ECE257A HW2

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I. Problem 1 - True or false questions. If false, explain why.

(1) With Nt transmit antennas, closed-loop MIMO can increase the link capacity by Nt times compared with SISO.

(2) MU-MIMO requires time, frequency and phase synchronization between different receivers.

(3) MU-MIMO can scale network capacity linearly with the number of transmitters.

(4) Channel partitioning MAC has higher efficiency than random access MAC because the former doesn't have to waste time on carrier sensing or random backoff

(5) In pure ALOHA, a node does not need a local clock. So it is much simpler than slotted ALOHA

(6) In 802.11 CSMA/CA, during backoff, a node needs to freeze its timer if the channel becomes busy again

(7) In 802.11 CSMA/CA, a transmitter's backoff counter is doubled if it doesn't hear an ACK confirmation from the receiver after a transmission.

(8) A WiFi access point can be considered a router running IP routing protocols.

Answer :

(1) False. Increase by approximately $log(N_t)$ times by Shannon's equation.

(2) False. Only transmitters need to synchronize with each other.

(3) False. MU-MIMO cannot scale network capacity linearly with the number of transmitters when $N_r < N_t$.

(4) False. It has more idle so lower efficiency.

(5) True.

(6) True.

(7) False. The contention window (CW) is doubled. The backoff counter is chose randomly between 0 to (CW size - 1).

(8) False. Wireless routers can work as access points, but not all access points can work as routers. A router can manage local area networks, communicate with outside network systems, dispatch data in multiple directions, establish a point of connectivity. An access points can only provide access to the network.

Reference : https://www.ligowave.com/difference-between-access-point-and-router

II. Problem 2 - Understand MIMO gains.

(1) (10pt) Explain the asymptotic gains from the following 4 MIMO schemes: receiver diversity, open-loop transmit diversity, closed-look transmit diversity, spatial multiplexing, and multi-user MIMO. In particular, explain how the MIMO capacity increases with the number of antennas, and intuitively why. Review the lecture notes and references, and provide the answers based on your own understanding.

(2) (8pt) Compare two networks: a single-user MIMO network with one 4-antenna transmitter and one 4-antenna receiver, versus a MU-MIMO network with 4-antenna access point and 4 single-antenna users. Suppose the channel matrices are the same for these two setups. Will the two networks have the same total throughput? Why? (Note: Here we count the net throughput, not bit-rate).

(3) (8pt) Consider a 2x2 MIMO link, if both transmitter's antennas are placed very close to each other, and receiver's antennas are also close to each other, then the spatial multiplexing gain may be low due to channel correlations of nearby antennas. What if we separate the receiver's antennas far enough away from each other, but keep the transmitter's antennas close to each other? (Hint: Think of the problem of achieving multiplexing gain as the problem of solving a system of equations) In this case, will the link still likely have higher capacity than SISO? (Hint: Can there be any diversity gain?)

Answer :

(1)

Receiver diversity : $log(N_r)$ times. Suppose antenna i receives signal $y_i = h_i x + n_i = hx + n_i$, the corresponding SNR is $r_i = \frac{h^2}{\sigma^2}$. Adding up all the antenna paths yields $y = \sum_{i=1}^{N_r} y_i = N_r hx + \sum_{i=1}^{N_r} n_i$. The combined SNR has $r_{\sum} = \frac{N_r h^2}{N_r \sigma^2} = \frac{N_r h^2}{\sigma^2}$, so the SNR is increased by N_r times. By Shannon's equation the capacity increases by $log(N_r)$ times.

Open-loop transmit diversity : Same. The combined SNR at receiver is $r_{\sum} = \frac{\epsilon_x}{\sigma^2} \frac{{h_1}^2 + {h_2}^2 + ... + {h_{N_t}}^2}{N_t} = \frac{\epsilon_x}{\sigma^2} E[{h_1}^2]$. So the combined SNR is only hardened to the average SNR, by Shannon's equation the capacity is about the same.

Closed-look transmit diversity : $log(N_t)$ times. Received power becomes $N_t x^2$ restricted by the constraint that total transmit power remains constant, so SNR increases by N_t times. By Shannon's equation the capacity increases by $log(N_t)$ times.

Spatial multiplexing : $min(N_t, N_r)$ times. This intuition is by the spatial multiplexing MIMO can send the number of rank signals. Where the rank is the rank of the system of linear equations which is equal to $min(N_t, N_r)$. This means the capacity is increased by $min(N_t, N_r)$ times.

Multi-user MIMO : N_t times. When $N_t >= N_r$ the multi-user MIMO can send N_t signals which means the capacity is increased by N_t times.

(2) Yes, since the first network is a 4×4 spatial multiplexing MIMO and second network is a 4×4 MU-MIMO, and their channel matrices are the same, this means that they can send same number of signals. So their total throughput is the same.

(3) No. When the two transmitter antenna are close to each other, this means the channel gain from both transmitter antenna to either of the receiver antenna is similar to each other. This yields correlated system of linear equations. This means the capacity is just like SISO.

III. Problem 3 - Understand the working principle of MU-MIMO.

(1) Consider the following MU-MIMO scenario: a single 3-antenna transmitter (TX) is transmitting data to 3 single-antenna users RX1, RX2, and RX3 simultaneously. Suppose the channel gain values hij are known to the TX. Suppose the transmitter wants to ensure RX1 receivers a symbol x, but RX2 and RX3 hear nothing (essentially they hear 0, or a null value). Then what should each of the 3 transmit antennas send? (Hint: Construct a system of equations and solve it.)

(2) Consider a MU-MIMO network where a 2-antenna transmitter is transmitting data to 2 single-antenna users RX1 and RX2. Suppose the announcement packet and data packet are 100 Bytes and 1 KB respectively. The CSI feedback packet and ACK packet are 100 Bytes, 100 Bytes for both users. The data packet is sent at 100MBps, and all other packets are sent at 10MBps. Then what is the maximum achievable throughput of the network?

Answer :

(1)

$$\begin{bmatrix} x \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \times \begin{bmatrix} \frac{(h_{22}h_{33}-h_{23}h_{32})}{H}x \\ \frac{(h_{23}h_{31}-h_{21}h_{33})}{H}x \\ \frac{(h_{21}h_{32}-h_{22}h_{31})}{H}x \end{bmatrix}$$

Where

$$H = h_{11}(h_{22}h_{33} - h_{23}h_{32}) + h_{12}(h_{23}h_{31} - h_{21}h_{33})$$

+$h_{13}(h_{21}h_{32} - h_{22}h_{31})$ So the first antenna should send $\frac{(h_{22}h_{33}-h_{23}h_{32})}{H}x$, the second should send $\frac{(h_{23}h_{31}-h_{21}h_{33})}{H}x$, and the third should send $\frac{(h_{21}h_{32}-h_{22}h_{31})}{H}x$.

(2) announcement : 100 Bytes, takes $\frac{100}{10M} = 10\mu$ seconds

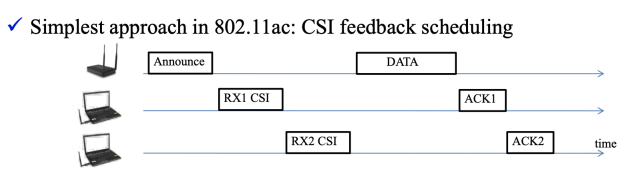

Fig. 1. CSI feedback scheduling.

data : 1000 Bytes, takes $\frac{1000}{100M} = 10\mu$ seconds RX1 CSI : 100 Bytes, takes $\frac{100}{10M} = 10\mu$ seconds RX2 CSI : 100 Bytes, takes $\frac{100}{10M} = 10\mu$ seconds ACK1 : 100 Bytes, takes $\frac{100}{10M} = 10\mu$ seconds ACK2 : 100 Bytes, takes $\frac{100}{10M} = 10\mu$ seconds 1000 Bytes data is sent in 60μ seconds so the maximum achievable throughput is $\frac{1000}{60\mu} = 16.66M$ Bps.

IV. Problem 4 - MAC protocols.

Summarize the pros and cons of the following MAC protocols: TDMA, FDMA, Polling, Token Rings, Slotted LOHA, pure ALOHA, CSMA/CD.

Answer:

TDMA

Pros: Simple, since the signals don't transmit at the same time there is no interference of signals. Single frequency can be shared by multiple users.

Cons: Unused slots go idle. Each user has fixed time slots to transmit signal. Synchronization is required to accommodate the time slots.

FDMA

Pros: Easy to implement. Synchronization is not required.

Cons: Unused transmission time in frequency bands go idle. Adjacent channel may interfere with each other. Requires precise frequency carrier.

Polling

Pros: Slots are not wasted. Transmission reliability.

Cons: Requires extra time for polling. The polling still need to go through the nodes even they don't have data to transmit. Single point failure of the master node. Polling overhead.

Token rings

Pros: Avoids single node failure. Stations can be added or removed easily.

Cons: Token can be lost. The token has to go through each node even they have nothing to transmit, this causes queuing delay latency. Token overhead.

Slotted ALOHA

Pros: Single active node can continuously transmit at full rate of channel. Simple. Highly decentralized. Only need to sync each slot.

Cons: Collisions, wasting slots. Inefficient collision resolution Idle slots, under-utilizing channel. Requires clock synchronization.

Pure ALOHA

Pros: Signal can start transmitting at any time. Doesn't require clock synchronization, simpler than slotted ALOHA.

Cons: Higher chance of collisions, more time is wasted. Efficiency is 50% lower compared with slotted Aloha.

CSMA/CD

Pros: Collisions are detected quickly, less time is wasted when collision occurs. Avoids any wasteful transmission. Priorities can be assigned to certain nodes.

Cons: Collisions can still occur. Wireless communication devices cannot listen while transmitting, so we cannot do CSMA for wireless.

V. Problem 5 - Slotted ALOHA with heterogeneous nodes.

Consider two nodes, A and B, that use the slotted ALOHA protocol to contend for a channel. Suppose node A has more data to transmit than node B, and node A's retransmission probability pA is greater than node B's retransmission probability, pB.

a) Provide a formula for node A's average throughput. What is the total efficiency of the protocol with these two nodes?

b) If pA = 2 pB, is node A's average throughput twice as large as that of node B? Why or why not? If not, how can you choose pA and pB to make that happen?

c) In general, suppose there are N nodes, among which node A has retransmission probability 2p and all other nodes have retransmission probability p. Provide expressions to compute the average throughputs of node A and of any other node.

Answer:

(a) A's average throughput is $P_A(1-P_B)$. The total efficiency of the protocol with these two nodes is $P_A(1-P_B)+P_B(1-P_A)$.

(b) If $P_A = 2P_B$, A's average throughput is $P_A(1-P_B) = 2P_B(1-P_B) = 2P_B - 2(P_B)^2)$ and B's average throughput is $P_B(1-P_A) = 2P_B(1-2P_B) = 2P_B - 4(P_B)^2)$, we can see unless P_B is zero, or A's average throughput is not twice as large as B's average throughput. To make that happen, $P_A(1-P_B) = 2P_B(1-P_A)$, that is $P_A(1+P_B) = 2P_B$, or $P_A = \frac{2P_B}{1+P_B}$.

(c) A's average throughput is $2p(1-p)^{N-1}$. Other node's average throughput is $p(1-p)^{N-2}(1-2p)$.

VI. Problem 6 - Understanding CSMA/CA.

Answer the following questions: (1) CSMA/CD is not used in current wireless networks such as WiFi. Suppose WiFi radios become full-duplex in future, will CSMA/CD work just like in classical Ethernet?

(2) What's the hidden terminal problem in CSMA/CA? Does RTS/CTS fully solve the problem?

(3) What's the negative impacts of the exposed terminal problem in CSMA/CA? Does RTS/CTS solve the problem?

(4) What's causing the performance anomaly of 802.11? Explain the difference between time fairness and packet fairness.

Answer:

(1) Even if the transmitter is full-duplex that it has separate transmitting antenna and a receiving antenna, since the receiving antenna is so close to the transmitting antenna, the self interference is just the two strong if the transmitting antenna is also sending something. And the signal strength of wireless network decreases sharply by distance, so the received signal will just be too weak compared to the interference.

(2) The hidden terminal problem is when there are two client's which they cannot hear each other, but they can both hear the access point. Since they couldn't hear each other they send message to the AP at the same time, and it may cause collision at the access point. RTS/ CTS only alleviates the problem but not solve the problem since RTSs from different clients may still collide with each other.

(3) The exposed terminal problem happens when there are two access points and two clients client1 - AP1 - AP2 - client2. Client1 and AP1 can hear each other, AP1 and AP2 can hear each other, AP2 and client2 can hear each other, but no other pairs. When AP1 wants to send to client1 and AP2 wants to send to client2, they can do so simultaneously because they will not interfere with each other. But in reality, because of listen before talk, AP1 will hear that the channel is busy with AP2 transmitting, and decide not to transmit the signal. The negative impact of the exposed terminal problem is that it reduces spatial reuse opportunities therefore reduces effective total network throughput. RTS/CTS will not solve the problem but only make things worse because will make them more unlikely to send signals simultaneously, even if it doesn't it still need extra time to send the RTS/CTS signals.

(4) The performance anomaly happens because 802.11 only ensures packet fairness but not time fairness. With packet fairness, both me and neighbor have equal opportunity to send a packet. Using the slide example, I send a packet in $\frac{B}{b_{54}}$ time, and my neighbor send a packet in $\frac{B}{b_6}$ time. In average, my effective throughput to send a package is $\frac{B}{\frac{B}{b_{54}}+\frac{B}{b_6}}$, and so is my neighbor's.

If it ensures time fairness, my bit rate will still be lower than sending alone, but will be 9 times the neighbor's bit rate, since we transmit the equal time. The time fairness ensures that each user has the same amount of time to transmit their data, hence the larger the bit rate the more data they can send. Whereas packet fairness ensures that each user has the same chance to send a packet, each user send the same amount of data/ packet.