ECE257A Review Problems Lecture 9-11

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I. Lecture 9. MAC overview; CSMA

1. Slotted ALOHA and unslotted ALOHA: operations, pros and cons, and efficiency.

2. How does collision detection and exponential backoff work in CSMA/CD? Why is exponential backoff needed?

Answer:

1. Slotted ALOHA : Time is divided into equal size slots, nodes are synchronized, and all nodes can detect collision. When the node obtains a fresh frame, transmits in next slot. If no collision, send a new frame in next slot. If collision, node retransmits frame in each subsequent slot with probability p until success.

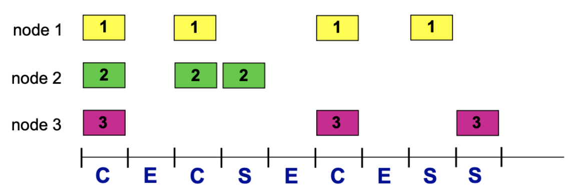

Fig. 1. Slotted Aloha

Pure ALOHA : When frame first arrives, transmit immediately. Upon collision, retransmit with probability p.

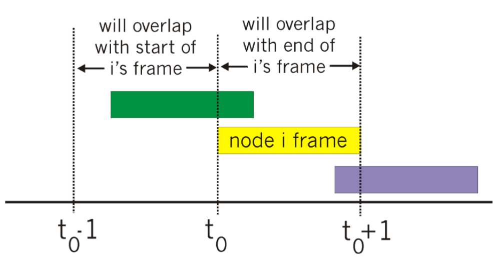

Fig. 2. Pure Aloha

Slotted ALOHA vs. Pure ALOHA		
Pure ALOHA	Simpler than slotted ALOHA; no clock synchronization.	Collisions can occur and only 18% maximum efficiency.
Slotted ALOHA	Single active node can continuously transmit at full rate of channel. Simple, highly decentralized, only need to sync each slot.	Collisions, wasting slot, inefficient collision resolution, idle slots, under-utilizing channel. Requires clock synchronization.

2. CSMA/CD : Listen before transmission. If the channel is idle, transmit the entire frame. If the channel is sensed busy, defer transmission. Collisions can still occur, and propagation delay means two nodes may not hear each other's transmission. Collision detection measures signal strengths and compares transmitted vs. received signals. Collision is detected within a short time and colliding transmission is aborted. After aborting, enter Binary Exponential Backoff (BEB) to avoid collisions : Transmitter chooses K at random from $0, 1, 2, ..., 2m - 1$ after m collisions. The transmitter waits for $K \times 512$ bit times and returns to sensing.

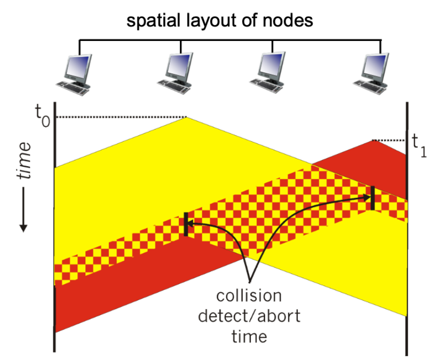

Fig. 3. CSMA/CD

II. Lecture 10. CSMA

1. Pros and cons of major MAC paradigms: channel partitioning, taking turns, random access

2. Why carrier sensing alone doesn't prevent collision in wireless networks? Why CSMA/CD doesn't work for wireless networks?

3. Understand the CSMA/CA operations in 802.11

4. How does random backoff work in 802.11 CSMA/CA?

5. What's hidden terminal? How does it affect WiFi performance? How does RTS/CTS remedy the problem?

6. What's exposed terminal? How does it affect WiFi performance?

7. Understand the differences between bit-rate, capacity, and throughput.

8. What's frame fragmentation and aggregation? How do they affect 802.11 network performance?

9. Qualitative understand of the relation between SNR and link throughput.

10. What are the major challenges for rate adaptation in 802.11?

11. Cause and effect of the rate anomaly in 802.11.
Answer:
1.

Pros and cons of major MAC paradigms		
Protocol	Pros	Cons
Polling	Low collision rate; easy to implement.	Overhead associated with polling; single point of failure; latency in waiting for the central coordinator to finish polling others.
Token Passing	Low collision rate; easy to implement.	Overhead associated with passing the token; The token becomes a single point of failure; Latency in waiting for the token to become available.
TDMA	Low collision rate; full channel utilization in high traffic demand.	Low channel utilization in low traffic demand; need clock synchronization.
FDMA	Full channel utilization in high traffic demand; no clock synchronization.	Low channel utilization in low traffic demand.
CDMA	analog comm voice only	
Pure ALOHA	Simpler than slotted ALOHA; no clock synchronization.	Collisions can occur and only 18% maximum efficiency.
Slotted ALOHA	Single active node can continuously transmit at full rate of channel. Simple, highly decentralized, only need to sync each slot.	Collisions, wasting slot, inefficient collision resolution, idle slots, underutilizing channel. Requires clock synchronization.
CSMA/CD	Ability to detect collision and abort transmission. Priorities can be assigned to certain nodes.	Collisions can still occur. Wireless communication devices cannot listen while transmitting, so we cannot do CSMA for wireless.
CSMA/CA	analog comm voice only	

2. Collisions can still occur because propagation delay means two nodes may not hear each other's transmission. We cannot do CSMA/CD on a wireless network since wireless communication devices cannot listen while transmitting, they are usually half-duplex. The ratio of transmitted to received signal power is typically larger than 60dB, so transmission drowns out the ability of the radio to hear a collision. Even if the transmitter is full-duplex, what it hears may be different from what the receiver actually experiences.

3. CSMA/CA in 802.11 : If the sender senses the channel is idled, it transmits the entire frame. If senses the channel is busy then set a random back-off time, the timer counts down while the channel is idled, and transmits when the timer expires. If no ACK it means transmission failure, then increase random back-off interval. Receiver return ACK if the frame is received.

Forcing transmitters to wait for a random amount of time can reduce the change of collision. If the medium is sensed busy, the back-off time is picked between 0 and contention window size (CW) randomly. The back-off timer is then decremented in each slot until reaching 0 and then transmit. It is frozen if medium is busy. Collision may still occur if two transmitters pick the same back-off time. After every failed transmission attempt, it is assumed that a collision has occurred. Thus increasing the CW exponentially starting from 32 up to 1024, and reset to 32 upon success.

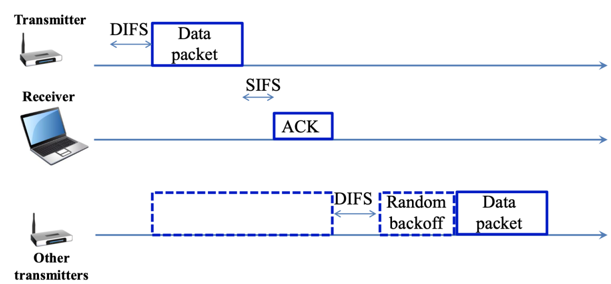

Fig. 4. CSMA/CA in 802.11

4. Random backoff in 802.11: Stations listen to the channel and transmit after DIFS plus the back-off time the channel is idled. Avoid collision by random back-off. Each station maintains a contention window (CW) initialized to $CW_{min} = 32$. Randomly pick a number k between $\{0, 1, ..., CW - 1\}$. Count down from k when the channel is idle, freeze the back-off countdown if the channel becomes busy during back-off, and start transmission when $k = 0$ if the channel is still idle. Double CW for every unsuccessful transmission up to CW_{max}, and reset CW to CW_{min} after every successful transmission.

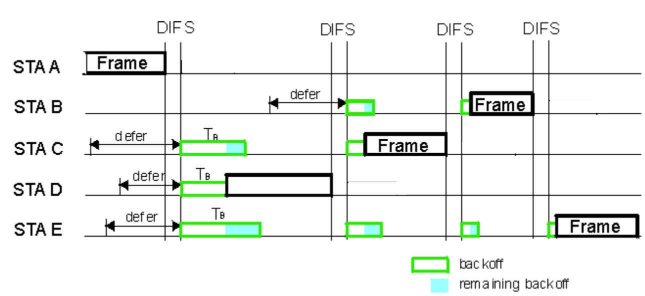

Fig. 5. CSMA/CA random back-off in 802.11

5. Hidden terminal problem: Client1 and Client 2 cannot

hear each other, and the lack of signaling between Client1 and Client2 causes collision at the access point. Their transmissions may overlap with higher probability even if they choose different CW sizes.

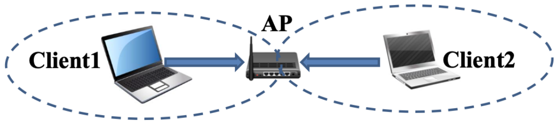

Fig. 6. Limitaion of CSMA/CA: hidden terminal problem

RTS/CTS: allow the sender to reserve the channel to avoid collisions of long data frames. The sender first transmits small request-to-send (RTS) packets using CSMA, and AP broadcasts clear-to-send (CTS) in response to RTS, CTS is heard by all nodes. The sender transmits data frame and other stations defer transmissions.

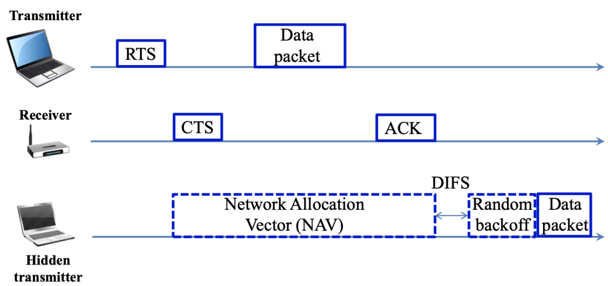

Fig. 7. RTS/CTS handshake: virtual carrier sensing

Virtual Carrier Sensing: Nodes maintain Network Allocation Vector (NAV), time that must elapse before a station can sense the channel for idle status, embedded in the duration field in RTS and CTS. The medium is considered to be busy throughout the NAV. RTS/ CTS only alleviates but does not completely solve the hidden terminal problem.

6. Exposed terminal problem: Carrier sensing prevents neighboring senders from transmitting simultaneously, though they do not interfere with each other's receiver. This reduces spatial reuse opportunities and thus reduces effective total network throughput. RTS/CTS only makes this problem worse.

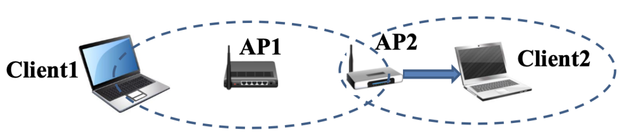

Fig. 8. Limitaion of CSMA/CA: exposed terminal problem

7.

Network capacity, Bit-rate and Throughput	
Network capacity	Theoretical capacity the network has.
Bit-rate	Network capacity eliminating the data rate required by protocol communication
Throughput	Bit-rate minus packet header overhead.

8. Large frame reduces overhead but is less reliable. We need to discard the frame even if only one bit is an error. The packet delivery ratio of an N-bit packet is $(1 - BER)^N$. Fragmentation is breaking a frame into small pieces so that a burst of bit-errors only affects small fragments. Aggregation is combining multiple small frames in order to reduce the overhead, but a minor error may corrupt the whole big frame. Maximizing net throughput is a trade-off between discarding more frames or having a larger overhead.

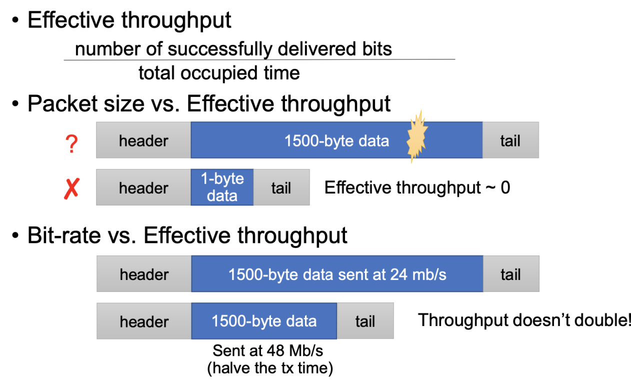

Fig. 9. Packet header overhead

9. According to Shannon's equation capacity gain

$$C = Blog_2(1 + SNR)$$

10. The major challenges of bit-rate adaptation in 802.11 are :

(a) Channel quality changes very quickly especially when the device is moving.

(b) The server and device can't tell the difference between poor channel quality due to interference/collision or distance (low signal level). Ideally, we want to decrease the rate due to interference/collision but not low signal strength.

11.

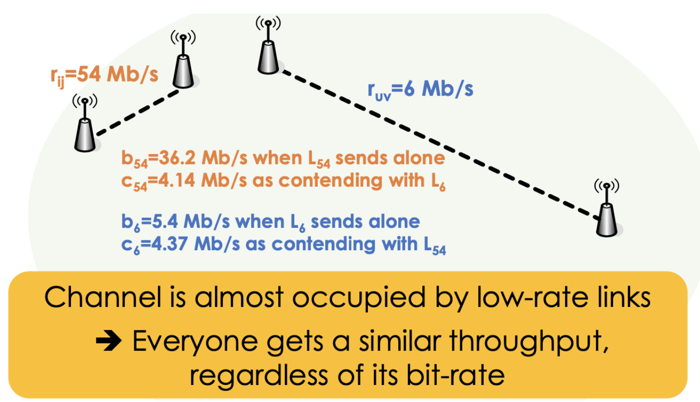

Fig. 10. 802.11 rate anomoly

Rate anomaly is the phenomenon that the throughput of a node sending at a high rate is degraded by a node sending at a low rate. The cause is that 802.11 supports multiple transmission bit rates each of which has a different modulation and coding scheme, among these rates it ensures packet fairness instead of time fairness. Packet fairness ensures each station has an equal probability to win the contention, so the average number of delivered packets for all nodes is roughly the same. Time fairness ensures each node occupies roughly the same proportion of channel time.

III. Lecture 11. MAC models

1. Basic concept of stochastic process, Markov process, Markov chain.

2. Markov chain concepts: transition probability, transition matrix, equilibrium state.

3. Basic properties of state vector, transition matrix.

4. Construct a Markov chain transition matrix for a given Markov chain problem

5. Model slotted ALOHA as a Markov chain and solve for its steady state; model slotted ALOHA

performance based on the steady-state model

6. Model unslotted ALOHA using Markov chain

7. Model CSMA/CD and CSMA/CA (under certain simplifications) using Markov chains

8. Model similar MAC protocols using Markov chains.

Answer:

1. Random process: A function whose output varies over time and is defined by a set of random variables.

Markov process: A memoryless random process, the value of the random variable at instant n depends only on its immediate past value at instant $n-1$. The value of random variable $S(n)$ represents the state of the system at a given time instance n.

Markov chain: A Markov process with a discrete state space. Memoryless property still holds, $S(n)$ is a function of $S(n-1)$ only.

2. Transition probability $p_{ij}(n)$: probability that system is in state i at time n, given that it was in state j at past time $n-1$, i.e.,

$$p_{ij}(n) = p[S(n) = i|S(n-1) = j]$$

If transition probability is independent of time, i.e.,

$$p_{ij} = p[S(n) = i|S(n-1) = j]$$

then the Markov chain is a homogeneous Markov chain.

Transition Matrix: Denote $s_i(n)$ as the probability that the system lies in state i in any time instance n, i.e., $s_i(n) = P[S(n) = i]$. Also, suppose there are m states in total. Then,

$$s_i(n) = \sum_{j=1}^{m} p_{ij} s_j(n-1)$$

We can express this in matrix form as: $s(n) = Ps(n-1)$ where

$$P = \begin{bmatrix} p_{11} & \dots & p_{1m} \\ \vdots & \ddots & \vdots \\ p_{m1} & \dots & p_{mm} \end{bmatrix}$$

is the state transition matrix. $s(n) = [s_1(n)s_2(n)...s_m(n)]^T$ is the state vector.

At steady state, as $N \to \inf$ the transition probabilities no longer depend on n and the state vector settles down to a fixed value that satisfies $Ps = s$. This also implies that the probability that the system lies in a certain state $s_i(n)$ and the components in P^n no longer depend on time n, each row in P^n comprises of identical values.

How to solve for the steady state s? $Ps = s$ alone is not solvable because P has a maximum rank of $m-1$, not full rank. Need one more equation

$$\sum_{i=1}^{m} s_i(n) = 1, n = 0, 1, ...$$

3. Because state vector $s(n)$ describes the probabilities of all possible states, we have

$$\sum_{i=1}^{m} s_i(n) = 1, n = 0, 1, ..,$$

The column of P represents the transition out of a given state, so we have

$$\sum_{i=1}^{m} p_{ij} = 1,$$

4.

5. Modeling Slotted ALOHA: Assume that users are allowed to transmit only at the start of a time step, time slot duration equals frame duration. N users each transmitting with probability p in each slot.

u_0: Probability that all users are idle.

u_1: Probability that exactly one user attempts to access.

$1 - u_0 - u_1$: Probability that more than one users attempt to access.

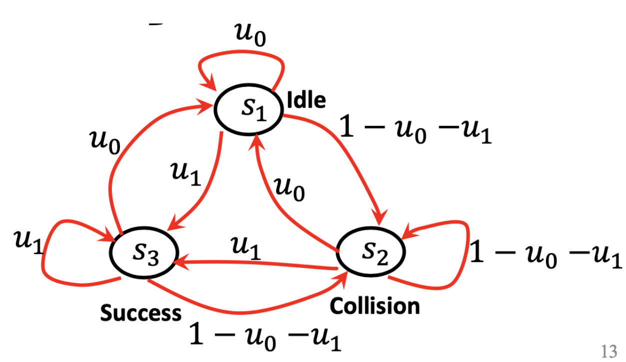

Fig. 11. Slotted ALOHA state transition diagram

Transition matrix

$$P = \begin{bmatrix} u_0 & u_0 & u_0 \\ 1-u_0-u_1 & 1-u_0-u_1 & 1-u_0-u_1 \\ u_1 & u_1 & u_1 \end{bmatrix}$$

At equilibrium, the state vector is obtained by solving two equations:

$$Ps = s, s_1 + s_2 + s_3 = 1$$

Solution:

$$s_1 = u_0, s_2 = 1 - u_0 - u_1, s_3 = u_1$$

The efficiency of slotted ALOHA equals the steady-state probability that the system lies in the success transmission state, i.e.,

$$E(p) = s_3 = u_1$$

The probability that k users attempt to access the channel is binomial:

$$u_k = \binom{N}{k} p^k (1-p)^{N-k}$$

so

$$E(p) = s_3 = u_1 = Np(1-p)^{N-1}$$

To achieve maximum efficiency, we need:

$$dE(p)/dp = 0$$

which yields $p = \frac{1}{N}$. Maximum efficiency

$$E^*(p) = (1 - \frac{1}{N})^{N-1}$$

Recall

$$lim_{n \to \inf} (1 + \frac{x}{n})^n = e^x$$

For large N,

$$E(p) \approx e^1$$

6. Modeling ALOHA: Assume users are allowed to transmit at any time they want. All frames have equal duration T. A collision occurs if a frame is sent at time t and there are other transmissions starting during the time period $t-T$ to $t+T$, so for a successful transmission at a given time step, the channel must be quiet and all other users must be idle for $2T$.

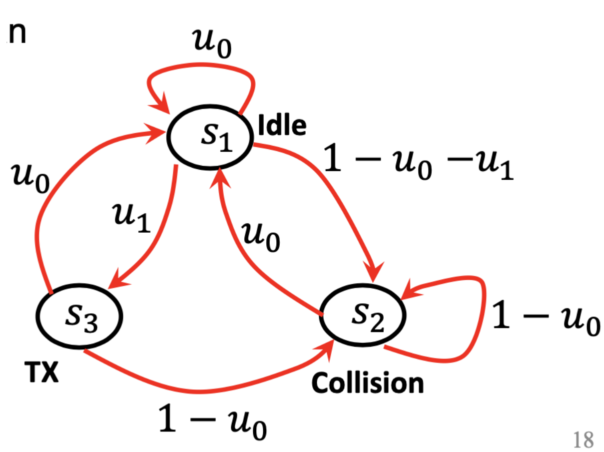

Fig. 12. ALOHA state transition diagram

u_0: Probability that all users are idle.

u_1: Probability that exactly one user attempts to access.

$1 - u_0 - u_1$: Probability that more than one users attempt to access

Transition matrix

$$P = \begin{bmatrix} u_0 & u_0 & u_0 \\ 1 - u_0 - u_1 & 1 - u_0 & 1 - u_0 \\ u_1 & 0 & 0 \end{bmatrix}$$

At equilibrium, the state vector is obtained by solving two equations:

$$Ps = s, s_1 + s_2 + s_3 = 1$$

Solution:

$$s_1 = u_0, s_2 = 1 - u_0 - u_0 u_1, s_3 = u_0 u_1$$

The efficiency of slotted ALOHA equals the steady-state probability that the system lies in the success transmission state, i.e.,

$$E(p) = s_3 = u_0 u_1$$

Probability that k users attempt to access the channel is binomial:

$$u_k = \binom{N}{k} p^k (1-p)^{N-k}$$

To achieve maximum efficiency, we need:

$$dE(p)/dp = 0$$

which yields

$$p = \frac{1}{2N}$$

Maximum efficiency

$$E^*(p) = \frac{1}{N}(1 - \frac{1}{2N})^{2N-1}$$

Recall

$$lim_{n \to \inf} (1 + \frac{x}{n})^n = e^x$$

So for large N,

$$E(p) \approx \frac{1}{2e}$$

7. Modeling CSMA/CD: Assume there are N users, frame duration τ_t. The Time step of Markov chain equals the collision detection latency $T = \tau_c$, also $n = \tau_t/\tau_c \gg 1$. The probability that a user attempts transmission equals a, $a < 1$ so this is implicitly modeling a random back-off strategy, the longer back-off window is equivalent to smaller a. A user can have at most one frame waiting for transmission, i.e. no queueing. Frame arrival probability equals a. All users have the same contention window size instead of using binary exponential back-off.

u_0: Probability that all users are idle.

u_1: Probability that exactly one user attempts to transmit.

$$u_k = \binom{N}{k} a^k (1-a)^{N-k}$$

t_n: Once started, a transmission takes n slots to complete

Transition matrix

$$P = \begin{bmatrix} u_0 & 0 & 0 & 0 & \dots & 0 & 1 & 1 \\ u_1 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 1 & 0 & 0 \\ 1 - u_0 - u_1 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \end{bmatrix}$$

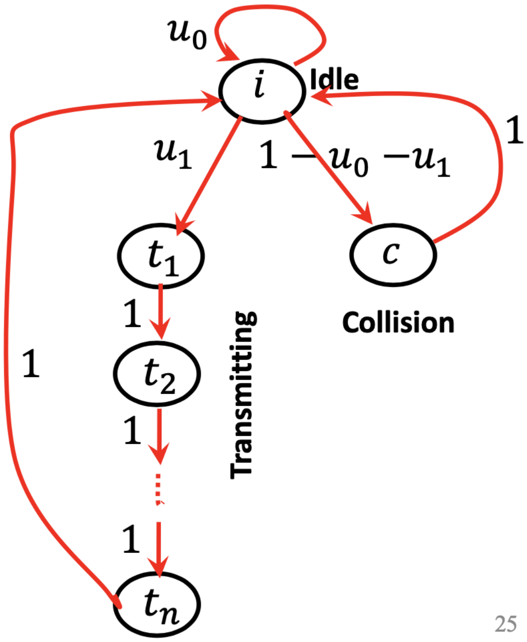

Fig. 13. CSMA/CD state transition diagram

State vector

$$s = [s_i s_{t_1} s_{t_2} ... s_{t_n} s_c]^T$$

At equilibrium, the state vector is obtained by solving two equations:

$$Ps = s, \sum s = 1$$

Solution:

$$s = \frac{1}{2 + u_1(n-1) - u_0} \begin{bmatrix} 1 \\ u_1 \\ u_1 \\ \vdots \\ u_1 \\ 1 - u_0 - u_1 \end{bmatrix}$$

Effective throughput:

$$Th = \sum_{i=1}^{n} s_{t_i} = \frac{nu_1}{2 + u_1(n-1) - u_0}$$

8. Modeling 802.11 CSMA/CA: Assume there are N users, frame duration τ_t, maximum back-off window size if ω slots. The duration of one contention window slot equals the propagation delay plus carrier sensing delay. The Time step of Markov chain equals one contention window slot. Duration of one frame equals n contention window slots. The probability that a user has a frame waiting to be transmitted at any time slot equals a. A user can have at most one frame waiting, i.e. no queueing. All users have the same contention window size ω, instead of using binary exponential back-off.

The probability that a user fires at a particular back-off window slot is given by $\alpha = 1/\omega$, so the user population seen by each slot in the back-off window is $N' = \alpha N = N/\omega$. The probability that k users attempt a transmission during a given reservation slot is:

$$u_k = \binom{N'}{k} a^k (1-a)^{N'-k}$$

x: The probability that no users have frame to send across the entire contention window (ω slots) $x = u_0^\omega$

y: probability that only one user in any of the reservation slots requests a transmission and all users in the previous slots did not attempt to access the channel.

$$y = u_1 + u_0 u_1 + u_0^2 u_1 + ... + u_0^{\omega-1} u_1 = u_1 \frac{1 - u_0^\omega}{1 - u_0}$$

z: the probability that more than one user in any of the reservation slots requests a transmission $z = 1 - x - y$

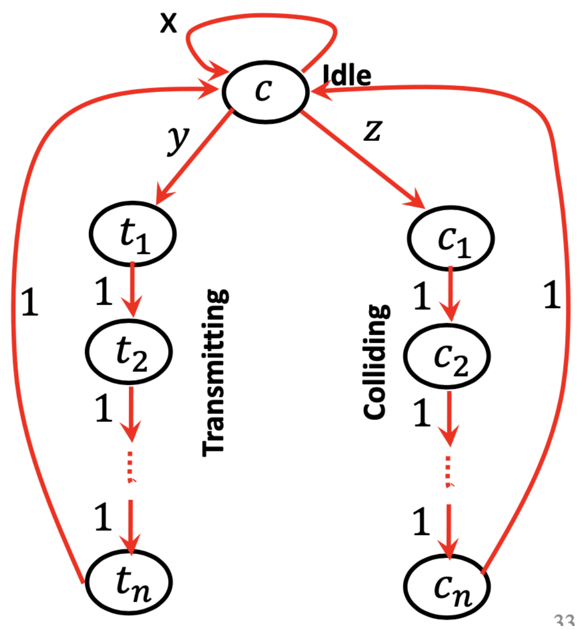

Fig. 14. CSMA/CA 802.11 state transition diagram

Transition matrix

$$P = \begin{bmatrix} x & 0 & 0 & 1 & 0 & 0 & 1 \\ y & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

State vector

$$s = [s_i s_{t_1} s_{t_2} ... s_{t_n} s_{c_1} s_{c_2} ... s_{c_n}]^T$$

At equilibrium, the state vector is obtained by solving two equations:

$$Ps = s, \sum s = 1$$

Solution:

$$s = \frac{1}{n(1-x)+1}\begin{bmatrix}1\\y\\y\\\vdots\\y\\z\\z\\\vdots\\z\end{bmatrix}$$

Effective throughput:

$$Th = \sum_{i=1}^{n} s_{t_i} = \frac{ny}{n(1-x)+1}$$

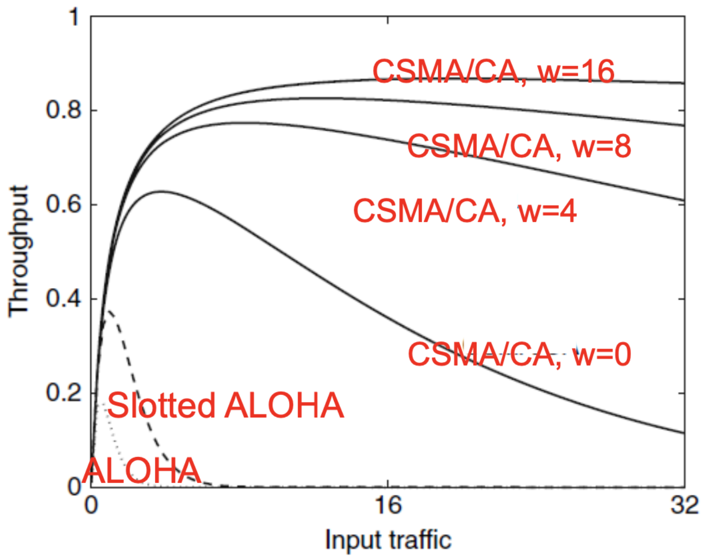

Fig. 15. Performance analysis