Further study of 802.11 multi-hop communications

- modeling the hidden terminal problem

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Introduction – motivation (1/4)

- Motivation
  - The performance of packet radio system with hidden terminal degrades significantly.
  - CSMA can't cope with hidden terminal problem.
  - 802.11 MAC (CSMA/CA) can't eliminate the hidden terminal problem in multi-hop ad-hoc mode either.
  - Mathematical modeling of the hidden terminal problem, e.g. throughput and delay is expected, as well as a solution proposal.
  - The latest development in multihop MAC are based on Leonard's work in 1975 [2] [3].

Introduction – basic concept (2/4)

- Basic concept review:
  - Hidden terminal problem:

    Both of terminal A and B want to send data to C, both A and B sense C is free, when they send to C, their packets collide at C.
  - Carrier Sense Medium Access
    - Sensing the medium before transmitting.
    - Deferring the transmission to a later time, if the medium is busy.
    - Transmitting, if the medium is sensed as free.
  - 802.11 MAC mechanism to cope with hidden terminals
    - Virtual carrier sense mechanism: RTS, CTS, NAV.
    - NAV State is combined with the clear channel assessment (CCA), which is the physical carrier sense, to indicate the busy state of the medium.

Introduction – Notation (3/4)

- Following important system variables have been defined:

S: channel throughput rate, which is the average number of packets generated per transmission time, i.e., it is the input rate normalized with respect to T.

T: time required for transmission of a packet, which is assumed to be fixed length. Without loss of generality, we choose T = 1.

G: mean offered traffic rate (including packets to be retransmitted). $G \geq S$.

$\overline{X}$: avergage retransmission delay.

τ : propagation delay.

δ : normalized retransmission delay. $\delta = \overline{X}/T$.

α : normalized propagation delay. $\alpha = \tau/T$.

Introduction – throughput characteristics (4/4)

The basic equation for the throughput S of nonpersistent CSMA:

$$S = \frac{Ge^{-\alpha G}}{G(1+2\alpha)+e^{-\alpha G}}$$

The throughput equation for 1-persistent CSMA is given by:

$$S = \frac{G\left[1+G+\alpha G\left(1+G+\alpha G/2\right)\right]e^{-G(1+2\alpha)}}{G(1+2\alpha)-\left(1-e^{-\alpha G}\right)+\left(1+\alpha G\right)e^{-G(1+\alpha)}}.$$

Hidden terminal problem – the model

- Environment assumption: a lardge number of terminals communicating with a single station over a shared radio channel. All terminals are in line-of-sight and within range of the station but not necessarily with respect to each other.
- Hearing graph matrix definition:
    - by definition, terminal i ”hears” terminal j if they are within range and in line-of-sight of each other.

$$m_{ij} = \begin{cases} 1, & if \ i \ hears \ j \\ 0, & otherwise \end{cases}$$

Hidden terminal problem – the model

- Partition of M: All terminals with identical rows or collums in M are in one group. Thus, all terminals within a group hear exactly the same subset of terminals in the population.
- Hearing graph: A link between two nodes k and l represents the fact that group k and l hear each other. Let h(i) be the set of groups that group i can hear. We define:
    - Independent groups: any group can only hear only itself.
    - Dependent groups: there are inter-group hearing.

$$M = \begin{pmatrix} 1 & 1 & & 0 & 0 \\ 1 & 1 & & 0 & 0 \\ & \cdots & \vdots & \cdots & \\ 0 & 0 & & 1 & 1 \\ 0 & 0 & & 1 & 1 \end{pmatrix}$$

Hidden terminal problem – the model

- Traffic model:

  Let S_i be the throughput of goupr *i*, let *S* be the total throughput and utilization of the channel.

$$S = \sum_{i=1}^{N} S_i$$

$$\delta = (S_1, \quad S_2, \quad \cdots, \quad S_N),$$

$$u = (u_1, \quad u_2, \quad \cdots \quad u_N), \quad where\, u_i = (S_i / S), \quad u$$

describes a direction in N-dimensional space.

- Channel capacity: the capacity of the channel along the direction *u* is defined as:

$$c(u) = \max_{0 \le S \le 1} S$$

Hidden terminal problem - analysis

- We wish to anser two basic questions:
  - Question 1: Given an input pattern u, what is the channel capacity C(*u*)? In other words: Is a given set of input rates achievable or does it saturate the channel?
  - Question 2: For a given achievable set of input rates, what is the relative performance of the various groups?

- Let's first answer the questions with regard to 1-persistent CSMA of the independent groups case.

Hidden terminal problem –1-persistent CSMA, independent group case

- By definition, a packet transmission is said to be *i-successful* if the packet is free from interference caused by packets from group *i*.
- An arbitrary packet from group *i* is successful if the following two mutually independent conditions are satisfied:
  - *e1: The packet transmission is i-successful.*
  - *e2. The packet is j-successful, for all j != i.*

Hidden terminal problem –1-persistent CSMA, independent group case

- According to the throughput equation of 1-persistent CSMA without hidden terminal, we have:

$$\Pr(e_1) = \frac{[1+G_i+\alpha G_i(1+G+\alpha G_i/2)]\exp\{-G(1+2\alpha)\}}{G_i(1+2\alpha)-(1-\exp\{-\alpha G_i\})+(1+\alpha G_i)\exp\{-G_i(1+a)\}}$$

- We can also get (more detail see pp1419 [2]):

$$\Pr(e_2) = \prod_{j\neq i} \frac{(1+\alpha G_j)\exp\{-2G_j\}}{G_j(1+2\alpha)-(1-\exp\{-\alpha G_j\})+(1+\alpha G_j)\exp\{-G_j(1+\alpha)\}}$$

Hidden terminal problem –1-persistent CSMA, independent group case

- Conditions e1 and e2 are mutually indepedent, we have

$$P_{si} = \frac{S_i}{G_i} \Pr\{e_1\} \Pr\{e_2\}$$

- The probability of success of an arbitrary packet from group *i* is:

$$\Pr_{si} = \frac{S_i}{G_i} = \frac{[1 + G_i + \alpha G_i (1 + G + \alpha\, G_i/2)]}{(1 + \alpha G_i) \exp\{-G_i (1 - 2a)\}} \prod_{j=1}^{N} \frac{(1 + \alpha G_j) \exp\{-2G_j\}}{G_j (1 + 2\alpha) - (1 - \exp\{-\alpha G_j\}) + (1 + \alpha G_j) \exp\{-G_j (1 + \alpha)\}}$$

Hidden terminal - examples

- The simulation results show that channel capacity experiences a drastic decrease between the two cases: N=1, no hidden terminals and N=2.
- For N>=2, slotte ALOHA perforn better than CSM.

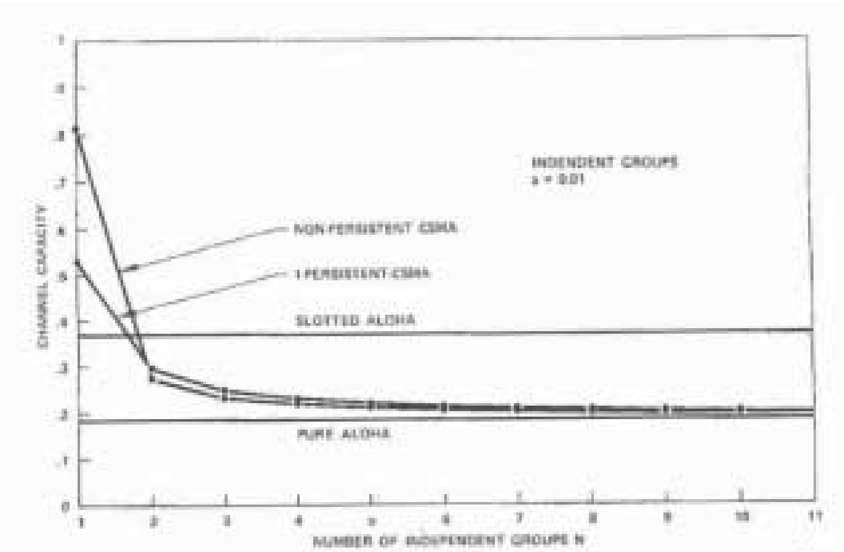

Fig. 1. Independent groups case – channel capacity versus the number of groups

Busy-Tone Multiple-Access (BTMA)

- Assumption: the station is within range and in line-of-sight of all terminals. The total available bandwidth is to be divided into two channels: a message channel and a busy-tone (BT) channel.
- Operations: as long as the station senses (terminal) carrier on the incoming message channel it transmits a (sine wave) busy tone signal on the busy tone channel.Terminal dertermine the state of the message channel by sensing the busy-tone channel.

Busy-Tone Multiple-Access (BTMA) Throughput characteristics

- Under stationary conditions and the model assumptions, a lower bound on the channel utilization S_l is given by:

$$S \geq S_l = \frac{b_m}{W} \frac{\exp(-\gamma m(0, T_m))}{\overline{B} + \overline{I}}$$

Busy-Tone Multiple-Access (BTMA) Numerical results

- When all the system parameters have fixed values, the information capacity of the channel is defined as the maximum achievable throughput, which is obtained at an optimum value of the system parameters.
- The table I shows that the lower bound and upper bounds are very close, which means our results are quite accurate.

TABLE I
ACCURACY OF THE APPROXIMATIONS

	τ	S_l	S_u	f
$F = 10^{-3}$, $\psi = 10^{-3}$, $t_d = 7 \times 10^{-4}$	10	0.0897	0.0897	0.0008
	100	0.4580	0.4581	0.0084
	400	0.6245	0.6269	0.0333
	500	0.6201	0.6238	0.0414
	600	0.6084	0.6137	0.0495
$F = 10^{-2}$, $\psi = 10^{-3}$, $t_d = 7 \times 10^{-4}$	10	0.0890	0.0890	0.0006
	100	0.4586	0.4387	0.0067
	500	0.6411	0.6440	0.0334
	600	0.6338	0.6380	0.0400
	700	0.6222	0.6279	0.0465
$F = 10^{-1}$, $\psi = 10^{-3}$, $t_d = 5 \times 10^{-4}$	10	0.0818	0.0818	0.0004
	100	0.4443	0.0444	0.0045
	500	0.6635	0.6653	0.0226
	600	0.6625	0.6651	0.0271
	700	0.6565	0.6599	0.0315
$F = 0.5$, $\psi = 10^{-3}$, $t_d = 5 \times 10^{-4}$	10	0.0473	0.0473	0.0002
	100	0.3206	0.3206	0.0021
	500	0.6318	0.6322	0.0106
	1000	0.6807	0.6825	0.0210
	2000	0.6406	0.6476	0.0417
$F = 0.7$, $\psi = 10^{-3}$, $t_d = 5 \times 10^{-4}$	100	0.2249	0.2249	0.0012
	500	0.5511	0.5512	0.0062
	1000	0.6540	0.6546	0.0125
	2000	0.6830	0.6853	0.0248
	3000	0.6583	0.6639	0.0370
$F = 0.9$, $\psi = 10^{-3}$, $t_d = 5 \times 10^{-4}$	1000	0.4692	0.4692	0.0041
	2000	0.6018	0.6020	0.0083
	3000	0.6552	0.6558	0.0124
	4000	0.6779	0.6790	0.0165
	5000	0.6858	0.6876	0.0206

Busy-Tone Multiple-Access (BTMA) Numerical results

- In Fig. 1, we plot for various F (the false alarm probability), the maximum capacity of the channel.
- It shows that certain range yields the best performance.
- Note: ψ is the fraction of total BW assigned to busy tone channel.

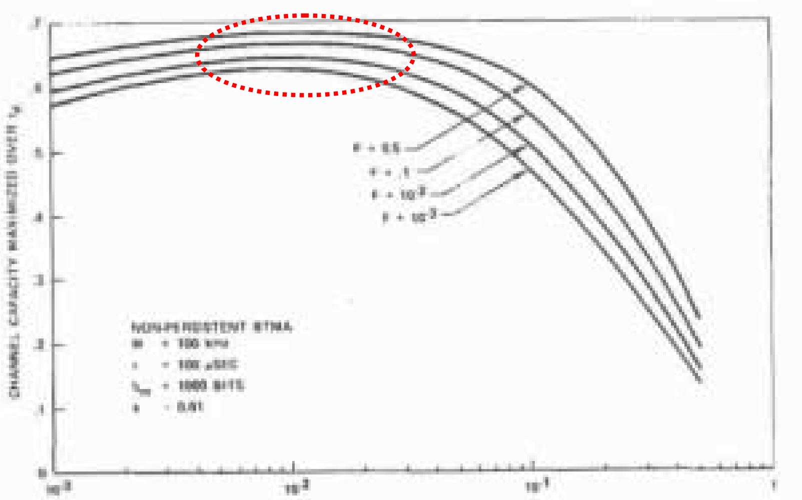

Fig. 1 BTMA—channel capacity (maximized over t_d) versus ψ.

Busy-Tone Multiple-Access (BTMA) Numerical results

- Table II shows that BTMA is quite good solution to the ”hidden terminal” problem. It provides a max. channel capacity of 0.68 and 0.72 with hidden terminal, comparing with 0.82 for nonpersistent CSMA with no hidden terminals.

TABLE II
CAPACITY C FOR THE VARIOUS PROTOCOLS CONSIDERED (a = 0.

Protocol	Capacity C
Pure ALOHA	0.184
Slotted ALOHA	0.368
1-persistent CSMA	0.529
Slotted 1-persistent CSMA	0.531
Nonpersistent BTMA	
W = 100 kHz	0.680
W = 1000 kHz	0.720
0.1-persistent CSMA	0.791
Nonpersistent CSMA	0.815
0.03-persistent CSMA	0.827
Slotted nonpersistent CSMA	0.857
Perfect scheduling	1.000

Homework

- HW1: Why BTMA can cope with hidden terminal problem, while CSMA can do nothing, and 802.11 MAC tried to do so but failed to eliminate the problem?
- HW2: Please give an realization of 5x5 hearing Matrix for dependent groups with hidden terminal.
- HW3: Please prove the throughput equation P_{si} for non-persistent CSMA independent group case.

Reference

[1] Found A. Tobagi, Leonard Kleinrock, ”Packet switching in radio channels: Part II – the hidden terminal problem in carrier sense multiple-access and the busy-tone solutions”, vol. com-23, no.12, 1975, IEEE Trans. on Communications.

Some latest works:

[2] J.J. Garcia-Luna-Aceves, Chane L. Fullmer, ”Floor acquisition multiple access (FAMA) in single-channel wireless networks”, Mobile Networks and Applications, NO.4, 1999

[3] J.J. Garcia-Luna-Aceves, Asimakis Tzamaloukas, ”Reciever-Initiated Collision Avoidance in Wireless Networks”, Wireless Networks NO.8, 2002