

CMPE 257: Wireless and Mobile Networking

SET 3a:

Medium Access Control Protocols

MAC Protocol Topics

- Modeling and performance analysis of collision avoidance MAC protocols

MAC Protocols

- Contention based MAC protocols:
 - Collision avoidance (CA) with CSMA to combat the ``hidden terminal'' problem.
 - Include IEEE 802.11, FAMA, RIMA, etc.
- Schedule based MAC protocols:
 - Collision free
 - Require time-slotted structure

Contention-based MAC protocols

- Focus on sender-initiated MAC: IEEE 802.11 and its variants.
- Most work is simulation based, some analytical work is confined to single-hop networks.
- Interaction between spatial reuse and CA needs closer investigation.

Analytical Work

- Takagi and Kleinrock [TK84] use a simple network model to derive the optimal transmission range of ALOHA and CSMA protocols for multi-hop networks. (*An interesting read.*)
- Wu and Varshney [WV99] use this model to derive the throughput of non-persistent CSMA and some busy tone multiple access (BTMA) protocols.
- We [WG02] follow Takagi and Wu's line of modeling to analyze collision avoidance MAC protocols in multi-hop ad hoc networks.

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Preliminaries for Markov Regenerative Processes

- Limiting probability of state j :
Def.: $P(j) = \lim_{t \rightarrow \infty} P(X(t) = j)$
Calc.: $P(j) = E(\text{time in } j \text{ in one cycle}) / E(\text{time of one cycle})$
- Steady-state probability of state j ($R(j)$):
Def: The (long-run) proportions of transition into state j .
- $D(j)$: Mean time spent in state j per transition.
- Theorem to calculate $P(j)$:

$$P(j) = \frac{R(j)D(j)}{\sum_i R(i)D(i)}$$

- Throughput

$$Th = P_{\text{success}}$$

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Analytical Modeling

- Network model
 - Nodes are randomly placed according to 2-dimensional Poisson distribution:

$$p(i, S) = \frac{(\lambda S)^i}{i!} e^{-\lambda S}$$

where i is the # of nodes, S is the size of an area and λ is the density. *Note: λS is the average # of nodes.*

- Each node has equal transmission and reception range R .
- The average number of competing stations within a station's transmission and reception range R is N .

$$N = \lambda \pi R^2$$

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Analytical Modeling

- Key assumptions
 - Time slotted: each slot lasts τ .
 - We use the time-slotted system as an approximation.
 - Each node is ready to transmit independently in each time slot with probability p .
 - Each node transmits independently in each time slot with probability p' .
 - Heavy traffic assumption: All node always have packets to be sent.
 - Perfect collision avoidance (a FAMA property), later extended to imperfect collision avoidance

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Channel Model

- Model the channel as a circular region where there are some nodes.
- Nodes within the region can communicate with one another but have weak interaction with nodes outside the channel.
- Channel status is only decided by the successful and failed transmissions of nodes in the region.
- The radius of the circular region R' is modeled by αR where $1/2 \leq \alpha \leq 2$ and there are in effect $M = \alpha^2 N$ nodes in the region.

$$M = \lambda \pi R'^2 = \lambda \pi (\alpha R)^2 = \alpha^2 (\lambda \pi R^2) = \alpha^2 N$$

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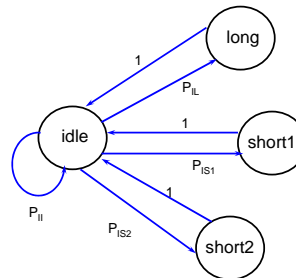
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Channel Model

- 4-state Markov chain



Channel: A region within which all the nodes share the same view of busy/idle state and have weak interactions with nodes outside.

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Channel Model

- Calculate the duration of states and transition probabilities between states.
- Calculate the long-term probability that the channel is in idle state and get the relationship between the *average* ready probability p and the *average* transmission probability p' :
 - $p' = p \cdot \text{Prob}\{\text{the channel is sensed idle}\}$.
- p' is more important here, because it is the actual transmission probability after collision avoidance and resolution.

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Channel States

- Idle:** the channel is sensed idle.

$$T_{idle} = \tau$$

- Long:** the state when a successful four-way handshake is done.

$$T_{long} = l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau$$

- Short1:** the state when more than one node around the channel transmit RTS packets at the same time slot.

$$T_{short1} = l_{rts} + \tau$$

- Short2:** the state when one node around the channel initiates a failed handshake to nodes outside the region.

$$T_{short2} = l_{rts} + l_{cts} + 2\tau$$

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Transition Probabilities

■ Idle to Idle P_{ii}

- There are on average M nodes competing for the channel:

$$M = \lambda \pi R^2 = \lambda \pi (\alpha R)^2 = \alpha^2 (\lambda \pi R^2) = \alpha^2 N$$

- The prob. of having i nodes competing for the channel:

$$M^i e^{-M} / (i!)$$

- The average trans. prob. is that none of them transmits in the next slot:

$$P_{ii} = \sum_{i=0}^{\infty} (1-p')^i \frac{M^i}{i!} e^{-M} = e^{-p'M}$$

Transition Probabilities

■ Idle to Long P_{il}

- Let P_s denote the prob. that a node starts a successful 4-way handshake at a time slot.
- The transition happens if only one of i nodes initiates the above handshake while the other nodes do not transmit:

$$P_{il} = \sum_{i=1}^{\infty} i p_s (1-p')^{i-1} \frac{M^i}{i!} e^{-M} = p_s M e^{-p'M}$$

Transition Probabilities

■ Idle to Short1 P_{is1}

- Given i competing nodes, the prob. of more than one nodes competing in a time slot equals:

1- Prob. {no node transmits} - Prob. {only one node transmits}, i.e.,

$$1 - (1-p')^i - i p' (1-p)^{i-1}$$

- So the average transition prob. equals:

$$P_{is1} = \sum_{i=2}^{\infty} [1 - (1-p')^i - i p' (1-p)^{i-1}] \frac{M^i}{i!} e^{-M} = 1 - (1 + M p') e^{-p'M}$$

■ Idle to Short2 $P_{is2} = 1 - P_{ii} - P_{il} - P_{is1}$

Transition Probabilities

- Let π_i, π_l, π_{s1} and π_{s2} denote the steady-state probs. of states **Idle**, **Long**, **Short1** and **Short2** respectively.

- From the Channel Markov Chain, we have

$$\begin{aligned} \pi_{ii} P_{ii} + \pi_l + \pi_{s1} + \pi_{s2} &= \pi_i \\ \pi_i P_{il} + 1 - \pi_i &= \pi_l \\ \pi_i &= \frac{1}{2 - e^{-p'M}} \end{aligned}$$

Channel Idle State

- We can calculate the long-term prob. that the channel is found idle:

$$\begin{aligned} \Pi_i &= \frac{\pi_i T_{idle}}{\pi_i T_{idle} + \pi_l T_{long} + \pi_{s1} T_{short1} + \pi_{s2} T_{short2}} \\ &= \frac{T_{idle}}{T_{idle} + P_{il} T_{long} + P_{is1} T_{short1} + P_{is2} T_{short2}} \\ &\quad (\pi_l P_{il} = \pi_l, \pi_i P_{is1} = \pi_{s1} \text{ and } \pi_i P_{is2} = \pi_{s2}) \end{aligned}$$

- Then we obtain the relationship between ρ' and ρ . ($\rho' = \rho \Pi_i$)

$$\rho' = \frac{\rho T_{idle}}{T_{idle} + P_{il} T_{long} + P_{is1} T_{short1} + P_{is2} T_{short2}} = F(\rho, p_s)$$

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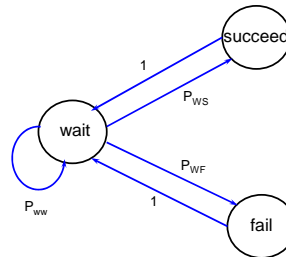
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Node Model

- 3-state Markov chain



We derive the saturation throughput with regard to ρ' assuming that each node always has a packet to send.

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Nodal States

- Wait**: the state when the node defers for other nodes or backs off.

$$T_{wait} = \tau$$

- Succeed**: the state when the node can complete a successful 4-way handshake.

$$T_{succeed} = l_{rts} + l_{cts} + l_{data} + l_{ack} + 4\tau$$

- Fail**: the state when the node initiates an unsuccessful handshake.

$$T_{fail} = l_{rts} + l_{cts} + 2\tau$$

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Transition Probabilities

- Wait to Succeed** P_{ws}

- We first need to calculate $P_{ws}(r)$, the prob. that node x initiates a successful 4-way handshake with node y at a time slot given that they are apart at a distance r . (Details omitted here.)

- The *pdf* of distance r follows:

$$f(r) = 2r, \quad 0 < r < 1$$

where we have normalized r with regard to R .

- Then we have

$$P_{ws} = \int_0^1 2r P_{ws}(r) dr$$

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Transition and Steady-State Probabilities

- **Wait to Wait** $P_{ww} = (1-p')e^{-p'N}$
 - The node does not initiate any transmission and there is no node around it initiating a transmission.
- Let π_s, π_w and π_f denote the steady-state probs. of states **Succeed**, **Wait** and **Fail** respectively.
- From the Node Markov Chain, we have

$$\begin{aligned} \pi_w P_{ww} + \pi_s + \pi_f &= \pi_w \\ \pi_w P_{ww} + 1 - \pi_w &= \pi_w \\ \pi_w &= \frac{1}{2 - (1-p')e^{-p'N}} \end{aligned}$$

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Steady-State Probabilities and Throughput

- The steady-state prob. of **Succeed**

$$\pi_s = \pi_w P_{ws} = \frac{P_{ws}}{2 - (1-p')e^{-p'N}}$$

- Please note $\pi_s = p_s$, so we obtain another equation that links p_s and p' and can solve p_s . (Ref [Slide #17](#))

$$p_s = G(p', p)$$

- Then we can calculate throughput as follows:

$$\begin{aligned} Th &= \frac{\pi_s \cdot l_{data}}{\pi_w T_w + \pi_s T_s + \pi_f T_f} \\ &= \frac{\pi_s \cdot l_{data}}{\pi_w T_w + \pi_s T_s + (1 - \pi_w - \pi_s) T_f} \end{aligned}$$

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Throughput Analysis

- Throughput Th which is a complex function of p' and other variables.
- No closed-form formulae can be given. However, Matlab or similar tools can be used to obtain the numerical results. *An exercise: Reproduce the analytical results in [\[WG02\]](#).*
- We compare the performance of collision avoidance protocols with the ideal CSMA protocol (with a separate, perfect acknowledgment channel) reported in [\[WV99\]](#).

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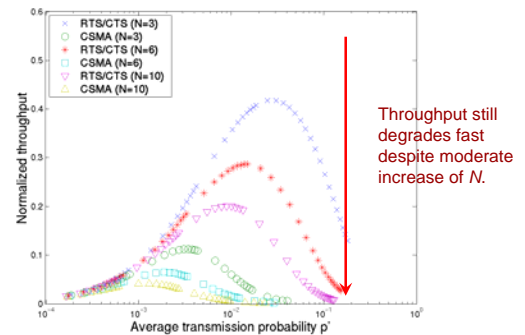
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Analytical Results

- Throughput for long data packet: $rts = cts = ack = 5 \tau$, $data = 100 \tau$.



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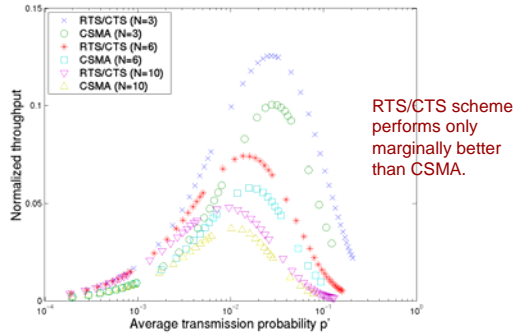
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Analytical Results

- Throughput for short data packet: $rts = cts = ack = 5 \tau$, $data = 20 \tau$.



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Predictions from the Analysis

- RTS/CTS scheme outperforms CSMA protocol even when its overhead is rather high, showing the importance of CA in contention-based MAC.
- CA becomes more and more ineffective when the number of competing nodes within a region increases, because the probability of transmission in each time slot is very small.
- Due to "hidden terminals," the number of nodes that can be accommodated in a network is quite limited, much smaller than that in a single-hop network.

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Simulation Environment

- GloMoSim 2.0 as the network simulator.
- Nodes are distributed uniformly in concentric circles to approximate the Poisson distribution.
- Each node chooses one of its neighbors randomly as the destination whenever a packet is generated.
- Performance metrics are obtained from the innermost N nodes and averaged over 50 network topologies.
- We vary N , the average number of competing nodes in a neighborhood, to change the contention level (neighbors and hidden nodes).

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Simulation Environments

- 2Mbps channel with direct sequence spread spectrum (DSSS) parameters

RTS	CTS	data	ACK	DIFS	SIFS
20-byte	14-byte	1460-byte	14-byte	50 μ s	10 μ s

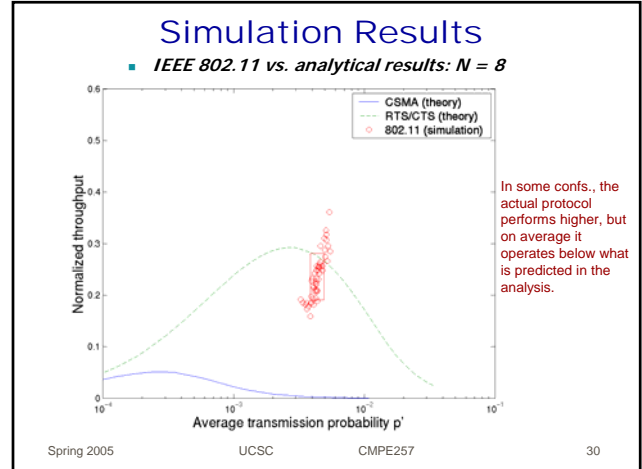
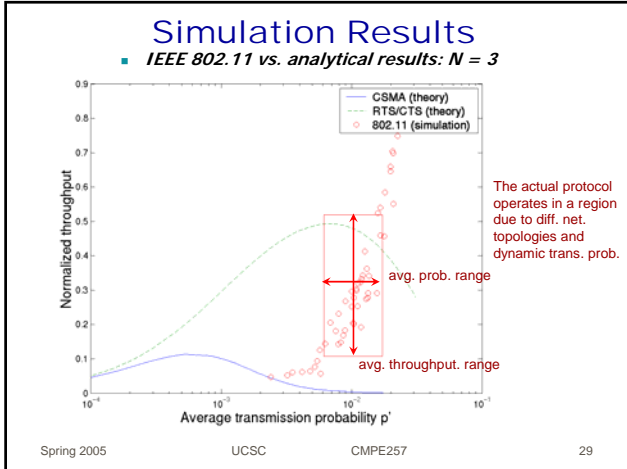
contention window	slot time	sync. time	prop. delay
31-1023	20 μ s	192 μ s	1 μ s

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- ### Simulation Results
- IEEE 802.11 MAC protocol has inherent fairness problem, which can lead to very high throughput in some configurations.
 - IEEE 802.11 MAC protocol does not have *perfect* collision avoidance and cannot achieve the max throughput predicted in the analysis in most cases.
 - When network size increases, CA becomes less effective and increasing spatial reuse becomes more important.
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- ### Summary
- Collision avoidance is still very useful, especially in sparse networks.
 - Collision avoidance loses its effectiveness in dense networks:
 - More stringent multi-hop coordination
 - Reduced spatial reuse
 - The fairness problem which refers to the severe throughput degradation of some nodes is another actively pursued research topic.
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Suggested Work

- Read the implementation of FAMA and IEEE 802.11 MAC in GloMoSim (you may need to migrate FAMA from version 1.2.3 of GloMoSim as FAMA is no longer included in newer versions of GloMoSim.) You can also use ns2 which is more up-to-date.
- Evaluate the performance of FAMA and IEEE 802.11 MAC in fully-connected networks, networks with an access point (AP) and multi-hop networks.
- See how collision avoidance and spatial reuse can influence the actual protocol throughput and see if any improvement can be done.
- Implement RIMA protocols and see if you can find sensible ways to decide some variables that are not specified in the RIMA protocols.

References I

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- [TK84] H. Takagi and L. Kleinrock, *Optimal Transmission Range for Randomly Distributed Packet Radio Terminals*, IEEE Trans. on Comm., vol. 32, no. 3, pp. 246-57, 1984.
- [WV99] L. Wu and P. Varshney, *Performance Analysis of CSMA and BTMA Protocols in Multihop Networks (I). Single Channel Case*, Information Sciences, Elsevier Sciences Inc., vol. 120, pp. 159-77, 1999.
- [WG02] Yu Wang and JJ, *Performance of Collision Avoidance Protocols in Single-Channel Ad Hoc Networks*, IEEE Intl. Conf. on Network Protocols (ICNP '02), Paris, France, Nov. 2002.