satisfying constraints (20)*: Use of
870 receiver RS mode plus $\text{PCS} \geq (3 + \Delta)d_{\max}$. 870

871 *Proof for 3)*: We only present the proof for 3). The proofs
872 for 1) and 2) are similar. Suppose we assume the contrary:
873 DATA–ACK collisions occur at B or D in spite of the use of RS
874 mode and $\text{PCS} \geq (3 + \Delta)d_{\max}$. With respect to Fig. 13, since
875 A and C cannot sense each other, we have 875

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

876 First, suppose that DATA from A to B collides with D's ACK
877 at B. With RS mode, the order of arrivals of the DATA and ACK
878 at B does not matter. In order that there is collision, SIR at B
879 must be insufficient. Equivalently 879

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

880 From (21), we have 880

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

881 Using triangular inequality 881

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

882 We have 882

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

883 From (23) and (24), we have 883

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

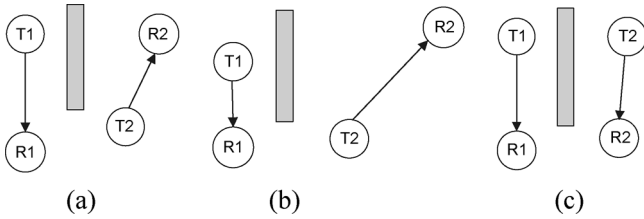


Fig. 14. HN induced by obstructions.

884 According to (22), we have

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

885 From (25) and (26), we have

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

886 However, this contradicts with the condition $PCS \geq (3 +$
887 $\Delta)d_{\max}$.

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

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

890

APPENDIX B

891 A. Discussion of HN Induced by Obstructions

892 In some cases involving obstructions (instead of regular
893 power propagation), the HN problem becomes more compli-
894 cated, and we may need additional mechanisms to alleviate HN.
895 Consider the scenario in Fig. 14(a). There is an obstruction be-
896 tween T1 and T2, but not between R1 and R2. The obstruction
897 leads to a sharp drop of signal strength, and here, we assume
898 that the "channel gain" between T1 and T2 is zero. Even with
899 HFD for the Basic Mode, when T1 is transmitting a DATA
900 packet to R1, T2 cannot sense it and may transmit packets and
901 corrupt T1's packet at R1 (T2 is the HN). With the RTS/CTS
902 mode, the situation is better since T2 can still hear R1's CTS.
903 However, if T2 transmits an RTS first, T1 cannot receive it and
904 may go ahead to send an RTS to R1, which may lead to a failure.

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

921 1) The HN (T2 in the above example) will send an RTS
922 before transmitting DATA. The targeted receiver of the
923 HN (R2) will wait for a period of SIFS + RTS + SIFS
924 before replying a CTS.

2) The nontargeted receiver above (R1) will relay the RTS to
925 its transmitter (T1). The transmitter will not send DATA
926 to the receiver during the NAV. 927

The protocol may not completely avoid collisions since
928 multiple nodes may try to relay the RTS, leading to relay-RTS
929 collision. An algorithm is needed to elect a representative node
930 to relay the RTS. The details are an interesting subject for future
931 study. 932

There are also other scenarios to consider. In Fig. 14(b),
933 assume that T2's transmission does not cause insufficient SIR
934 at R1 (i.e., with "RS mode," R1 can always receive T1's
935 transmissions), but R1's transmission causes insufficient SIR at
936 T2 (i.e., R1's transmission can corrupt the ACK from R2). The
937 relay scheme above still applies here, but it generates additional
938 RTS/CTS packets. An alternative is to use "Delayed ACK"
939 operated in the Basic Mode (no RTS/CTS is needed), which
940 is described as follows. 941

Since T1 and T2 cannot sense each other, they may be
942 transmitting DATA packets at the same time. After R1 finishes
943 receiving, its ACK may interfere with link 2. The idea of
944 "Delayed ACK" is to let R1 do carrier sensing before returning
945 an ACK, instead of sending ACK immediately after SIFS. If
946 R1 senses no transmission (after receiving DATA from T1),
947 it delays its ACK by SIFS+ACK (in case R2 is returning
948 an ACK to T2); if R1 senses a transmission, it waits until
949 the transmission ends and delays its ACK for an additional
950 SIFS+ACK. Meanwhile, T1 is not aware of the delay and
951 may go into exponential backoff. However, immediately after it
952 receives the delayed ACK from R1, T1 gets out of the backoff
953 state so that it does not need to continue to count down. We
954 note in passing that 802.11e has some sort of a delayed ACK
955 feature. Delayed ACK, however, does not entirely avoid T1's
956 retransmission if the ACK is delayed too much. 957

Another scenario is shown in Fig. 14(c) in which the ACK
958 from either R1 or R2 may interfere with the other link. In
959 addition, R1 and R2 cannot sense the transmissions of T2
960 and T1, respectively. "Delayed ACK" does not apply here,
961 and we have to fall back to the Relay scheme—In this sce-
962 nario, R1 relays the CTS from R2 to T1, and vice versa.
963 In the Relay scheme, since either RTS or CTS needs to be
964 relayed in different scenarios, we also call it "RTS/CTS Relay
965 scheme." 966

A strategy is to combine the delayed-ACK scheme with the
967 RTS/CTS Relay Scheme. Since the RTS/CTS Relay Scheme
968 is more expensive (i.e., it requires RTS/CTS, which may be
969 further duplicated and relayed), it should be used only as an
970 alternative when "Delayed ACK" algorithm does not work. The
971 above has only sketched a plausible solution for HN that is
972 caused by obstructions. This subject certainly deserves more
973 careful investigations in the future. 974

APPENDIX C

975

A. PE Algorithm for Discovering InRs

976

To construct the InRs, each node A periodically broadcasts
977 special PE packets and receives PE packets from nearby nodes.
978 The transmission power for PE packets is the same as that for
979

980 regular packets, and we assume that all nodes use the same
981 transmit power and receiver sensitivity.

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

992 A point to note about the PE algorithm is that they are not
993 the same as RTS/CTS packets and are not used for carrier-
994 sensing purposes. They are special packets used for distributed
995 discovery of InRs. Also, the PE packets need to be transmitted
996 only when the network topology or conditions have changed.
997 The periodic transmissions of PE packets above are mainly
998 for simplification and to make the algorithm more robust.
999 When nodes are not highly mobile, PE packets introduce little
1000 overhead because the broadcast period can be long.

1001 B. Condition for Correct Operation of PE

1002 The following condition is sufficient to ensure that a node
1003 can discover all the InRs relevant to itself:

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

1004 or

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

1005 where PERange is the transmission range of the PE packets.

1006 *Note:* To meet (28), PE packets must be transmitted at a
1007 sufficiently low rate, such as that used by RTS/CTS packets.

1008 *Proof:* Consider three nodes: Nodes A and B form links
1009 (A, B) and (B, A) ; and node C forms links with other nodes.
1010 Without loss of generality, assume that $P(A, B) < C_t P(C, B)$
1011 so that the transmission by C can interfere with reception at B .
1012 We want to show the following: 1) nodes A and B , and 2) node
1013 C and any other node D that forms link with C can find out the
1014 existence of this InR.

1015 *Proof of 1):* By definition, we have $|A - B| \leq d_{\max}$. If
1016 (28) holds, we have

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

1017 The above implies that $\text{PERange} - d_{\max} > |C - B|$, since
1018 $P(\cdot)$ is a decreasing function of distance. Therefore

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

1019 and

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

This means that, if $P(A, B) < C_t P(C, B)$, then the PE pack-
1020 ets of C can reach A and B . By measuring the received
1021 power of C 's PE packets and checking their source address to
1022 identify the sender, B can derive C and $P(C, B)$. Similarly,
1023 B can derive A and $P(A, B)$ from A 's PE packets. Therefore,
1024 B can find out that $P(A, B) < C_t P(C, B)$ and, hence, the
1025 existence of InR between link $(A, B)/(B, A)$ and any other
1026 link with C being the transmitter or receiver—Note that these
1027 links are contained in the active link list in C 's PE packets
1028 received by B .
1029

Now, the PE packets of B contain information on
1030 $[C, P(C, B)]$ and $[A, P(A, B)]$. Upon receiving B 's PE pack-
1031 ets, A can also find out that $P(A, B) < C_t P(C, B)$ and, hence,
1032 the existence of InR between link $(A, B)/(B, A)$ and any other
1033 link with C being the transmitter or receiver—Note that these
1034 links are contained in the active link list in C 's PE packets
1035 received by A .
1036

Proof of 2): From the proof of 1), we have $\text{PERange} -$
1037 $d_{\max} > |C - B|$. Therefore
1038

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

and

1039

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

Thus, the PE packets of B , which contain $[C, P(C, B)]$,
1040 $[A, P(A, B)]$, and active links (A, B) and (B, A) can reach C
1041 and any node D that forms link with C , from which they can
1042 discover the associated InRs.
1043

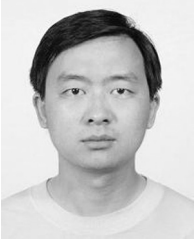
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AUTHOR QUERIES

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”.

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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.

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PROOF

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.

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 LANs (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)

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87 range¹ is larger than the link distance (transmitter–receiver
 88 distance) plus the interference range (IR),² HN can be removed,
 89 and RTS/CTS (which implements virtual carrier sensing) is
 90 no longer needed. A recent work [3] gives a similar result.
 91 According to our “link-based” analysis in this paper, however,
 92 this condition is not sufficient for the elimination of HN in
 93 general.

94 References [4]–[6] extended the investigation in [1]. In par-
 95 ticular, the “self-HN interference” phenomenon of a single
 96 multihop traffic flow was studied. The successive packets of
 97 the same traffic flow may self-interfere among themselves as
 98 they hop from node to node. Detailed explanations on how
 99 self-HN interference causes throughput degradation as well as
 100 triggers the rerouting instability phenomenon were given in
 101 [5]–[8]. However, the studies in [4]–[8] only provided solutions
 102 to alleviate “symptoms” of HN, and these solutions do not
 103 remove the “root” of the problem: the HN itself. In contrast,
 104 this paper focuses on solutions that remove HN.

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

117 II. HIDDEN-NODE-FREE DESIGN (HFD)

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

123 A. Definition and Examples

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

127 1) *Definition of HN*: Link i is said to be hidden from link j if
 128 the following conditions are true. 1) T_j cannot carrier-sense the
 129 transmission on link i , and 2) link i may cause transmission fail-
 130 ures on link j , or vice versa, so that transmission on at least one
 131 of the links will fail when both links transmit simultaneously
 132 (Note that by “simultaneous,” we refer to the situation when
 133 the transmissions by different nodes overlap in time. Their

¹This 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.

²A 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.

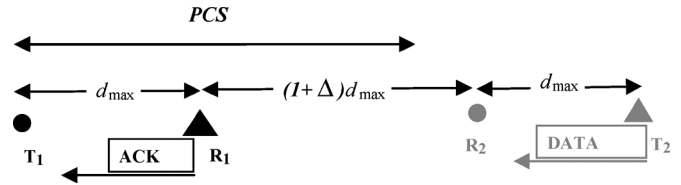


Fig. 1. PCS not sufficiently large leads to HN due to insufficient SIR.

transmissions may actually be initiated at different instances so
 that the start times of the transmissions are different).

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) SIR³ 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 trans-
 mitter 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

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

³SIR 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.

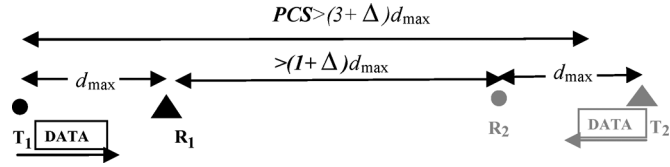


Fig. 2. Lack of receiver “RS mode” leads to HN no matter how large PCS and SIR are.

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

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

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

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

217 This HN problem can be solved with a receiver “RS mode”
 218 which can be enabled in some 802.11 products (e.g., Atheros
 219 WiFi chips). With RS mode, a receiver will switch to receive the

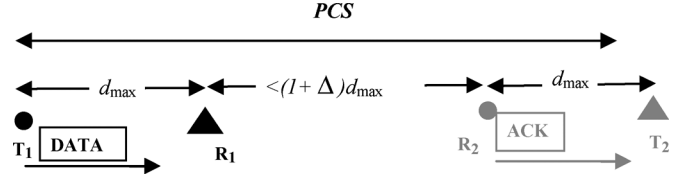


Fig. 3. With RS mode, PCS not sufficiently large still leads to HN due to insufficient SIR.

stronger packet as long as its power is C_t times⁴ higher than the
 220 current packet. If the new packet is an 802.11 DATA targeted
 221 for it, the node will reply with an ACK after Short InterFrame
 222 Space (SIFS), whether the medium around this node is idle
 223 or not. 224

4) *Example 3—Simultaneous Transmissions, Receiver RS*
 225 *Mode, and Insufficient SIR:* One might wonder, given the
 226 example in Fig. 2, why the default receiver operations of all
 227 commercial products and the NS2 simulator do not assume
 228 RS mode. The reason is that, without a sufficiently large PCS,
 229 enabling RS mode may lead to HN collisions, as described
 230 below. 231

RS mode alone cannot prevent HN without a $PCS > (3 + 222$
 $\Delta)d_{\max}$. To see this, consider the example in Fig. 3, where
 233 $PCS < (3 + \Delta)d_{\max}$ and $|R_1 - R_2| < (1 + \Delta)d_{\max}$. Assume
 234 that T_1 transmits a DATA to R_1 first. During the DATA’s period,
 235 T_2 starts to send a shorter DATA packet to R_2 . With RS mode,
 236 R_2 switches to receive T_2 ’s DATA and sends an ACK after
 237 the reception. If T_1 ’s DATA is still in progress, R_2 ’s ACK will
 238 corrupt the DATA at R_1 . 239

Therefore, it is not advisable to use RS mode if PCS is not
 240 large enough, which is the case in most commercial products.
 241 The NS2, which simulates operations in commercial products,
 242 for example, assumes $PCS = 2.2$ times the maximum transmis-
 243 sion range (TxRange) of DATA. If d_{\max} , which is the maximum
 244 link length allowed in the network, is set to TxRange, then
 245 such HN collisions will inevitably occur. As a result, most
 246 commercial products do not use RS mode by default. However,
 247 without RS mode, HN collisions like that in Fig. 2 inevitably
 248 occur. Either way, HN occurs. 249

B. HFD for Basic Access Mode 250

From the above examples, we summarize the requirements
 251 for a HFD for basic mode in IEEE 802.11. It includes two
 252 requirements. 253

- 1) A range requirement 254

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

If $C_t = 10$, and $\alpha = 4$ 255

$$PCS \geq 3.78d_{\max} \quad (3)$$

- 2) and the receiver’s RS mode. 256

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

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

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

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

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

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

309 To further elaborate on the implementation details, in prac-
 310 tice, PCS and d_{\max} are determined by the transmission power
 311 P_t and receiving thresholds. We can write

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

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

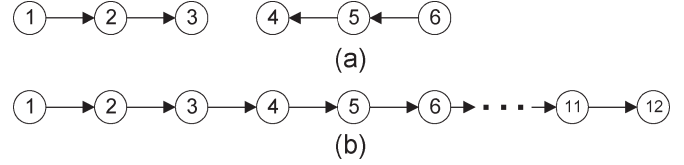


Fig. 4. Traffic flows that can give rise to HN.

where P_{link} is the received power threshold we impose for
 link establishment. A link will not be set up during the ini-
 tial 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 dif-
 ferent 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 tun-
 ing P_{link} (if we keep P_t unchanged). For example, if we
 want $\text{PCS} = 3.78d_{\max}$, with the assumption of two-ray ground
 model with the “path loss exponent” $\alpha = 4$, (4) and (5) become

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

$$A \frac{P_t}{\text{PCS}^4} = P_{\text{PCS}} \quad (7)$$

where A is a constant [12]. Therefore

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

or

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

III. REMOVAL OF HN PERFORMANCE PROBLEMS

“TCP unfairness” and “rerouting instability” are two perfor-
 mance 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.

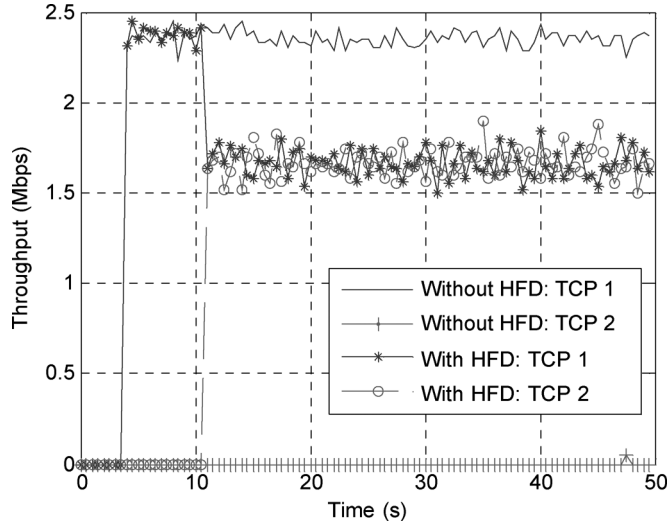


Fig. 5. TCP unfairness (fairness) without (with) HFD.

347 A. TCP Unfairness

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

359 B. Rerouting Instability

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

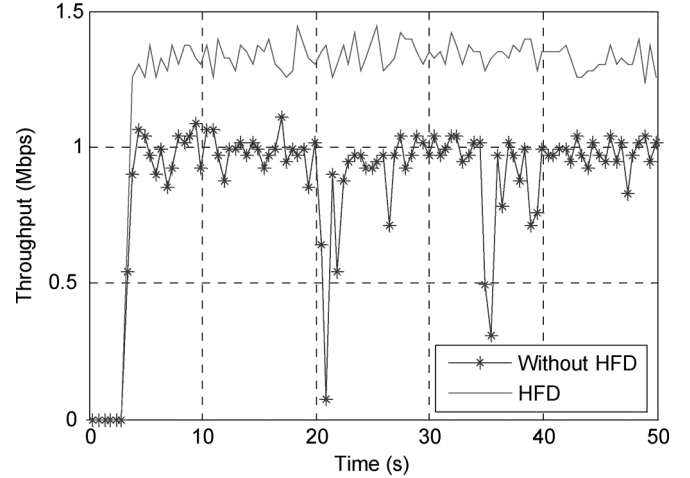


Fig. 6. Throughput instability (stability) of an 11-hop UDP flow without (with) HFD.

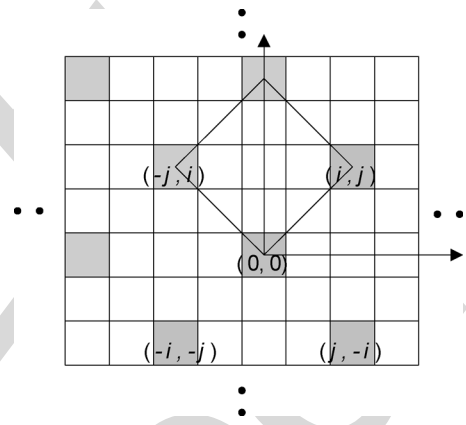


Fig. 7. Channel assignment ($N = 8$) with square cells.

373 IV. CHANNEL ASSIGNMENT IN WiFi 374 CELLULAR WITH HFD

375 There are three orthogonal channels for 802.11b/g and eight
 376 orthogonal channels for 802.11a. When multiple WLANs are
 377 deployed to form a large WiFi cellular network, there is the
 378 issue of how to assign these channels to the different WLANs
 379 while keeping the network free of HN. On one hand, channel
 380 assignment can separate cells with the same channel further
 381 apart so that intercell physical interference can be reduced

or totally eliminated, relaxing the HFD's requirements on the
 382 carrier-sensing range. On the other hand, more spectrum re-
 383 sources (channels) will be used. Thus, an issue is whether a
 384 careful channel assignment can yield better spectrum efficiency
 385 or not while ensuring no HN in the network. We address
 386 this issue by examining possible channel assignment schemes
 387 systematically.

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

401 A. Channel Assignment

402 In a regular topology, we can assign the channels in a regular
 403 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

404 is well known [12]. If a cell is in the form of a square, by
405 emulating the channel assignment for hexagon cells, we can
406 assign a channel as in Fig. 7 (the gray cells use the same
407 channel). We denote by (i, j) the “offsets” (in two axes) of
408 one of the four adjacent cells that use the same channel as cell
409 $(0, 0)$, where $i \geq 0$, and $j \geq 0$. As illustrated in Fig. 7, for cell
410 $(0, 0)$, the four adjacent cells are cells (i, j) , $(-j, i)$, $(-i, -j)$,
411 and $(j, -i)$.

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

418 For an offset assignment (i, j) , the number of frequency
419 channels used to fill the whole WiFi cellular network is $N =$
420 $i^2 + j^2$. To see this result, consider the square formed by
421 the APs at cells $(0,0)$, (i, j) , $(i - j, j + i)$, and $(-j, i)$. With
422 reference to Fig. 7, the area of the square is $i^2 + j^2$. Within
423 this square, an area of one unit is covered by the gray color.
424 The whole plane can be divided by similar squares described
425 above. If we omit the boundary effect (assume that the plane
426 is infinitely large), one channel can cover $1/(i^2 + j^2)$ of the
427 whole plane. Therefore, $N = i^2 + j^2$ channels are needed.

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

- 438 1) There is no protocol interference or physical interference
439 between adjacent cells using the same channel. With this
440 design, transmissions on cells are independent.
- 441 2) There is protocol interference, but no physical interfer-
442 ence between adjacent cells using the same channel. In
443 this case, the carrier-sensing mechanism may be overly
444 aggressive so that legitimate simultaneous transmissions
445 on different cells may be prevented by the protocol
446 operation.
- 447 3) There is physical interference between adjacent cells
448 using the same channel. With this design, some simul-
449 taneous transmissions on different cells need to be pre-
450 vented. Therefore, to avoid HN (with HFD), there must
451 be protocol interference.

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

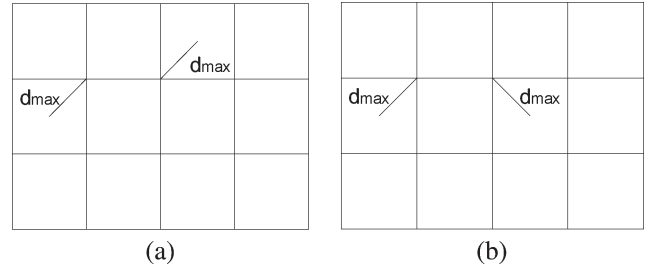


Fig. 8. Minimum distance between two cells. (a) $i > 0$, $j > 0$. (b) $i > 0$, $j = 0$.

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

454 For DA1, two transmissions on adjacent cells using the same
455 channel must not physically interfere with each other. A certain
456 minimum number of channels (N_{\min}) are required to guarantee
457 this. Consider Fig. 8, d_{\max} is the distance between the AP at
458 the center of a cell and a client at the corner of the cell. The
459 two cells in consideration use the same channel. Without loss of
460 generality, we assume that $i \geq 1$, and $j \geq 0$ (since i, j cannot be
461 both zero). In Fig. 8(a), where $i = 2$ and $j = 1$ (generally, when
462 $i, j > 0$), the distance between the two corners (i.e., between
463 the two clients) is $\sqrt{(i-1)^2 + (j-1)^2}$; in Fig. 8(b), where
464 $i = 2$ and $j = 0$ (generally, when $i > 0$, $j = 0$), the distance
465 is $\sqrt{(i-1)^2 + 0^2}$. Combining the two cases, the distance
466 between the two closest corners of two adjacent cells which use
467 the same channel is $\sqrt{(i-1)^2 + [\max(j-1, 0)]^2}$. Now, this
468 distance must be larger than the IR. Therefore, we require
469

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

470 Now, $d_{\max} = 1/\sqrt{2}$. Assuming $\Delta = 0.78$ [as in (3)], the
471 offsets (i, j) that satisfy this requirement are
472

$$(1, 3), (1, 4), \dots, (2, 2), (2, 4), \dots, (3, 0), (3, 1), \dots$$

473 Requirement (9) is the no-physical interference requirement.
474 Given this requirement, carrier sensing still needs to work
475 properly if simultaneous transmissions on adjacent cells are to
476 be allowed. Specifically, we require
477

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

478 where PCS is the PCS range. The lower bound on PCS in
479 (10) is to ensure that carrier sensing works properly to prevent
480 simultaneous transmission within the same cell. The maximum
481 distance between two wireless stations in the same cell is
482 $2d_{\max}$. The upper bound on PCS in (10) ensures that a station
483 does not sense other stations in adjacent cells. There is no need
484 for sensing beyond a cell since (9) ensures that there is no
485 interference beyond a cell.

486 Note that PCS can be adjusted by tuning the receiver sensitiv-
ity for carrier sensing while maintaining the same transmission

487 power. Generally, the maximum PCS PCS_{\max} is defined by the
488 transmission power and the lowest received power required to
489 decode the PHY header. If we want to make actual operating
490 PCS smaller than PCS_{\max} , the following two requirements
491 must both be satisfied before PCS is triggered.

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

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

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

$$(1, 3), (1, 4), \dots, (2, 4), \dots, (3, 0), (3, 1), \dots$$

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

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

505 C. Design Alternative 2 (DA2): No Physical Interference, But 506 With Protocol Interference Among Adjacent Cells

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

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

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

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

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

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

D. Design Alternative 3 (DA3): With Physical Interference Among Adjacent Cells 531 532

For DA3, adjacent cells using the same channel may physi- 533
cally interfere with each other. That is, (9) is not satisfied 534

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

The offsets that satisfy (14) are 535

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

Therefore, we see that the channels used are 536

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

Note that $N \leq 5$ is due to the particular regular (i, j) channel 537
assignment strategy we assume. There could be other cell 538
assignments that yield different results of N . 539

Design Alternatives 1 and 2 are HN-free if $PCS \geq 2d_{\max}$. 540
The next few sections consider different ways of setting PCS 541
for DA3 to make it HN-free. 542

1) *General HFD*: According to (2), the general HFD 543
requires 544

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

Inequality (15) is independent of the network topology. In a 545
given topology, however, it may be overkill because each node 546
adopts the PCS range for “the worst case.” 547

2) *HFD With Nonuniform PCS*: General HFD can remove 548
HN, but without considering the actual topology. If we take 549
the actual link layouts into consideration and allow the PCS 550
range to vary from node to node [relaxing the requirement 551
in (15)], EN can be reduced by allowing more noncolliding 552
transmissions to proceed simultaneously. 553

Note that, in previous sections, “PCS” is defined from the 554
perspective of a transmitter. That is, with respect to a transmit- 555
ter, its transmission will prevent all the nodes within its PCS 556
range from transmitting. In this section, however, we define 557
“PCS” from the perspective of a receiver. That is, a node will be 558
prevented from transmitting by the transmission from any node 559
within its PCS range. 560

For clarity, we use “ PCS^T ” to denote PCS with respect 561
to transmitters, and “ PCS^R ” to denote PCS with respect to 562
receivers. If all nodes transmit at the same power (P_t), the 563
 PCS^R of a node a , $PCS^R(a)$, is only related to its receiver 564
sensitivity for carrier-sensing purposes. Clearly, for uniform 565
PCS in the previous section, $PCS^T = PCS^R$, since all the nodes 566
have the same transmit power and carrier-sensing sensitivity. 567

In this section, we assume that all nodes use the same trans- 568
mit power and data rate. In the following algorithm, each node 569
computes the PCS^R it should assume in its receiver design. 570

3) *HFD With Nonuniform PCS*: For any node a 571

- 1) Denote the set of links whose sender is node A 572
by $L(A) = \{a_1, a_2, a_3, \dots, a_n\}$. Denote the set of 573
links which has an “interference relationship” (“InR”) 574
with link k by $I(k)$ [links that are either physically 575

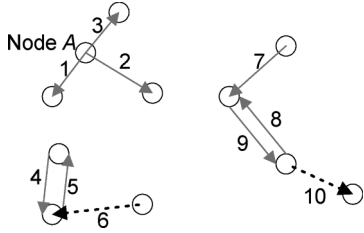


Fig. 9. Node A 's interference link set $M(A) = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$.

576 interfered by link k or vice versa. As detailed in
 577 Appendix A, there is “InR” between links i and j if
 578 any inequality in (19) or (20) is NOT true]. Define
 579 node A 's “interference link set,” $M(A) = I(a_1) \cup$
 580 $I(a_2) \cup I(a_3) \cup \dots \cup I(a_n)$.

- 581 a) For example, in Fig. 9, $L(A) = \{1, 2, 3\}$, $I(1) =$
 582 $\{2, 3, 4, 5\}$, $I(2) = \{1, 3, 7, 8, 9\}$, and $I(3) =$
 583 $\{1, 2\}$. Therefore, $M(A) = \{1, 2, 3, 4, 5, 7, 8, 9\}$.
 584 These links have been marked with red color.
 585 b) For each node to find out the necessary information
 586 about InRs, a “Power-Exchange Algorithm” (PE)
 587 is used, which is explained in the Appendix C.
 588 2) PCS of node A is computed as $PCS^R(A) =$
 589 $\max_{k \in M(A)} (|A - T_k|)$, where link k is a member
 590 of $M(A)$, and T_k is the sender of link k . Set the
 591 receiver carrier-sensing threshold of node A according
 592 to $PCS^R(A)$.⁵

593 Note that to obtain the distance $|A - T_k|$, A should be able
 594 to decode the PE packets (to be explained in Appendix C)
 595 from T_k and, thus, deduce the distance from the power of
 596 the received packet $P(T_k, A)$. Therefore, we set $PERange \geq$
 597 $(3 + \Delta)d_{max}$ here.

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

611 V. NUMERICAL RESULTS

612 In this section, we give the NS2 simulation results of a
 613 square-cellular topology under different design alternatives
 614 (simulations of a hexagon-cellular topology yield very sim-
 615 ilar results [11]). The square-cellular network has $10 * 10 =$
 616 100 APs (see Fig. 7). The size of each cell is $205 \text{ m} * 205 \text{ m}$.

⁵With 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)].

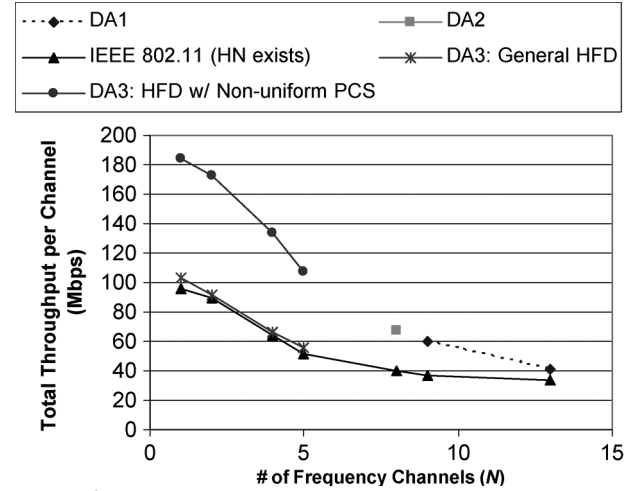


Fig. 10. Throughput per channel for different HFD Design Alternatives (“DA”) in square-cellular networks.

Therefore, $d_{max} = 205/\sqrt{2}$ m. We ensure that $d_{max} \leq 617$
 TxRange (i.e., the maximum transmission range). Around 400 618
 clients are randomly placed in this area with a uniform distrib- 619
 ution. Each client is associated with the nearest AP and sends a 620
 saturated traffic flow to the AP. The results are shown in Fig. 10. 621

In Fig. 10, for IEEE 802.11, PCS = 550 m, but “RS mode” 622
 is not enabled; therefore, it is not HN-free. For other cases, “RS 623
 mode” is enabled, and PCS is set in such a way as to ensure an 624
 HN-free property. 625

As discussed in Section IV, DA1 corresponds to $N > 8$, and 626
 DA2 corresponds to $N = 8$. In both cases, we set PCS = $2d_{max}$ 627
 (the minimum requirement). We obtained the throughput per 628
 channel C for different values of N . That is, C is the total 629
 throughput divided by N . As shown in Fig. 10, for $N \geq 8$, C 630
 decreases as N increases. In fact, the total throughput ($C * N$) 631
 is roughly constant for $N \geq 8$. This implies that DA1 and DA2 632
 do not put extra frequency channels to good use, and it is not 633
 advisable to insist on having no physical interference among 634
 cells using the same channels. 635

DA3 is adopted when $N < 8$. In this case, simulations 636
 with two different HFDs—General HFD [with PCS = 550 m, 637
 slightly larger than $(3 + \Delta)d_{max}$, so that General HFD and 638
 802.11 in the simulations only differ by RS mode being en- 639
 abled in General HFD] and HFD w/ nonuniform PCS—were 640
 carried out. 641

As shown in Fig. 10, for $N < 8$, “HFD w/ nonuniform PCS” 642
 significantly improves C compared to “General HFD.” This 643
 is because “HFD w/ nonuniform PCS” takes into account the 644
 actual topology and InRs, while “General HFD” tries to remove 645
 HN for “the worst case.” In an actual topology where clients 646
 are randomly located, the lengths of some links may be much 647
 smaller than d_{max} , and “the worst case,” as shown in Fig. 1, 648
 may not appear. This relaxes the requirement of PCS, and the 649
 nonuniform PCS design takes advantage of this to reduce ENs 650
 and increases the capacity. 651

The overall results in Fig. 10 also indicate that careful assign- 652
 ment of frequency channels for different cells usually cannot 653
 improve the capacity of such cellular WiFi networks. If there 654

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

660 VI. TRADEOFF BETWEEN HN AND EN

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

669 To illustrate this point, we first consider the Basic Access
 670 Mode. We simulate a square-cellular topology with $4 * 4 =$
 671 16 APs (i.e., 16 cells). The size of each cell is $175 \text{ m} * 175 \text{ m}$,
 672 and $d_{\max} = 175/\sqrt{2} \text{ m} \approx 123.8 \text{ m}$. Around 64 clients are
 673 randomly placed with a uniform probability distribution. Each
 674 client is associated with the nearest AP and sends a saturated
 675 flow to the AP. Two settings are simulated: “RS mode w/ differ-
 676 ent PCSs” and “IEEE 802.11.” The results are shown in Fig. 11.
 677 In the first set of curves, RS mode is enabled (as in HFD), but
 678 PCS may or may not meet the requirement of General HFD.
 679 When PCS = 470 m, the requirement of General HFD is met
 680 ($470 \text{ m} > 3.78 d_{\max}$). We progressively decrease PCS below
 681 the requirement of General HFD to see its effect on EN and
 682 HN. In the “IEEE 802.11” curves, there is no “RS mode.”
 683 We use “total throughput” as an indication of EN—Lower
 684 EN leads to higher throughput (higher HN can also lead to
 685 throughput degradation, but it is secondary compared to EN)
 686 and uses MAC-layer “collision probability” as an indication
 687 of HN (since HNs lead to heavy packet collisions). Also, as
 688 discussed earlier, HN causes unfairness problem. Therefore,
 689 we compute the Jain’s Fairness Index to quantify the fairness
 690 among individual throughputs of all the flows.

691 There are three key observations from Fig. 11.

- 692 1) As expected, when PCS decreases, EN decreases and HN
 693 increases (therefore fairness decreases too) in both curves
 694 (“RS mode w/ different PCSs” and “IEEE 802.11”). In
 695 other words, the EN–HN tradeoff exists in both curves
 696 [Fig. 11(a) and (b)].
- 697 2) With the same PCS setting, “RS mode w/ different PCSs”
 698 always gives a higher throughput and a lower collision
 699 probability than “IEEE 802.11” [Fig. 11(a)]. Although we
 700 started out to remove HN in this paper, in practice, one
 701 can relax the requirement of PCS to achieve a tradeoff
 702 between EN and HN. The overall performance of our
 703 proposed design, however, is always better than IEEE
 704 802.11 with the same PCS setting.

705 3) The tradeoff between EN and HN is manifested as a
 706 tradeoff between throughput and fairness [see Fig. 11(b)].
 707 There are also other minor observations. 1) Note that the
 708 “floor” collision probability in General HFD (when PCS =
 709 470 m in the “RS mode w/ different PCSs” curve) is about
 710 7%. These MAC-layer collisions are due to the fact that

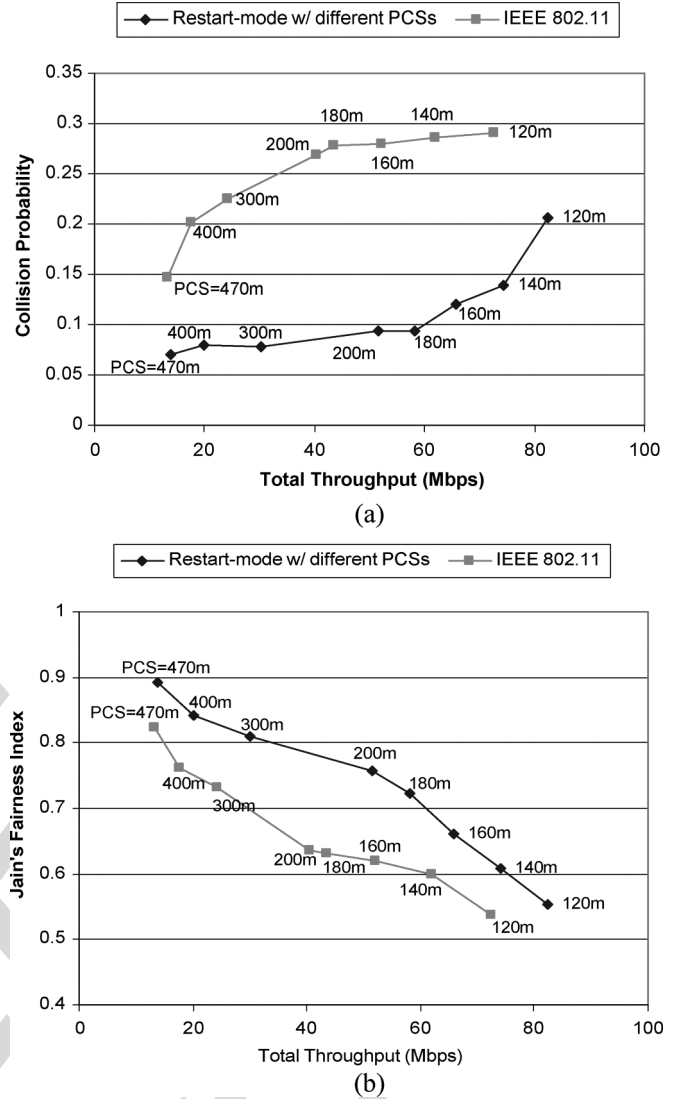


Fig. 11. Tradeoff between EN and HN. (a) Tradeoff between throughput and collision probability (the label beside each point shows the corresponding PCS value). (b) Tradeoff between throughput and fairness.

backoff timers of different nodes may still choose the same
 711 random number in a contention window even if HN is removed.
 712 However, this kind of collisions will not cause trouble since
 713 consecutive collisions (as in HN) are not likely due to the
 714 random backoff algorithm in 802.11. 2) With “RS mode w/
 715 different PCSs” in this particular simulation, PCS larger than
 716 300 m seems to have eliminated HN considerably. This is
 717 because when the clients are randomly located (and not very
 718 dense), most link distances are smaller than d_{\max} .
 719

In RTS/CTS mode, our related research has shown that
 720 EN can be effectively reduced compared to the Basic Access
 721 Mode. That scheme combines HFD for RTS/CTS mode and
 722 an EN-reducing algorithm called “Selective Disregarding of
 723 NAVs (SDN)” [15]. SDN enables each node to selectively
 724 disregard “false-alarming” RTS/CTS from links that actually do
 725 not interfere with its transmissions. This cannot be achieved in
 726 the Basic Access Mode because without RTS/CTS, PHY header
 727 gives no address information. Interested readers are referred to
 728

729 [15] for the scheme combining HFD and SDN. The tradeoff
730 between EN and HN still exists in that scheme.

731

VII. CONCLUSION

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

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

750 We have adapted the HFD principle for application in large-
751 scale WiFi cellular networks consisting of many adjacent
752 WLANs (a popular form of 802.11 deployments). We have
753 designed variations of HFD beyond the General HFD. One
754 version is “HFD with nonuniform PCS,” in which the PCSs
755 of different links are varied and minimized according to their
756 surroundings. Such individual PCS minimization reduces ENs
757 and increases spectrum spatial reuse. We have shown that the
758 total throughput can be increased by about 100% with this
759 design (see Fig. 10 for the case where number of channels
760 $N = 1$).

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

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

780

APPENDIX A

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

A. Constraints for Simultaneous Transmissions in 802.11

783

To understand the requirements of HFD, we need to first
784 understand the fundamental causes of HN. There are two types
785 of constraints concerning simultaneous transmissions in an
786 802.11 wireless network, as discussed below. 787

1) *802.11—Carrier-Sensing Constraints:* In the Basic Ac-
788 cess Mode, only PCS needs to be considered. For PCS, the
789 PHY header is decoded. The length field in the PHY header
790 informs the receiver of the duration of the payload that follows.
791 Consider two links i and j with senders and receivers T_i ,
792 T_j , R_i , and R_j , respectively. For brevity, we will also use
793 T_i , T_j , R_i , and R_j to denote their positions in the following
794 discussion. 795

Simultaneous transmissions on the two links are allowed
796 when 797

$$|T_i - T_j| > \text{PCS}. \quad (16)$$

However, the simultaneous transmissions will fail unless 798

$$|T_i - R_j| > \text{PCS} \quad (17)$$

$$|R_i - T_j| > \text{PCS}. \quad (18)$$

This is due to the “receiver capture” effect in most 802.11
799 products. If (17) is not true when T_i starts a DATA transmission
800 first, followed by T_j , then R_j will not attempt to receive the
801 DATA from T_j because it is in the process of receiving the
802 ongoing signal from T_i . Transmission on link j therefore fails.
803 Similar argument applies for (18). 804

2) *Physical No-Collision Constraints:* We now consider un-
805 der what conditions will there be no physical collision between
806 simultaneous transmissions over links i and j . Define $d_i =$
807 $|T_i - R_i|$ and $d_j = |T_j - R_j|$. Since each “atomic information
808 exchange” over an 802.11 link consists of two-way traffic,
809 DATA followed ACK in the reverse direction, the conditions
810 for the two transmissions not interfering with each other are as
811 follows [14]: 812

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

where $P(d)$ is the received power as a function of dis-
813 tance. It is a simplified form of $P(P_t; d)$ when we
814 assume that all the nodes use the same transmission
815 power P_t . 816

The first inequality on the left in (19) says that the DATA
817 signal on link j should be sufficiently small when it reaches the
818 receiver of link i compared with the DATA signal on link i ;
819 the second inequality on the left is for DATA on link j not
820 interfering with ACK on link i ; and so on [14]. As mentioned in
821 Section II, assuming the power propagation function in (1), (19)
822

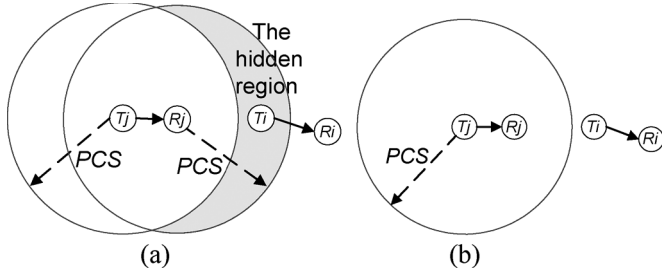


Fig. 12. (a) HN due to (17) and (18), and (b) RS mode removes the HN.

823 can be transformed into inequalities among distances instead of
824 power levels.⁶

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

825 3) *Goal of HFD*: Following the above discussion, HN can
826 arise out of two situations—When (16) is satisfied, the follow-
827 ing situations happen.

828 1) Equation (17) or (18) is not satisfied.

829 2) Equation (19) is not satisfied.

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

833 B. Proof of HFD for IEEE 802.11 Basic Access Mode

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

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

850 RS mode can be used to remove constraints (17) and (18).
851 Recall that with RS mode, when the power of a later-arriving
852 packet is more than C_t times that of the earlier packet, the
853 receiver switches to receive the stronger new packet. Thus, as
854 long as the SIR is sufficient, the order of transmissions does not
855 matter. Essentially, (17) and (18) will then be replaced by the

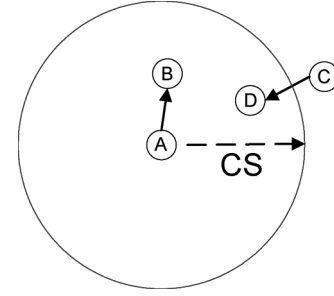


Fig. 13. Interaction of a pair of links.

same constraints as in (20), and consideration of (20) without
856 (17) and (18) is sufficient for our HFDs. 857

858 2) *Receive-Power Inequality*: With RS mode, we now only
859 need to make (16) sufficient for (20). Consider Fig. 13. Suppose
860 that A is transmitting a DATA to B, and C intends to transmit a
861 DATA to D. To avoid HN, the following must be true: 861

862 For any link (C, D) in the neighborhood of link (A, B) where
863 nodes A and C cannot carrier-sense each other, constraint (20)
864 must be satisfied. That is, there must not be any of the
865 following: 865

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

869 *Sufficient condition for satisfying constraints (20)*: Use of
870 receiver RS mode plus $\text{PCS} \geq (3 + \Delta)d_{\max}$. 870

871 *Proof for 3)*: We only present the proof for 3). The proofs
872 for 1) and 2) are similar. Suppose we assume the contrary: 872
873 DATA–ACK collisions occur at B or D in spite of the use of RS
874 mode and $\text{PCS} \geq (3 + \Delta)d_{\max}$. With respect to Fig. 13, since
875 A and C cannot sense each other, we have 875

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

876 First, suppose that DATA from A to B collides with D's ACK
877 at B. With RS mode, the order of arrivals of the DATA and ACK
878 at B does not matter. In order that there is collision, SIR at B
879 must be insufficient. Equivalently 879

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

880 From (21), we have 880

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

881 Using triangular inequality 881

$$|D - A| \leq |D - B| + |B - A|$$

$$|C - A| \leq |D - A| + |C - D|.$$

882 We have 882

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

883 From (23) and (24), we have 883

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

⁶All 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 $P(d_{\max}) \geq C_t P(\text{PCS} - 2d_{\max})$.

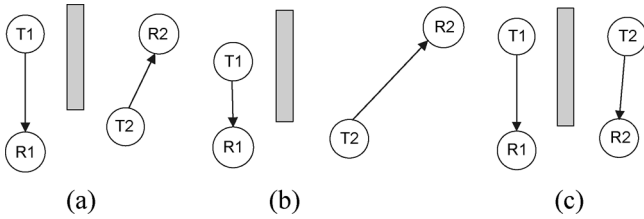


Fig. 14. HN induced by obstructions.

884 According to (22), we have

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

885 From (25) and (26), we have

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

886 However, this contradicts with the condition $PCS \geq (3 +$
887 $\Delta)d_{\max}$.

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

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

890

APPENDIX B

891 A. Discussion of HN Induced by Obstructions

892 In some cases involving obstructions (instead of regular
893 power propagation), the HN problem becomes more compli-
894 cated, and we may need additional mechanisms to alleviate HN.
895 Consider the scenario in Fig. 14(a). There is an obstruction be-
896 tween T1 and T2, but not between R1 and R2. The obstruction
897 leads to a sharp drop of signal strength, and here, we assume
898 that the "channel gain" between T1 and T2 is zero. Even with
899 HFD for the Basic Mode, when T1 is transmitting a DATA
900 packet to R1, T2 cannot sense it and may transmit packets and
901 corrupt T1's packet at R1 (T2 is the HN). With the RTS/CTS
902 mode, the situation is better since T2 can still hear R1's CTS.
903 However, if T2 transmits an RTS first, T1 cannot receive it and
904 may go ahead to send an RTS to R1, which may lead to a failure.
905 The problem here is that the transmitter (T1) is blind to
906 the transmissions on an interfering link (link 2) due to the
907 existence of obstructions. There is no easy solution unless
908 we make significant modifications to 802.11 MAC. One idea
909 is that, since only R1 knows the transmissions on link 2, it
910 can relay the information to T1, so that T1 can be prevented
911 from transmission when link 2 is busy. The protocol works as
912 follows. By default, each node operates normally with the Basic
913 Mode. If excessive collisions occur, the nodes then conjecture
914 that there is HN caused by obstructions, and each node in the
915 neighborhood then finds out the "local map" [i.e., the "channel
916 gains" between every pair of nodes of the neighborhood, as in
917 Fig. 14(a)] through a simple "PE" protocol similar to that in
918 Appendix C. Once HN caused by obstructions is confirmed,
919 instead of the normal operations, the nodes involved then
920 change their operations as follows.

921 1) The HN (T2 in the above example) will send an RTS
922 before transmitting DATA. The targeted receiver of the
923 HN (R2) will wait for a period of SIFS + RTS + SIFS
924 before replying a CTS.

2) The nontargeted receiver above (R1) will relay the RTS to
925 its transmitter (T1). The transmitter will not send DATA
926 to the receiver during the NAV. 927

The protocol may not completely avoid collisions since
928 multiple nodes may try to relay the RTS, leading to relay-RTS
929 collision. An algorithm is needed to elect a representative node
930 to relay the RTS. The details are an interesting subject for future
931 study. 932

There are also other scenarios to consider. In Fig. 14(b),
933 assume that T2's transmission does not cause insufficient SIR
934 at R1 (i.e., with "RS mode," R1 can always receive T1's
935 transmissions), but R1's transmission causes insufficient SIR at
936 T2 (i.e., R1's transmission can corrupt the ACK from R2). The
937 relay scheme above still applies here, but it generates additional
938 RTS/CTS packets. An alternative is to use "Delayed ACK"
939 operated in the Basic Mode (no RTS/CTS is needed), which
940 is described as follows. 941

Since T1 and T2 cannot sense each other, they may be
942 transmitting DATA packets at the same time. After R1 finishes
943 receiving, its ACK may interfere with link 2. The idea of
944 "Delayed ACK" is to let R1 do carrier sensing before returning
945 an ACK, instead of sending ACK immediately after SIFS. If
946 R1 senses no transmission (after receiving DATA from T1),
947 it delays its ACK by SIFS+ACK (in case R2 is returning
948 an ACK to T2); if R1 senses a transmission, it waits until
949 the transmission ends and delays its ACK for an additional
950 SIFS+ACK. Meanwhile, T1 is not aware of the delay and
951 may go into exponential backoff. However, immediately after it
952 receives the delayed ACK from R1, T1 gets out of the backoff
953 state so that it does not need to continue to count down. We
954 note in passing that 802.11e has some sort of a delayed ACK
955 feature. Delayed ACK, however, does not entirely avoid T1's
956 retransmission if the ACK is delayed too much. 957

Another scenario is shown in Fig. 14(c) in which the ACK
958 from either R1 or R2 may interfere with the other link. In
959 addition, R1 and R2 cannot sense the transmissions of T2
960 and T1, respectively. "Delayed ACK" does not apply here,
961 and we have to fall back to the Relay scheme—In this sce-
962 nario, R1 relays the CTS from R2 to T1, and vice versa.
963 In the Relay scheme, since either RTS or CTS needs to be
964 relayed in different scenarios, we also call it "RTS/CTS Relay
965 scheme." 966

A strategy is to combine the delayed-ACK scheme with the
967 RTS/CTS Relay Scheme. Since the RTS/CTS Relay Scheme
968 is more expensive (i.e., it requires RTS/CTS, which may be
969 further duplicated and relayed), it should be used only as an
970 alternative when "Delayed ACK" algorithm does not work. The
971 above has only sketched a plausible solution for HN that is
972 caused by obstructions. This subject certainly deserves more
973 careful investigations in the future. 974

APPENDIX C

975

A. PE Algorithm for Discovering InRs

976

To construct the InRs, each node A periodically broadcasts
977 special PE packets and receives PE packets from nearby nodes.
978 The transmission power for PE packets is the same as that for
979

980 regular packets, and we assume that all nodes use the same
981 transmit power and receiver sensitivity.

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

992 A point to note about the PE algorithm is that they are not
993 the same as RTS/CTS packets and are not used for carrier-
994 sensing purposes. They are special packets used for distributed
995 discovery of InRs. Also, the PE packets need to be transmitted
996 only when the network topology or conditions have changed.
997 The periodic transmissions of PE packets above are mainly
998 for simplification and to make the algorithm more robust.
999 When nodes are not highly mobile, PE packets introduce little
1000 overhead because the broadcast period can be long.

1001 B. Condition for Correct Operation of PE

1002 The following condition is sufficient to ensure that a node
1003 can discover all the InRs relevant to itself:

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

1004 or

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

1005 where PERange is the transmission range of the PE packets.

1006 *Note:* To meet (28), PE packets must be transmitted at a
1007 sufficiently low rate, such as that used by RTS/CTS packets.

1008 *Proof:* Consider three nodes: Nodes A and B form links
1009 (A, B) and (B, A) ; and node C forms links with other nodes.
1010 Without loss of generality, assume that $P(A, B) < C_t P(C, B)$
1011 so that the transmission by C can interfere with reception at B .
1012 We want to show the following: 1) nodes A and B , and 2) node
1013 C and any other node D that forms link with C can find out the
1014 existence of this InR.

1015 *Proof of 1):* By definition, we have $|A - B| \leq d_{\max}$. If
1016 (28) holds, we have

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

1017 The above implies that $\text{PERange} - d_{\max} > |C - B|$, since
1018 $P(\cdot)$ is a decreasing function of distance. Therefore

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

1019 and

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

This means that, if $P(A, B) < C_t P(C, B)$, then the PE pack-
1020 ets of C can reach A and B . By measuring the received
1021 power of C 's PE packets and checking their source address to
1022 identify the sender, B can derive C and $P(C, B)$. Similarly,
1023 B can derive A and $P(A, B)$ from A 's PE packets. Therefore,
1024 B can find out that $P(A, B) < C_t P(C, B)$ and, hence, the
1025 existence of InR between link $(A, B)/(B, A)$ and any other
1026 link with C being the transmitter or receiver—Note that these
1027 links are contained in the active link list in C 's PE packets
1028 received by B .
1029

Now, the PE packets of B contain information on
1030 $[C, P(C, B)]$ and $[A, P(A, B)]$. Upon receiving B 's PE pack-
1031 ets, A can also find out that $P(A, B) < C_t P(C, B)$ and, hence,
1032 the existence of InR between link $(A, B)/(B, A)$ and any other
1033 link with C being the transmitter or receiver—Note that these
1034 links are contained in the active link list in C 's PE packets
1035 received by A .
1036

Proof of 2): From the proof of 1), we have $\text{PERange} -$
1037 $d_{\max} > |C - B|$. Therefore
1038

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

and

1039

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

Thus, the PE packets of B , which contain $[C, P(C, B)]$,
1040 $[A, P(A, B)]$, and active links (A, B) and (B, A) can reach C
1041 and any node D that forms link with C , from which they can
1042 discover the associated InRs.
1043

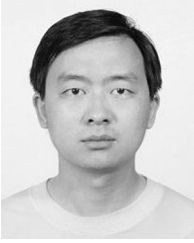
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AUTHOR QUERIES

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”.

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AQ8 = Please provide additional information in Ref. [6].

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