A Performance Evaluation Framework for IEEE 802.11 Ad-hoc Networks*

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ABSTRACT

Interferences in an ad-hoc network can be defined as a set of constraints that specify which groups of nodes cannot transmit simultaneously, and they have significant implications for the network capacity and other performance measures. This paper expounds the difference between two types of interferences: 1) physical interferences due to the receiver's inability to decode a signal when the powers received from other signals are large; and 2) protocol interferences imposed by the specific multi-access protocol being used to coordinate transmissions of nodes. We model interference types 1 and 2 in terms of graphs. Based on the insights obtained, we devise a scheme that modifies 802.11 slightly to make its capacity scale with the number of nodes.

Categories and Subject Descriptors

C.4 [**Performance of System**s]: *Modeling techniques*

General Terms

Measurement, Performance, Algorithms.

Keywords

Wireless Networks, Ad hoc Networks, IEEE 802.11, Performance Analysis, Capacity, Scalable Performance.

1. PHYSICAL CONSTRAINTS

Consider two links, links 1 and 2. Let T_1 (T_2) and R_1 (R_2) be the transmitter and receiver of link 1 (link 2), respectively. The "protocol model" in [1] assumes link 2 can interfere with link 1 if

$$|X_{T2} - X_{R1}| < (1+\Delta)|X_{T1} - X_{R1}| \quad (1)$$

and link 1 can interfere with link 2 if

$$|X_{T1} - X_{R2}| < (1+\Delta)|X_{T2} - X_{R2}| \quad (2)$$

where X_i is the location of node i, and $\Delta > 0$ is related to a power margin. Although the model in [1] is named a "protocol model", it does not fully characterize the specific multi-access protocol being used. It simply states that the power received by R_1 from T_1 must be sufficiently larger than the power received by R_1 from T_2 in order that the signal from T_1 can be successfully decoded. Therefore, simultaneous transmissions on links 1 and 2 result in a collision if (1) or (2) is true. A multi-access protocol can be used to prevent such collisions, but it may introduce additional extraneous constraints against spatial reuse.

2. IEEE802.11 PROTOCOL CONSTRAINTS

We derive the additional protocol constraints imposed by 802.11 below. We assume the use of RTS/CTS access mode. RTS/CTS can be decoded if the distance of transmission is less than the virtual carrier sensing range ($VCSRange$). Consider links 1 and 2, and suppose link 1's transmission is already in progress when link 2 has a packet to transmit. Link 2 cannot transmit if any of the following inequalities is satisfied:

$$|X_{T2} - X_{T1}| < VCSRange \quad (3)$$

$$|X_{T2} - X_{R1}| < VCSRange \quad (4)$$

$$|X_{R2} - X_{T1}| < VCSRange \quad (5)$$

$$|X_{R2} - X_{R1}| < VCSRange \quad (6)$$

If inequality (3) were satisfied, T_2 would have received the RTS of T_1 and the NAV contained in the RTS would prevent T_2 from transmitting. Similarly, if inequality (4) were satisfied, T_2 would have received the CTS of R_1. In inequalities (5) and (6), R_2 would have received the RTS of T_1 and CTS of R_1 respectively, and it would not reply to the RTS of T_2 if T_2 sent one.

In addition to virtual carrier sensing, physical carrier sensing may also prevent simultaneous transmissions. For physical carrier sensing, the preamble of the PHY header is decoded. There is a length field in the PHY header which informs the receiver of the duration of the payload that follows. Specifically, for links 1 and 2, when T_1 or T_2 can decode the PHY preamble transmitted by each other, simultaneous transmissions will be prevented:

$$|X_{T2} - X_{T1}| < PCSRange \quad (7)$$

Inequalities (3)-(7) are related to simultaneous transmissions of DATA packets that are prevented by virtual and physical carrier sensing. If none of (3)-(7) is satisfied, carrier sensing cannot prevent simultaneous transmissions of DATA packets on links 1 and 2 but the simultaneous transmissions may not be successful if one of the following is true:

$$|X_{R2} - X_{T1}| < PCSRange \quad (8)$$

$$|X_{T2} - X_{R1}| < PCSRange \quad (9)$$

For (8), if T_1 transmits first followed by T_2, then R_2 will not attempt to receive the signal form T_2. Similar argument for (9).

In addition, the ACK of one link may collide with the DATA or ACK of the other. Each atomic communication on a link *i* consists of a DATA frame in the forward direction and an ACK frame in the reverse link *i'*. So, simultaneous communications on two links *i* and *j* are interference-free if the link pairs *i* and *j*; *i* and *j'*, *i'* and *j*; and *i'* and *j'* are interference-free. This consideration

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yields three more pairs of inequalities similar to (1) and (2) with interchange of transmitters and receivers, referred to as (10)-(15).

The relative size of *PCSRange* and *VCSRange* matters as far as which of the inequalities (1)-(15) are distinct. Generally, there is a trade-off between the protocol's ability to prevent collisions due to physical interference of (1) and (2), and the protocol's ability to allow simultaneous transmissions not barred by (1) and (2).

3. GRAPH MODELS

3.1 Link-Interference Graph from Physical Constraints

To capture the physical constraints graphically, we introduce the physical link-interference graph (i-graph). In an i-graph, an arrow-shape vertex represents a wireless link with the arrowhead pointing toward the receiver. There is an i-edge between vertices 1 and 2 if inequality (1) or (2) is satisfied. Figures 1a and 1b show an example of mapping a network to an i-graph.

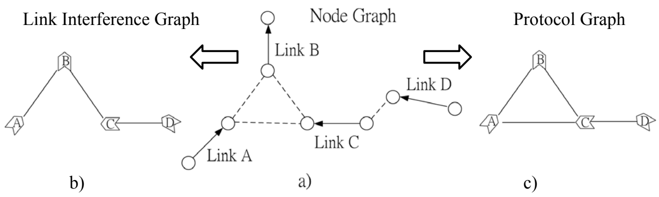

Figure 1. Mapping of a network a) to b) link-interference graph and c) protocol-interference graph

3.2 Protocol-Interference Graph from IEEE 802.11 Protocol Constraints

The protocol constraints may under- or over-estimate the physical constraints. We could use of a protocol-interference graph (p-graph) to model the constraints. The protocol introduces two more edge types: contention edges (c-edges) and additional interference edges (i'-edges). There is a c-edge between vertices 1 and 2 if at least of the inequalities (3)-(7) is satisfied. The c-edge represents the constraints imposed by carrier-sensing scheme of 802.11. There is an i'-edge between vertices 1 and 2 if at least one of the inequalities (8)-(15) is satisfied. The i'-edge represents additional collisions introduced by the protocol.

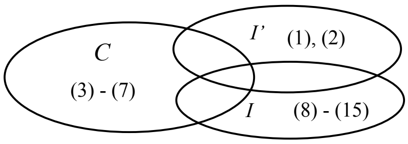

Figure 2. Relationships among different types of edges in a p-graph and the inequalities associated with the edges.

The p-graph of a wireless network consists of the vertices, i-edges, c-edges, and i'-edges. In case there are multiple edges of different types between two vertices, we will draw just one edge between the two vertices and say that the edge belongs to all the associated types. Figure 2 shows the relationships between the different edge types and the inequalities that define them. Much insight can be obtained by looking at the relative size of $|C|$, $|I|$, $|I'|$ and the overlaps between them.

Figure 1c shows a p-graph example. An edge is drawn between A and C in the p-graph but not in the i-graph. This edge, which satisfies one of (10)-(15), is an i'- but not an i-edge. Simultaneous transmissions on A and C are allowed by the protocol, but ACK on one link can collide with DATA on the other.

4. Selective Disregard of NAVs

To boost the capacity, a solution (Selective Disregard of NAVs (SDN)) is to eliminate the effect of c-edges on the protocol operation. Each node constructs the physical-interference edges (i-edges and subset of i'-edges) in its neighborhood based on the signal powers it hear from other links. When transmitting or receiving, the nodes of a link ignore the NAV in the RTS/CTS that they hear from another nearby link if there is no i- or i'-edges between the two links. The basic idea is to remove constraints (3) to (9) in the protocol operation. We defer the details of the algorithm and its extensions to another paper.

Table 1 shows the average throughputs and transport capacities [1] obtained from 500 runs of a simplified MATHLAB simulation experiment. n nodes are randomly placed inside a circle of radius 1250m. The transmit powers are kept constant as n varies. Each node could potentially transmit to all other nodes within the transmission range. The data rate is 11Mbps and the RTS/CTS/PHY rate is 2Mbps. The corresponding CSRange and transmission ranges are respectively 437m and 232m, assuming omni antenna. With this setting, all the i- and i'-edges are also c-edges in 802.11, thus all collisions are avoided. But legitimate simultaneous transmissions may be disallowed because many c-edges are not i- or i'-edges. SDN removes this defect.

As shown in Table 1, the 802.11 throughput and transport capacity reach a limit as n increases, while those of SDN do not. Indeed, if priorities are given to links of small hops, SDN performance scales very well with n. One could argue intuitively that for very large n, the small-hop SDN throughput should be of order $n + f(n)$, where $f(n)$ is an increasing function of n, if the boundary effect of the area containing the nodes can be ignored.

We note that SDN could also be modified to capture and work with the physical interferences from multiple nodes beyond the pair-wise physical interference model [1]. Furthermore, power control may eliminate some i-edges and i'-edges.

Table 1. Simulation results for 802.11 and SDN with random / small-hop transmission priorities: T = throughput (in 11 Mbps) and C = transport capacity (in 11 Mbps*km).

n	50	100	200	400
T (802.11)	7.2 / 8.0	12 / 14	14 / 15	14 / 14
T (SDN)	9.2 / 11	18 / 25	26 / 52	34 / 93
C (802.11)	1.1 / .66	1.5 / .79	1.9 / .63	1.9 / .41
C (SDN)	1.4 / 1.0	2.2 / 1.7	3.0 / 2.8	3.6 / 3.6

5. CONCLUSION

This paper has formulated a general framework to study the limits against spatial reuse imposed by multi-access protocols. By identifying the causes for the extraneous protocol constraints, we could devise strategies to overcome them. We have demonstrated this with a scheme that allows the capacity in 802.11 networks to scale as node density increases, without the need for adaptive power control.

6. REFERENCE

[1] P. Gupta, P. R. Kumar, "The Capacity of Wireless Network", *IEEE Trans. on Information Theory*, Vol. 46, No. 2, pp.388-404, Mar. 2000.