Removing Hidden Nodes in IEEE 802.11 Wireless Networks

Libin Jiang, Soung Chang Liew
Department of Information Engineering
The Chinese University of Hong Kong, Shatin, Hong Kong
Tel: (852) 6409 3740 Fax: (852) 2603 5032
{lbjiang3, soung}@ie.cuhk.edu.hk

Abstract-- This paper investigates the hidden-node phenomenon (HN) that arises in IEEE 802.11 wireless networks. HN can cause many performance problems, including throughput degradation, unfair throughput distribution among flows, and throughput instability. Previous investigations mostly focus on methods to alleviate these performance problems rather than direct elimination of HN. Such an approach may solve one but not all of these problems. This paper is a first attempt to identify the fundamental conditions leading to HN. In particular, we show that HN arises fundamentally as a result of the 802.11 protocol constraints. Based on the insight obtained from the analysis, we devise a Hidden-node-Free Design (HFD) that completely removes HN. Readers who are only interested in the results, but not the derivations, may skip Section 3.

1 Introduction

A well-known problem in IEEE 802.11 networks is the hidden-node phenomenon (HN), in which the mutual interference of nodes outside the carrier-sensing range of each other may increase the packet-collision rate significantly. This paper is a first attempt to provide a comprehensive analysis to the scenarios giving rise to HN, and to identify a set of sufficient conditions under which HN can be eliminated entirely.

In [1], two performance problems triggered by HN in 802.11 multi-hop networks were identified: (i) unfair throughput distributions among contending TCP flows; and (ii) throughput instability in a multi-hop TCP flow. Reference [1], however, did not provide a solution to HN, and concluded instead that 802.11 is not suitable for multi-hop networks.

Reference [2] provided a "node-based" analysis of HN. It was argued that when the physical carrier sensing range is larger than the transmission range plus the interference range, HN can be removed and RTS/CTS is no longer needed. According to our "link-based" analysis in this paper, however, this condition is not sufficient for eliminating HN in general.

Reference [3] studied the unfair throughput distributions among flows induced by HN, and proposed a set of algorithms to provide max-min fairness among the flows by dynamically adjusting the Initial Contention Windows of the nodes. In these algorithms, frequent information exchange among the nodes is needed. More importantly, this approach does not remove HN and instead focuses on eliminating one of its negative effects. HN remains and may continue to cause other problems. For example, HN can be considered as partial breakdown of the carrier-sensing capability. Since collisions are more likely without carrier sensing, the overall throughput may degrade besides the mere unfairness problem. Indeed, the Aloha network can be considered as a network in which all nodes are hidden from each other, and in that extreme case the throughput can be considerably lower than that in a full carrier-sensing network.

References [4] and [5] examined the problems in [1] in terms of a single-flow problem, as illustrated in Figure 1 (a). The successive packets of the flow may self-interfere among themselves at adjacent nodes. In this case, HN causes throughput degradation as well as triggers the re-routing instability phenomenon [5], [6]. Reference [5] established the analysis that relates the single-flow throughput to HN quantitatively.
Reference [4] proposed specific modifications of 802.11 protocol, while [5] tried to alleviate the problems through "offered load control" at the data source without perturbing the MAC protocol. Again, in both cases HN remains. For example, the "offered load control" in [5], while eliminating throughput instability, cannot remove the throughput degradation due to HN. Indeed, a conclusion of [5] is that the single-flow throughput under study was HN-limited rather than spatial-reuse-limited [5].

In short, HN can give rise to many performance problems, including throughput degradation, unfair throughput distribution, and throughput instability. Instead of trying to tackle these symptoms in an isolated manner, another approach is to explore how to eliminate HN entirely. This paper takes up the latter approach.

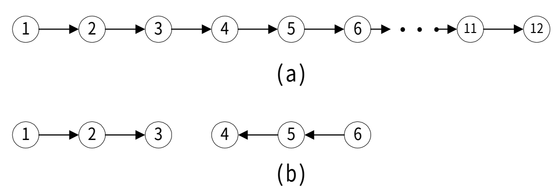


Figure 1 Traffic flows that can give rise to HN.

2 HFD

Definition of HN
A link with sender node A and receiver node B is said to suffer from HN if the data exchange in this link may fail because A did not sense the ongoing data exchange of another interfering link before initiating its transmission, or A can not be sensed by the sender of another interfering link after A has initiated its transmission. A network is said to suffer from HN if any of its link suffers from HN.

We now present a set of *sufficient conditions* for removing HN, which we refer to as Hidden-node Free Design (HFD). HFD consists of (i) a signal-reception mechanism called the Restart Mode; and (ii) two constraints on the power budget of links. Here we only present HFD for IEEE 802.11 *basic access mode* (DATA-ACK handshake).

(a) Receiver Restart Mode[1] (RS): As with the regular operation, a node with RS that has carrier-sensed a transmission in progress should not initiate a new DATA transmission of its own. However, if it receives a new transmission signal that is sufficiently larger that the previously sensed signal (say, with C_{rt} times the power of the previous signal), the receiver will switch to receive the stronger signal. If the new signal is an 802.11 DATA targeted for it, the node will reply with an **ACK after SIFS** (Short InterFrame Space), whether or not the medium around this node is idle.

(b) Two Link Power-Budget Requirements: In addition to (a), the following inequalities needs to be fulfilled to eliminate HN:

$$P(d_{\max}) \geq C_{rt} * P(CS - d_{\max}) \qquad (1)$$

$$P(d_{\max}) \geq C_t * P(CS - 2d_{\max}) \qquad (2)$$

where $P(.)$ is the received power as a function of distance, d_{max} is the maximum distance of a link, CS is the carrier-sensing range, Ct is the detection threshold, and C_{rt} is the restart threshold. An implicit assumption in the above inequality is that $P(.)$ is a decreasing function of distance. In our full paper, we will provide an algorithm that does not require this assumption. In other words, this assumption is needed only for performance evaluation, but not for actual operation of HFD.

Consider two packets arriving at a node, one after the other. The later packet arrives at the node before the earlier packet is finished. If the received power of the earlier packet is more than Ct times that of the later packet, then only the earlier packet can be decoded successfully. If the power of the later packet is more than C_{rt} times the earlier packet, the receiver will switch to the later packet and only decode it correctly. Other than these two cases, neither packet can be decoded correctly.

Note that the inequalities in (b) are requirements imposed on the network design. With $P(.)$ as a decreasing function of distance, links with too large a distance relative to the carrier-sensing range are not allowed in the network if HN is to be removed.

We could plug in suitable propagation models to the above requirements. The received power function is usually in the form of

$$P(d) \propto P_t / d^{\alpha} \qquad (3)$$

where P_t is the transmission power, d is the distance and α is the path-loss exponent, which ranges from 2 to 6 according to different environments. For example, if C_t=C_{rt}=10, α=4, (1) is contained in (2). The requirements become

$$CS \geq 2d_{\max} + 10^{1/4} d_{\max} \approx 3.78 d_{\max} \qquad (4)$$

[1] This mode can be enabled in some commercial 802.11 chips.

A corresponding HFD can be found for networks operated with the *RTS/CTS mode* (RTS-CTS-DATA-ACK handshake). The sufficient condition in (b) needs to be modified slightly. We defer this discussion to the full paper.

3 Proof of HFD

We now prove that HFD can remove HN in a network.

3.1 Constraints for Simultaneous Transmissions in 802.11

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

3.1.1 802.11-Carrier Sensing Constraints

In the *basic access mode* without RTS/CTS, only physical carrier sensing needs to be considered. The goal of carrier sensing is to (i) disallow simultaneous transmissions that may cause collisions while (ii) allowing simultaneous transmissions that are collision-free. However, the 802.11 carrier sensing may fail to achieve either in some situations. A detailed analysis is given in [7]. HFD will ensure (i) (HN-free), but not (ii) (Exposed Node-Free). However, a new mechanism will be included in the full paper to further remove Exposed Node Problem.

For physical carrier sensing, the preamble of the PHY header is decoded. The length field in the PHY header informs the receiver of the duration of the payload that follows. Consider two links *i* and *j*, with senders and receivers, *Si*, *Sj*, *Ri*, and *Rj*, respectively. For brevity, we will also use *Si*, *Sj*, *Ri* and *Rj* to denote their positions in the following discussion. Only when *Si* and *Sj* are far enough (so that they cannot decode the PHY preamble transmitted by each other) are simultaneous transmissions allowed. The corresponding inequality is

$$\left| S_i - S_j \right| > CS \qquad (5)$$

If (5) is satisfied, carrier sensing does not disallow simultaneous transmissions on links *i* and *j*. However, the simultaneous transmissions may fail unless

$$\left| S_i - R_j \right| > CS \qquad (6)$$

$$\left| R_i - S_j \right| > CS \qquad (7)$$

This is due to the default reception mechanism in most 802.11 products, which operates as follows. Suppose that (6) is not true, when *Si* starts a DATA transmission first, and *Sj* starts later, but before *Si* finishes the transmission. Then *Rj* **will not attempt** to receive the DATA from *Sj*. This is because *Rj* has begun the reception of *Si*'s DATA at the physical layer, even though it is not targeted for *Rj* (usually called "receiver capture"). Similar argument applies for (7).

Note that HN occurs in this scenario only when *Si* transmits first. In other words, violation of (6) or (7) makes HN POSSIBLE. The likelihood of this possibility is large because DATA frames usually occupy a larger portion of medium than ACK frames do, leading to a large "vulnerable region" [5].

Another scenario is when *Ri* and *Rj* are within CS range of each other, *Ri*'s ACK could prevent *Rj*'s reception of *Sj*'s DATA, and vice versa. We omit this situation, since ACK is usually small compared with DATA and the likelihood of such HN collisions is small. We will see later, however, the constraint "|*Ri*-*Rj*|>*CS*" does not change the HFD requirements in Section 2, since this constraint will be removed by RS mode anyway.

3.1.2 No-collision Constraints

We first consider under what conditions will there be no collision between simultaneous transmissions over links *i* and *j*. Define $d_i = |S_i\text{-}R_i|$ and $d_j = |S_j\text{-}R_j|$. Since each "atomic information exchange" over an 802.11 link consists of two-way traffic, DATA followed ACK in the reverse direction, the condition for the two transmissions not interfering with each other are as follows [7]:

$$\left\{\begin{array}{l} \frac{P(d_i)}{P(|S_j - R_i|)} > C_t \\ \frac{P(d_i)}{P(|S_j - S_i|)} > C_t \\ \frac{P(d_i)}{P(|R_j - R_i|)} > C_t \\ \frac{P(d_i)}{P(|R_j - S_i|)} > C_t \end{array}\right. \left\{\begin{array}{l} \frac{P(d_j)}{P(|S_j - R_i|)} > C_t \\ \frac{P(d_j)}{P(|S_j - S_i|)} > C_t \\ \frac{P(d_j)}{P(|R_j - R_i|)} > C_t \\ \frac{P(d_j)}{P(|R_j - S_i|)} > C_t \end{array}\right., i.e. \frac{Signal}{Interference} > C_t \qquad (8)$$

The first inequality on the left says that the DATA signal on link *j* should be sufficiently small when it reaches the receiver of link *i* compared with the DATA signal on link *i*; the second inequality on the left is for DATA on link *j* not interfering with ACK on link *i*; and so on [7].

3.1.3 Goal of HFD

HN can arise out of two situations—when (5) is satisfied but

- (6) or (7) is not satisfied, or
- (8) is not satisfied.

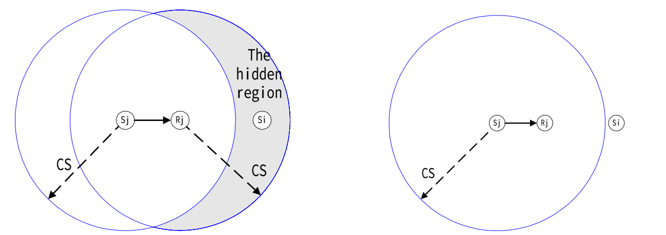
So, the goal of HFD is to identify the requirements so that, the above two cases will not happen, so long as (5) is satisfied.

3.2 HFD for IEEE 802.11 basic access mode

3.2.1 Receiver Restart Mode

In this section we first argue that (5) does not guarantee (6) and (7) – a counter example can be found to show the insufficiency. This leads to the fundamental requirement that (6) and (7) must be removed if HN is to be eliminated. This can be achieved with the receiver restart mode (RS).

To see why (5) is not sufficient for guaranteeing (6), consider the counter example in Figure 2 (a). There is inevitably a "hidden" region for *Sj*. If *Si* is within this hidden region, (5) holds but (6) is not satisfied. When *Si* starts transmitting a DATA packet earlier, followed by *Sj*, *Sj*'s DATA cannot be received by *Rj* (as discussed in 3.1.1). Note that HN exists no matter how large *CS* is — a naïve solution of increasing *CS* range is not viable.



(a) w/o RS (b) with RS

Figure 2 (a) Protocol constraints lead to HN, and (b) RS removes interference constraints.

RS can be used to remove the requirements (6) and (7) for successful reception. Recall that with RS, when a "new signal" is more than C_{rt} times the previous signal, the receiver switches to receive the stronger new signal. RS, however, introduces a new constraint for HN-free operation:

$$\frac{Signal}{Interference} > C_{rt} \qquad (9)$$

where *Interference* refers to the power of the "old signal" transmitted by a hidden node.

3.2.2 Receive-Power Inequality

With RS, we now only need to make (5) sufficient for (8) and (9). Consider Figure 3, suppose A is transmitting a DATA to B, and C intends to transmit a DATA to D. To avoid HN, the following must be true:

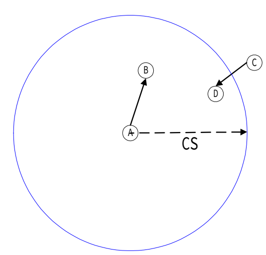


Figure 3 Interaction of a pair of links

For any link (C,D) in the neighborhood of link (A,B) where nodes A and C cannot carrier-sense each other, constraints (8) and (9) must be satisfied. That is, there must not be
(i) DATA-DATA collisions at B or D;
(ii) ACK-ACK collisions at A or C;
(iii) DATA-ACK collisions at B or D.

***Sufficient Condition for Satisfying Constraints** (8) **and** (9)*: Use of Restart Mode plus satisfaction of (1) and (2).

Proof for (iii): Due to the limited space, we only present the proof for (iii). The proofs for (i) and (ii) are similar, but with less a stringent sufficient condition. With respect to Figure 3, suppose C cannot carrier-sense A, and the alleged sufficiency conditions (1) and (2) are satisfied, but (iii) is not. As a result HN occurs. We prove that this leads to contradiction. Since A and C cannot sense each other,

$$P(|C-A|) < P(CS) \qquad (10)$$

First, assume A's DATA arrives at B earlier than D's ACK. If (iii) is not true, and D's ACK collides with A's DATA at B, then

$$P(|A-B|) \le C_t * P(|D-B|) \qquad (11)$$

From (10) and the assumption that $P(.)$ is a non-increasing function of distance, we have

$$P(|C-A|-|A-B|-|C-D|) < P(CS-|A-B|-|C-D|) \quad (12)$$

Using Triangular Inequality,

$$|D-A| \le |D-B| + |B-A|$$
$$|C-A| \le |D-A| + |C-D|$$

We have

$$|C-A| \le |D-B| + |B-A| + |C-D| \qquad (13)$$

Substituting (13) into (12),

$$P(|D-B|) < P(CS-|A-B|-|C-D|) \le P(CS-2d_{\max}) \qquad (14)$$

According to (11), we have

$$P(d_{\max}) \le C_t * P(|D-B|) \qquad (15)$$

From (14) and (15), we have

$$P(d_{\max}) < C_t * P(CS-2d_{\max}) \qquad (16)$$

But (16) contradicts with condition (2).

Now, consider the case where D's ACK arrives at B earlier than A's DATA. If (iii) is not true, then

$$P(|A-B|) \le C_{rt} * P(|D-B|) \qquad (17)$$

Since A must have sensed the medium to be idle for it to transmit, we have

$$|A-D| > CS$$

Thus, the triangular inequality gives

$$|B-D| \ge |A-D| - |A-B| > CS - d_{\max} \qquad (18)$$

Also,

$$|A-B| \le d_{\max} \qquad (19)$$

From (17), (18), and (19), we have

$$P(d_{\max}) \le P(|A-B|) \le C_{rt} * P(|B-D|) < C_{rt} * P(CS-d_{\max}) \quad (20)$$

But (20) contradicts with condition (1).
Therefore, D's ACK cannot collide with A's DATA at B.
Similarly, B's ACK cannot collide with C's DATA at D.

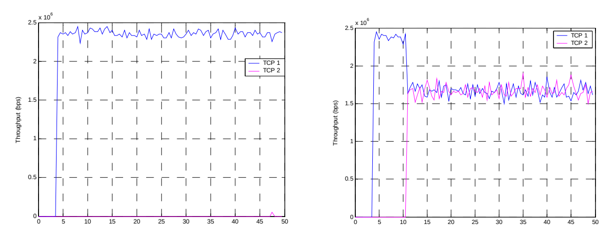
4 Removal of HN Performance Problems

"TCP unfairness" and "re-routing instability" are two performance problems triggered by HN identified previously [1]. This section validates by simulation that by removing HN, HFD also eliminates such performance problems. As in [1], we consider a chain topology, as shown in **Figure 1**. 12 nodes in a straight line are equally spaced by 140 meters. Results pertaining more complex network topologies will be presented in the full paper. In addition, the intricate tradeoffs between networks with HFD and without HFD will be discussed.

The simulations were conducted using NS2 [9]. The data rate is set at 11Mbps. Two-ray ground propagation model is adopted with $\alpha = 4$. C_{rt} and C_t, are set to 10dB. The carrier-sensing range is 550m. Thus, for HFD, the maximum link distance d_{max} according to (4) is 550/3.78 = 145m. The Ad-hoc On-Demand Distance Vector (AODV) routing protocol is used. All data sources are UDP or TCP traffic streams with fixed packet size 1460 Bytes.

TCP Unfairness

Consider **Figure 1** (b). TCP 1 is from node 1 to 3, and TCP 2 is from node 6 to 4. TCP 1 starts earlier at 3.0 sec, and TCP 2 starts at 10.0 sec. Without HFD, node 1 is hidden from node 5, causing node 5's DATA packet to collide at node 4 with node 1's DATA packet. Likewise, node 2 is hidden from node 6, causing node 6's DATA packet to collide at node 5 with 2's DATA packet. Because TCP 1 starts earlier, TCP 2 virtually has no chance to obtain any throughput (See Figure 4 (a)). Figure 4 (b) shows that the "unfairness" problem is eliminated with HFD.



(a) Without HFD (b) HFD

Figure 4 TCP fairness

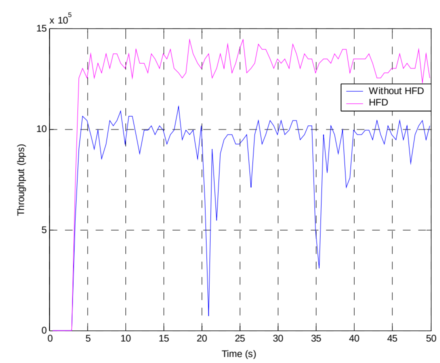


Figure 5 Throughput stability of an 11-hop UDP flow

Re-routing Instability

Re-routing instability is triggered by excessive packet collisions introduced by hidden terminals nodes (which is mistook for route unavailability). Consider Figure 1 (a). A UDP flow is sent by node 1 to node 12. Without HFD, node 5 is "hidden" from node 1, causing the packets of node 1 to repetitively collide at node 2 with node 5's packet. Likewise, nodes 2, 3, 4, 5, … face the same problems. Figure 5 shows that the throughput instability of an 11-hop UDP flow is removed with HFD. For this topology, HFD not only removes the instability, but also achieves higher throughput. The latter is not always true in other topologies. We defer the discussion to the full paper.

5 Conclusion

The contributions of this paper are two-fold: (1) It is a first attempt to identify accurately the fundamental conditions leading to HN; and (2) It provides with a set of sufficiency conditions for the removal of HN.

In the full paper, we will include details omitted here. They include: 1) HFD for RTS/CTS mode; 2) Discussion of HFD's effects on network capacity and connectivity in different topologies; and 3) A new mechanism called "Selective Disregarding NAVs" (SDN) that further removes the "Exposed Node problem" (i.e. simultaneous transmissions that are collision-free may be not allowed by the protocol) to achieve scalable throughput in large-scale 802.11 networks with high node density.

References

[1] Xu, S.; Saadawi, T., "Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?" *Communications Magazine, IEEE*, Volume: 39, Issue: 6, June 2001, Pages:130 - 137

[2] K. Xu, M. Gerla, S. Bae, "How Effective is the IEEE 802.11 RTS/CTS Handshake in Ad Hoc Networks?", *IEEE GLOBECOM '02*, Vol. 1 , pp. 17-21, Nov. 2002.

[3] X. Huang, B. Bensaou, "On Max-min Fairness and Scheduling in Wireless Ad-Hoc Networks: Analytical Framework and Implementation", *ACM MobiHoc'02*, Long Beach, USA, Oct. 2001.

[4] S. Ansari et al. "Performance Enhancement of TCP on Multi-hop Ad hoc Wireless Networks", *IEEE ICPWC'02*, pp. 90-94, Dec. 2002.

[5] Ping Chung Ng, Soung Chang Liew, "Offered Load Control in IEEE802.11 Multi-hop Ad-hoc Networks," to appear in *the 1st IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS)*, Oct 2004.

[6] Ping Chung Ng, Soung Chang Liew, "Re-routing Instability in IEEE 802.11 Multi-hop Ad-hoc Networks," *The 4th IEEE International Workshop on Wireless Local Network*, Nov 2004

[7] Ping Chung Ng, Soung Chang Liew, Libin Jiang, "A Performance Evaluation Framework for IEEE 802.11 Ad-hoc Networks," to appear in *ACM Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN' 2004).*

[8] R. Hekmat and P. V. Mieghem, "Interference in wireless multihop ad-hoc network," in *Med-hoc-Net*, (Sardegna, Italy), September 2002.

[9] "The Network Simulator – NS2", http://www.isi.edu/nsnam/ns