Medium Access

- **Fixed:**
  - **SDMA, FDMA, TDMA, CDMA**
- **Random Access**
  - **Aloha**
  - **Collision detection**
  - **CSMA**
  - **Hidden, exposed, near-far terminals**

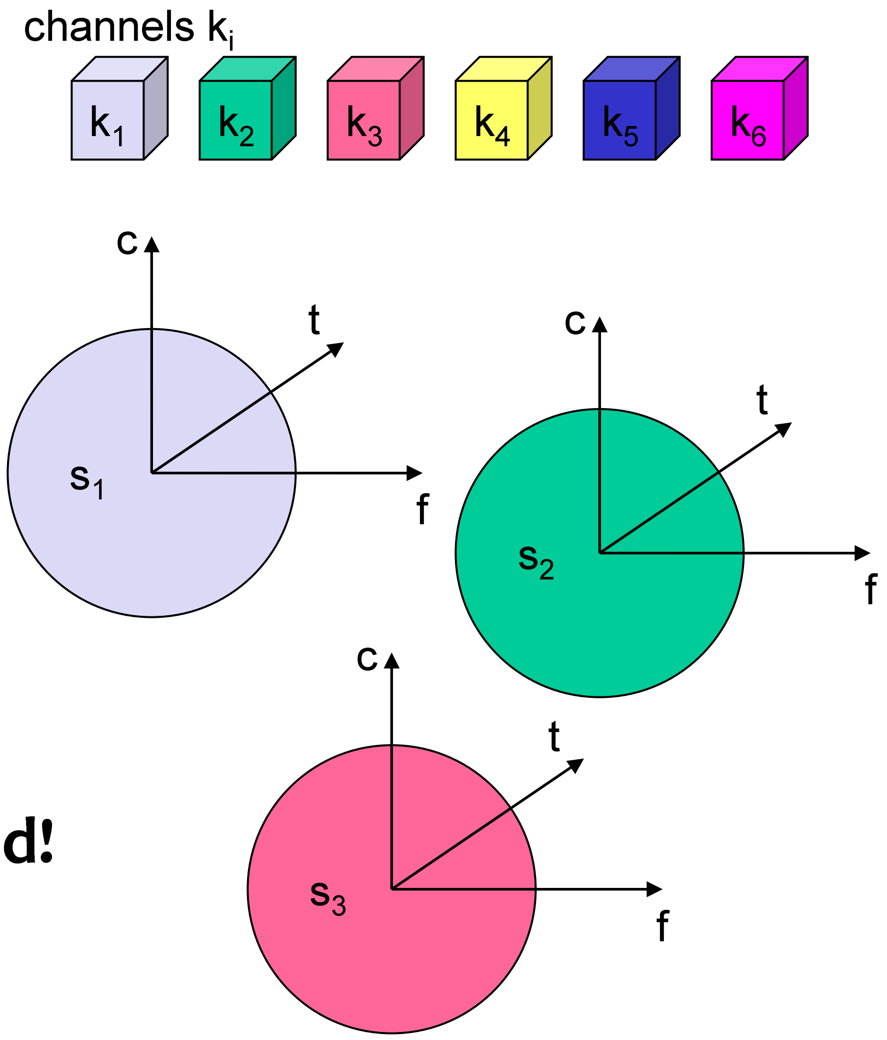
- **Reading:**
  - Schiller 2.5
  - Tanenbaum 2.6.2
  - Schiller 3 – 3.4.4

Multiplexing

- **Multiplexing in 4 dimensions**
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)

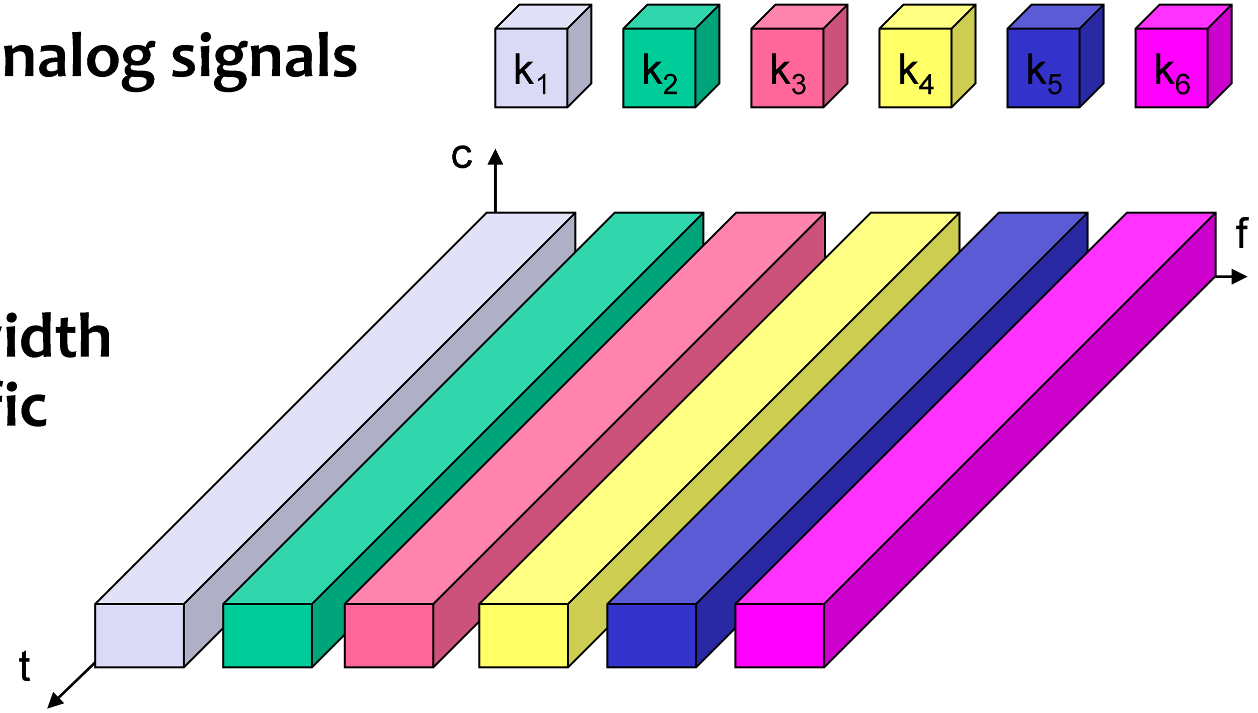
- **Goal: multiple use of a shared medium**

- **Important: guard spaces needed!**



Frequency multiplex

- Separation of the spectrum into smaller frequency bands
- A channel gets a certain band for the whole time
- Advantages
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages
  - waste of bandwidth for uneven traffic
  - inflexible

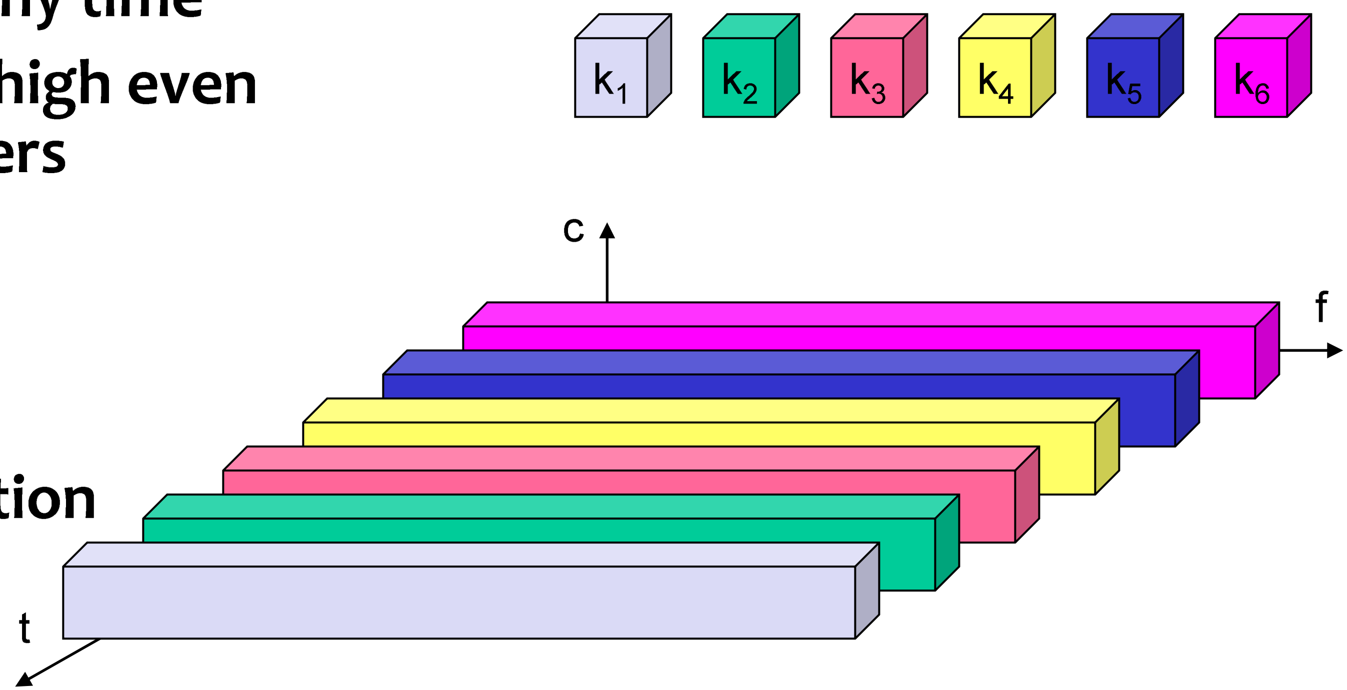


Time multiplex

- A channel gets the spectrum for a certain amount of time

- Advantages
  - only one carrier in the medium at any time
  - throughput high even for many users

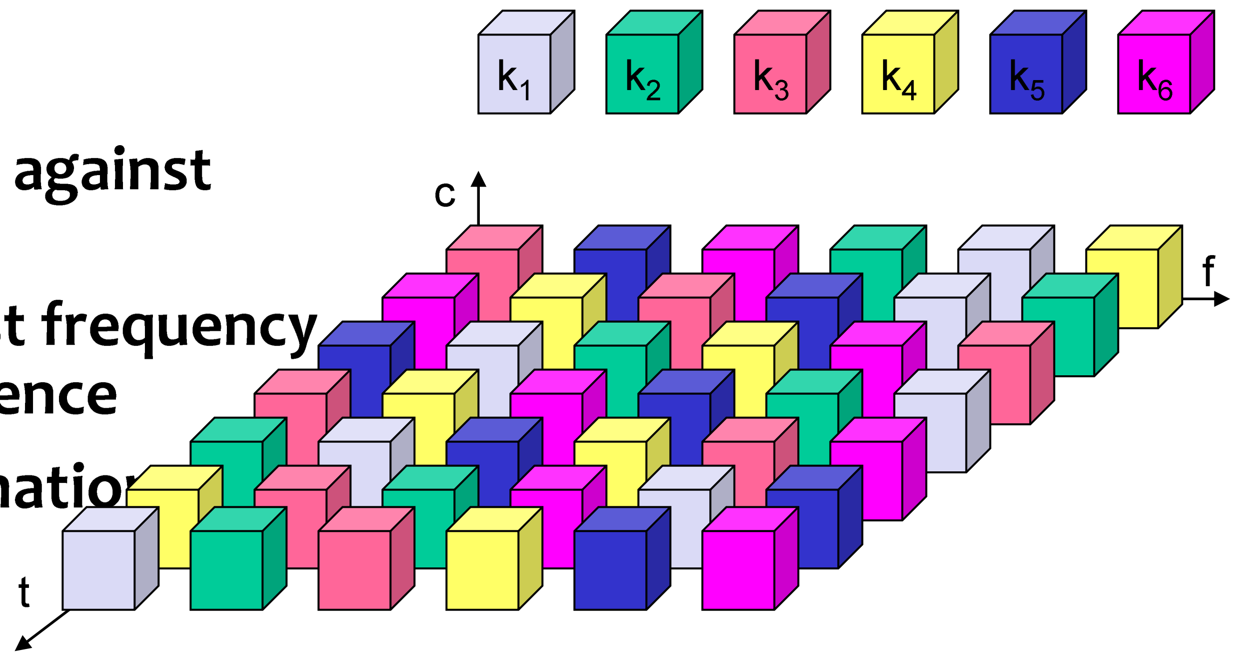
- Disadvantages
  - precise synchronization necessary



Time and frequency multiplex

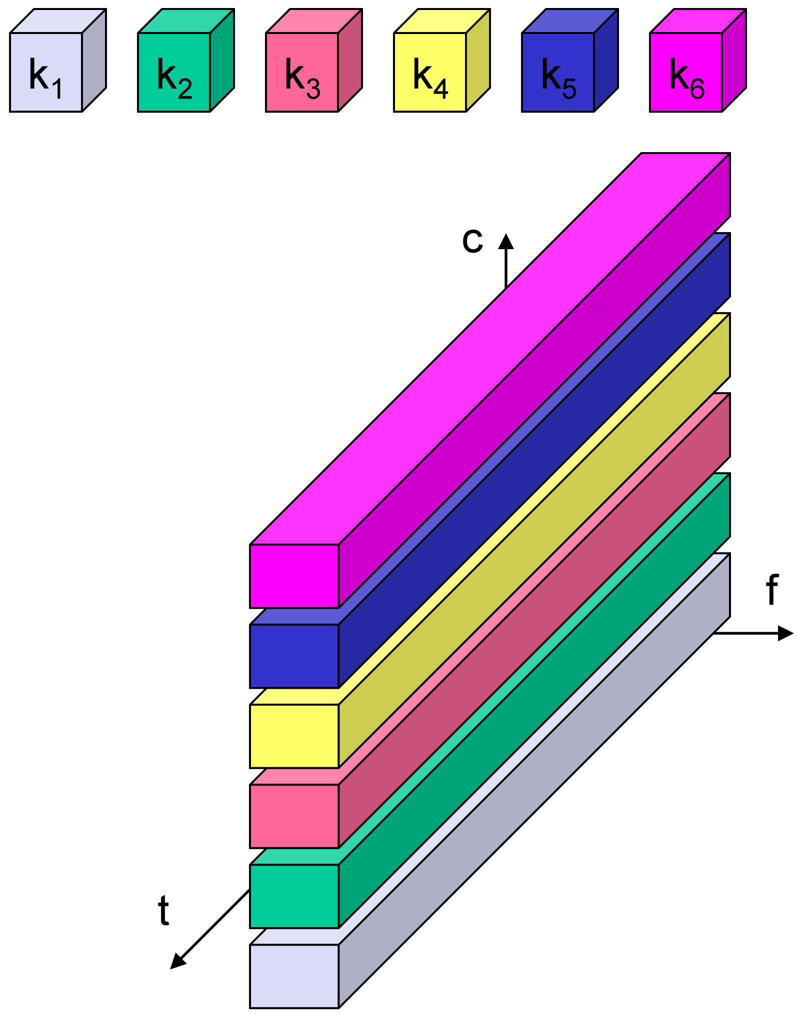
- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM

- Advantages
  - better protection against tapping
  - protection against frequency selective interference
- but: precise coordination required



Code multiplex

- Each channel has a unique code
- All channels use the same spectrum at the same time
- Advantages
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages
  - varying user data rates
  - more complex signal regeneration
  - <u>requires fine power control</u>



Access methods SDMA/FDMA/TDMA

- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - cell structure
- FDMA (Frequency Division Multiple Access)
  - assign afrequency to transmission channel sender <>receiver
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- TDMA (Time Division Multiple Access)
  - assign the fixed sending frequency to a transmission channel between a sender and a receiver for a certain amount of time
- CDMA (Code Division Multiple Access)
  - assign one code per user

Multiplexing, Duplexing

- Multiplexing = sharing among many users
  - Access mode, e.g. FDMA based on FDM
- Two party communication
  - Simplex = one way
  - Full duplex = two way, simultaneous
  - Half duplex = two way, either TX or RX
- Duplexing = multiplexing one's uplink and downlink
  - Can be full or half (hardware does either TX or RX)
  - TDD = time division duplexing
    - Time to comute between TX and RX
  - FDD = frequency division duplexing
    - Time to comute frequencies

CDMA - simplified

- Sender A
  - Binary sequence A = 00011011
  - Bipolar sequence (assign: "0"= -1, "1"= +1)
    - To send data bit "1"   A = (-1, -1, -1, +1, +1, -1, +1, +1)
    - To send data bit "0" -A= (+1, +1, +1, -1, -1, +1, -1, -1)
- Sender B
  - Binary sequence B = 00101110
  - Bipolar sequence (assign: "0"= -1, "1"= +1)
    - To send data bit "1"   B = (-1, -1, +1, -1, +1, +1, +1, -1)
    - To send data bit "0" -B= (+1, +1, -1, +1, -1, -1, -1, +1)
- Example A_s=0 B_s=1 bipolar signals superimpose/add in space
  - interference neglected (noise etc.)
  - Receive X = -A + B = (0, 0, 2, -2, 0, 2, 0, -2)
- Receiver wants to retrieve signals
  - apply inner product with bipolar key A
    - A_r= (0, 0, 2, -2, 0, 2, 0, -2) * A= 0 + 0 – 2 – 2 +0 – 2 + 0 – 2 = -8 (negative = "0" = A_s)
  - B_r = B * X
    - B_r = (0, 0, 2, -2, 0, 2, 0, -2) * B = 0 + 0 + 2 + 2 + 0 + 2 + 0 + 2 = 8 (positive = "1" = B_s)

CDMA – simplified

- Simplifying assumptions
  - Stations are perfectly synchonized
  - Chips add up linearly <= same received power
- Neighboring stations use orthogonal sequences
  - $S*T = (\Sigma S_i T_i)/m = (S_1T_1 + S_2T_2 + \ldots S_mT_m)/m = 0$
  - $S*(-T) = 0$
  - $S*S = (S_1S_1 + \ldots)/m = (1 + 1 + \ldots)/m = 1$
  - $S*(-S) = -1$
- Example: A sends 1, C sends 1, B sends 0
  - At reception $S = A - B + C$
  - To retrieve C, the receiver applies C's sequence on S
  - $S*A = (A - B + C) * A = A*A - B*A + C*A = 1 - 0 + 0$
  - $S*B = (A - B + C) * B = A*B - B*B + C*B = 0 - 1 + 0$
  - $S*C = (A - B + C) * C = A*C - B*C + C*C = 0 - 0 + 1$

CDMA example

a) **binary sequences fc A,B,C,D**

b) **bipolar sequences**

A: 0 0 0 1 1 0 1 1
B: 0 0 1 0 1 1 1 0
C: 0 1 0 1 1 1 0 0
D: 0 1 0 0 0 0 1 0

(a)

A: (–1 –1 –1 +1 +1 –1 +1 +1)
B: (–1 –1 +1 –1 +1 +1 +1 –1)
C: (–1 +1 –1 +1 +1 +1 –1 –1)
D: (–1 +1 –1 –1 –1 –1 +1 –1)

(b)

a) **6 transmissions examples**

Six examples:

– – 1 –	**C**	$S_1 = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$
– 1 1 –	**B + C**	$S_2 = (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2)$
1 0 – –	**A + $\overline{\mathbf{B}}$**	$S_3 = (\ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2)$
1 0 1 –	**A + B + C**	$S_4 = (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1)$
1 1 1 1	**A + B + C + D**	$S_5 = (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2)$
1 1 0 1	**A + B + $\overline{\mathbf{C}}$ + D**	$S_6 = (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0)$

(c)

a) **how a receiver recovers C**

$S_1 \bullet C = (1\ +1\ +1\ +1\ +1\ +1\ +1\ +1)/8 = 1$
$S_2 \bullet C = (2\ +0\ +0\ +0\ +2\ +2\ +0\ +2)/8 = 1$
$S_3 \bullet C = (0\ +0\ +2\ +2\ +0\ -2\ +0\ -2)/8 = 0$ C is silent
$S_4 \bullet C = (1\ +1\ +3\ +3\ +1\ -1\ +1\ -1)/8 = 1$
$S_5 \bullet C = (4\ +0\ +2\ +0\ +2\ +0\ -2\ +2)/8 = 1$
$S_6 \bullet C = (2\ -2\ +0\ -2\ +0\ -2\ -4\ +0)/8 = -1$

(d)

CDMA robustness

- What if codes are not orthogonal?
  - A = (-1, -1, -1, +1, +1, -1, +1, +1)
  - B' = (-1, -1, +1, -1, +1, +1, +1, +1)
  - A*B' = (+1+1-1-1+1-1+1+1) = 2 (needed 0 to be orthogonal)
  - S = A - B' = (0 0 -2 2 0 -2 0 0)
  - S*A = 6, meaning "1" OK
  - S*B' = -6, meaning "0" OK

- What if a chip is erased at reception?
  - S = A - B = (0, 0, -2, 2, 0, -2, 0, 2)
  - X_1 = (1, 0, -2, 2, 0, -2, 0, 2); X_1*A=7; X_1*B=-9 OK
  - X_1 = (0, 0, 0, 2, 0, -2, 0, 2); X_1*A=6; X_1*B=-6 OK
  - X_3 = (0, 0, 2, -1, 0, -2, 0, 2); X_3*A=1; X_3*B=-1
    - A&B are not silent? This bit is lost.

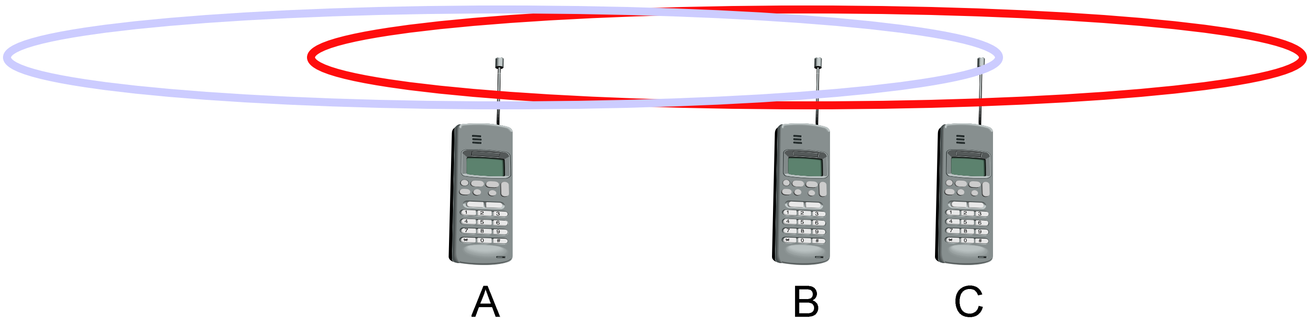
CDMA robustness

- What if power is not scaled at reception?
  - A - B = X = (0, 0, -2, 2, 0, -2, 0, 2)
  - A - 3B = X_1 = (2 2 -4 4 -2 -4 -2 4)
  - X_1 * A = 8 OK, X_1 * B = -24 OK

  - A/4 - 4B = X_2 = (3.75 3.75 -4.25 4.25 -3.75 -4.25 -3.75 4.25)
  - X_2 * B = -32 OK, X_2*A = 2 too close, A seems silent!

CDMA: near and far terminals

- Terminals A and B send, C receives
  - signal strength decreases ~ $1/d^2$
  - the signal of terminal B drowns out A's signal
  - C cannot receive A



- If C is arbiter, terminal B drowns out A already on the physical layer
- severe problem for CDMA
  - <u>precise power control needed!</u>
  - <u>affects battery UE life - why?</u>

CDMA - summary

- Separation using orthogonal codes
- One receiver can 'see' all senders
- Longer chip sequence => better error protection
- Received power depends on terminal/distance/conditions
  - Basestation needs to control uplink power
- Used by 3G (WCDMA)
- **CDMA != CSMA**

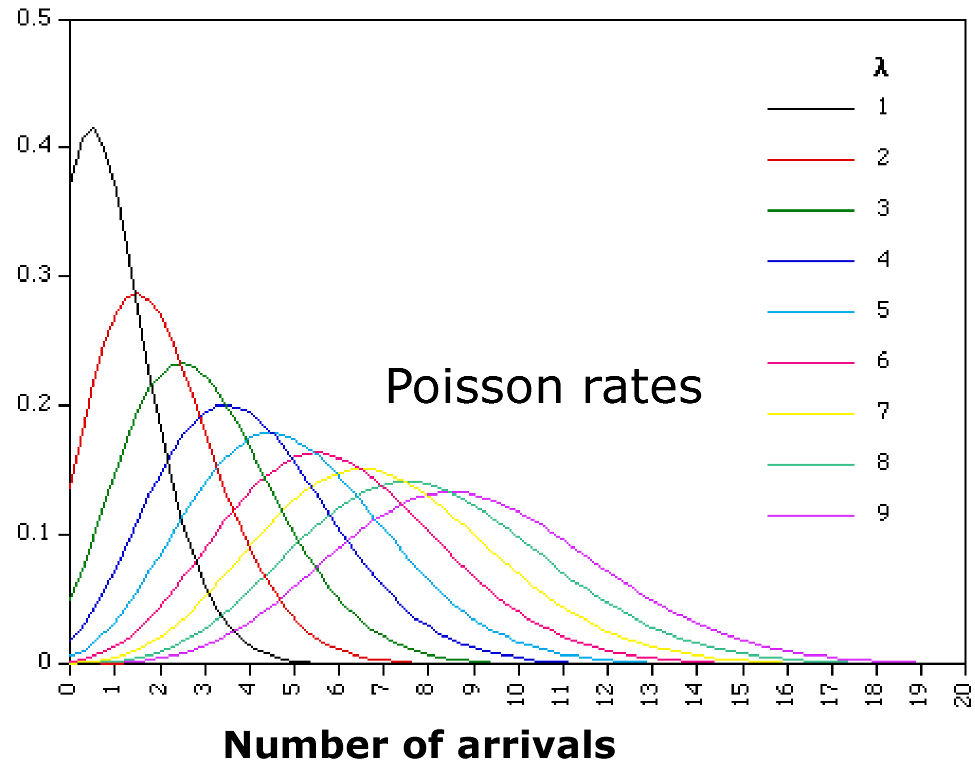
Comparison SDMA/TDMA/FDMA/CDMA

Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	all terminals are active for short periods of time on the same frequency	every terminal has its own frequency, uninterrupted	all terminals can be active at the same place at the same moment, uninterrupted
Signal separation	cell structure, directed antennas	synchronization in the time domain	filtering in the frequency domain	code plus special receivers
Advantages	very simple, increases capacity per km²	established, fully digital, flexible	simple, established, robust	flexible, less frequency planning needed, soft handover
Dis-advantages	inflexible, antennas typically fixed	guard space needed (multipath propagation), synchronization difficult	inflexible, frequencies are a scarce resource	complex receivers, needs more complicated power control for senders
Comment	only in combination with TDMA, FDMA or CDMA useful	standard in fixed networks, together with FDMA/SDMA used in many mobile networks	typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)	still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA

Reminder: Poisson distribution

- Rate parameter λ
  - arrivals/time unit

- Poisson arrivals:
  - hospital
  - call center calls
  - phone calls @ PBX
  - vacant parking spaces
  - Horsekick deaths in Prussian cavalry



Why NOT static allocation? (1)

1. varying number of users
2. fixed users, but different needs
3. bursty data, Poisson like

TDMA/FDMA – why do we need other schemes?...
efficiency

Why NOT static allocation? (2)

Example from queueing theory

- **Q: How many frames can a server process?**
- **A: depends on arrivals and on processing**

serving rate = μ/sec
arriving rate = λ/sec

Average waiting time T = $1/(\mu - \lambda)$
Queue length Q = $\lambda/(\mu - \lambda)$

Static channel allocation

Queueing Theory result

μ serving rate = 10000/sec
λ arriving rate = 5000/sec

- average waiting time $$T = \frac{1}{\mu - \lambda} = 0.2ms$$

- **Divide load to N smaller servers**
  - **Each channel gets λ/N arrivals, processed at μ/N**
  - **waiting time = N*T, N times longer!**
  - **N queues of size Q, N times more!**

<u>static access is not efficient for variable load</u>

Random access methods

Conditions:

- Poisson traffic : N stations independently generate λ frames/s
- Unique channel all stations can send/receive, same hardware
- Collisions: overlapped frames are lost
- Continuous time: frames come at any time

  or
- Discrete time: frames come at slot times
  - 0 = free slot
  - 1 = success
  - >1 = collision
- Carrier sense - stations can detect whether medium is free

Protocols for random access

- **ALOHA**
- **CS – carrier sense**
- **CSMA/CD**
- **CSMA/CA – without CD**

Pure ALOHA

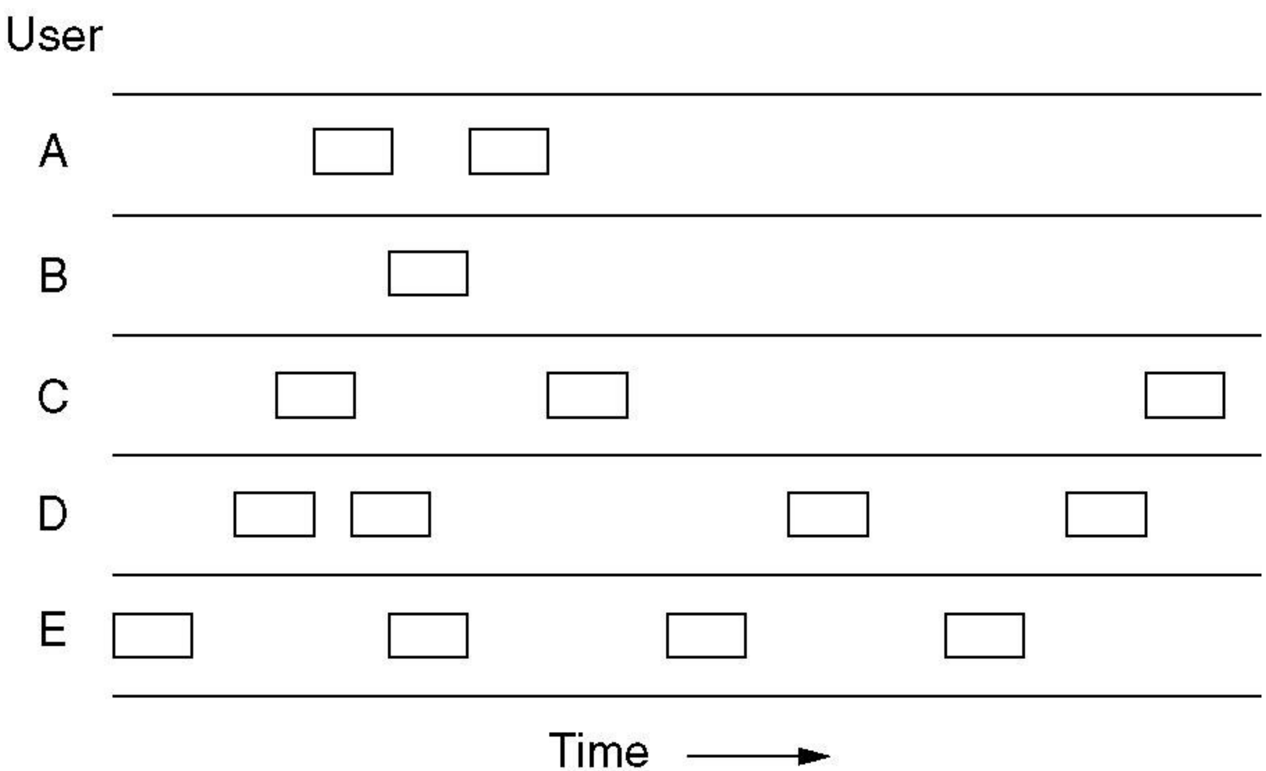
Simple: send whenever frame is available

- **On collision**
  - **random wait (why?)**
  - **retransmit**

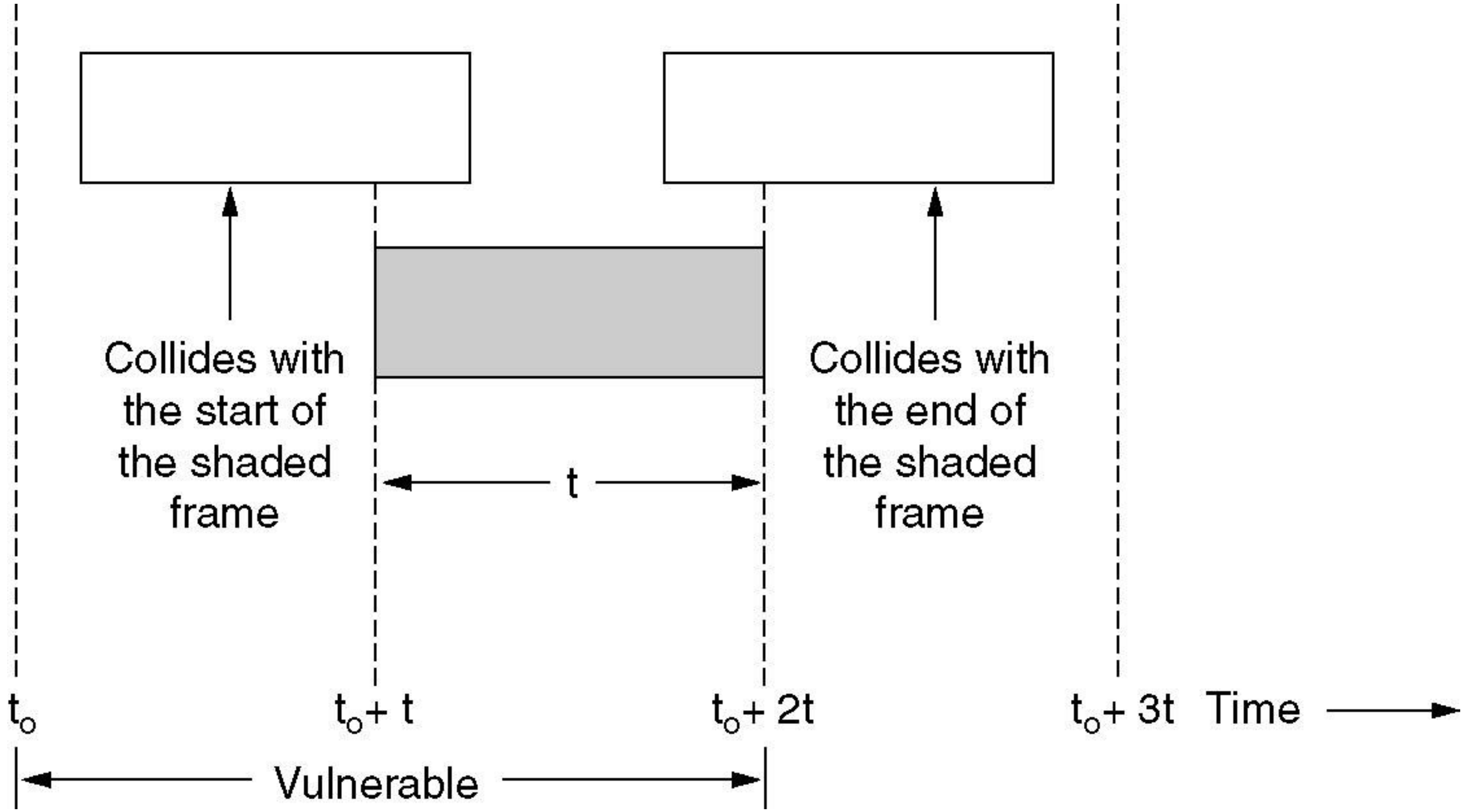
- **How to detect collisions?**
  - Star topology, 2 channels (*inbound*, *outbound*)
  - Only BS uses *outbound*
  - Stations send on *inbound*, read from *outbound*
  - BS repeats on *outbound* frames received on *inbound*

Pure ALOHA

- Same length frames --> better efficiency
- Collision probability grows with load
- Maximum throughput ~ 18%



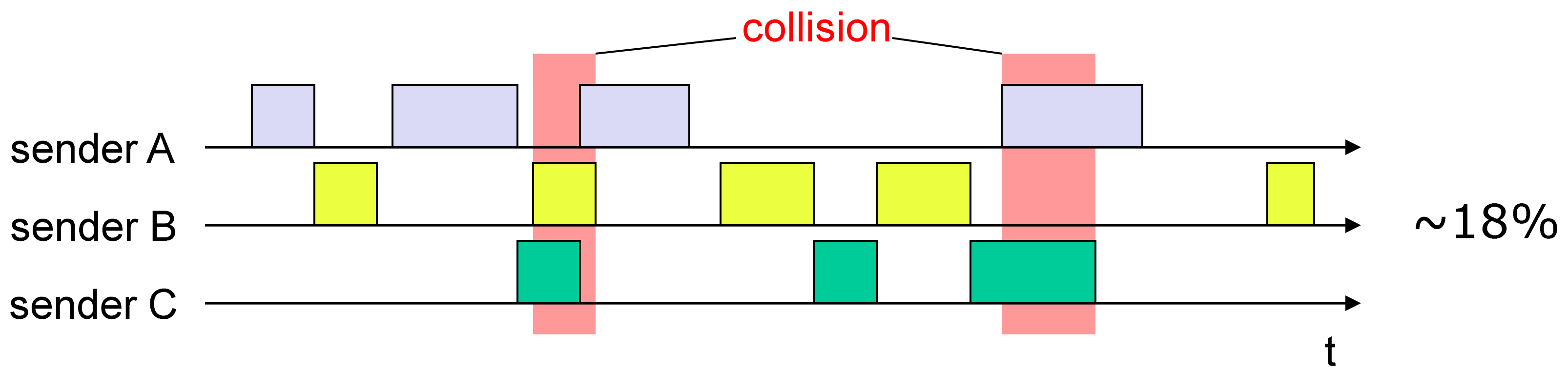
Efficiency of pure ALOHA



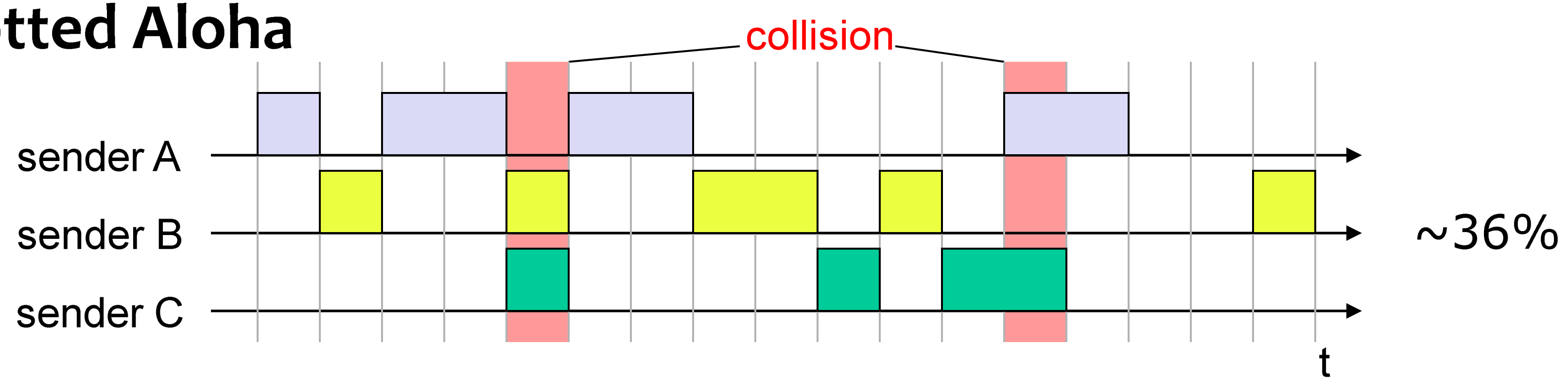
Vulnerable area can be decreased when sending only at beginning of slot

ALOHA pure/slotted

- **pure Aloha**



- **slotted Aloha**



Aloha pure/slotted

- pure Aloha
  - random, distributed (no arbiter), time-multiplex
  - ~ 18% capacity

- slotted Aloha
  - sending must always start at slot boundaries
  - ~ 36% capacity

- drawbacks
  - only appropriate for low load
  - "avoidable" collisions

Carrier Sense

Carrier Sense (CS) = ability to detect a sender

- Based on a power threshold
- No demodulation/decoding necessary
- For example 802.11g 6Mbps
  - 1Mbps threshold = -90dBm, card specific
  - CS threshold = -100dBm, tunable
- Hope to reduce collisions

CSMA and collision detection (CD)

- Aloha and CSMA without CD:
  - On collision, <u>continue sending</u> the entire frame
  - Waste time for one entire frame

- CSMA/CD = carrier sense multiple access with collision detection

a) Medium free? => send after IFG
  - Collision?
    - Stop transmission, but send minimum frame
    - Random wait; goto a)

b) Busy? => Wait till free; goto a)

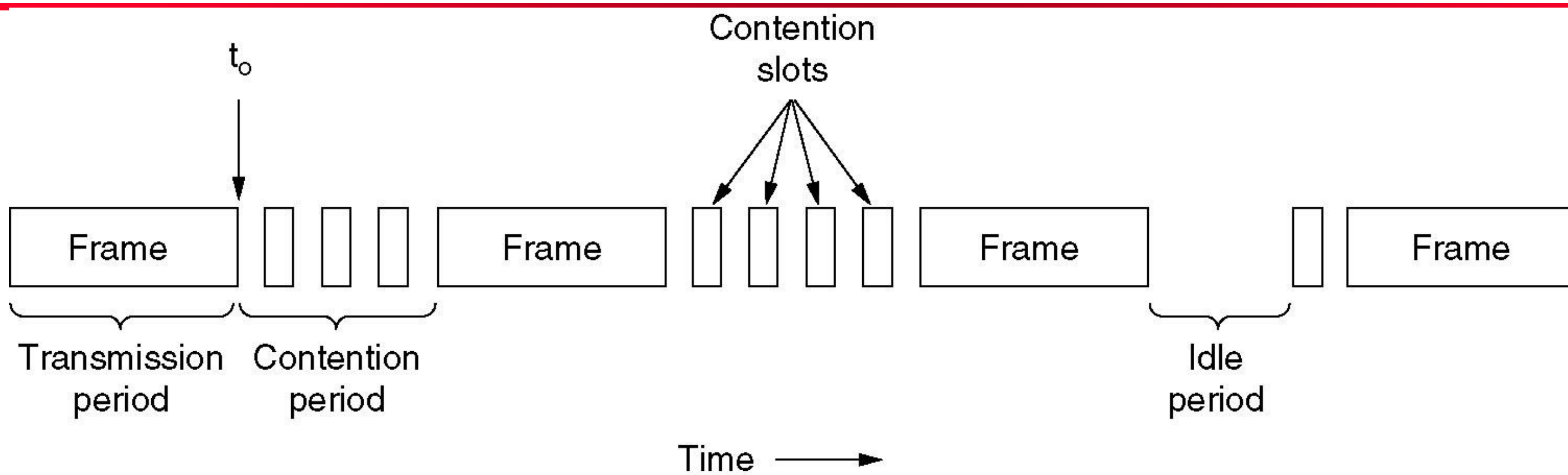
CSMA/CD

- <u>Abandon transmission once collision is detected</u>
- <u>No collisions after channel is effectively busy</u>
- Used by the classic Ethernet (now obsolete)
- How are collisions detected?

  Measure power,

  - Detection is *analog*
  - Sending station monitors medium permanently => half duplex
  - How to detect collision between two 0V signals?
    - Coding and modulation can make a difference CD
- On collision, the sender generates a jamming signal (48 biți)
  - Received by all other stations
  - At least a minimum size is sent, why?

CSMA/CD

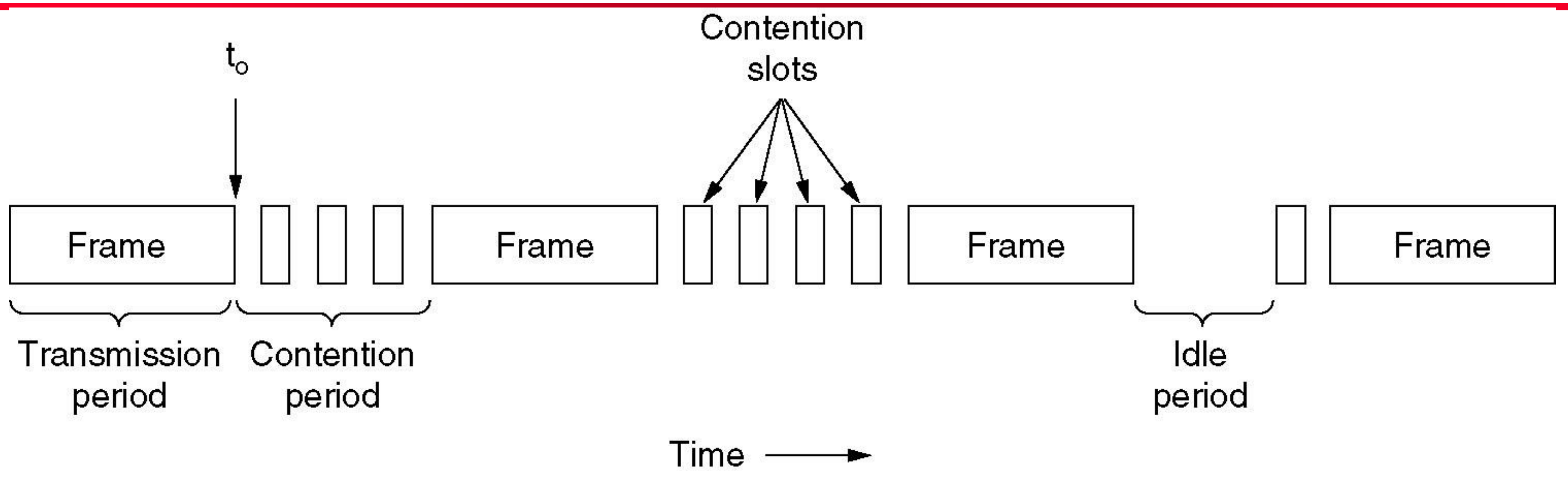


Contention period

- **Wait randomly after collision**
- **Contention periods alternate with free and busy periods**
- **How long does it take to detect?**
  - **Depends on propagation time τ**

- **It is true that after τ, the channel is considered busy by all?**

CSMA/CD

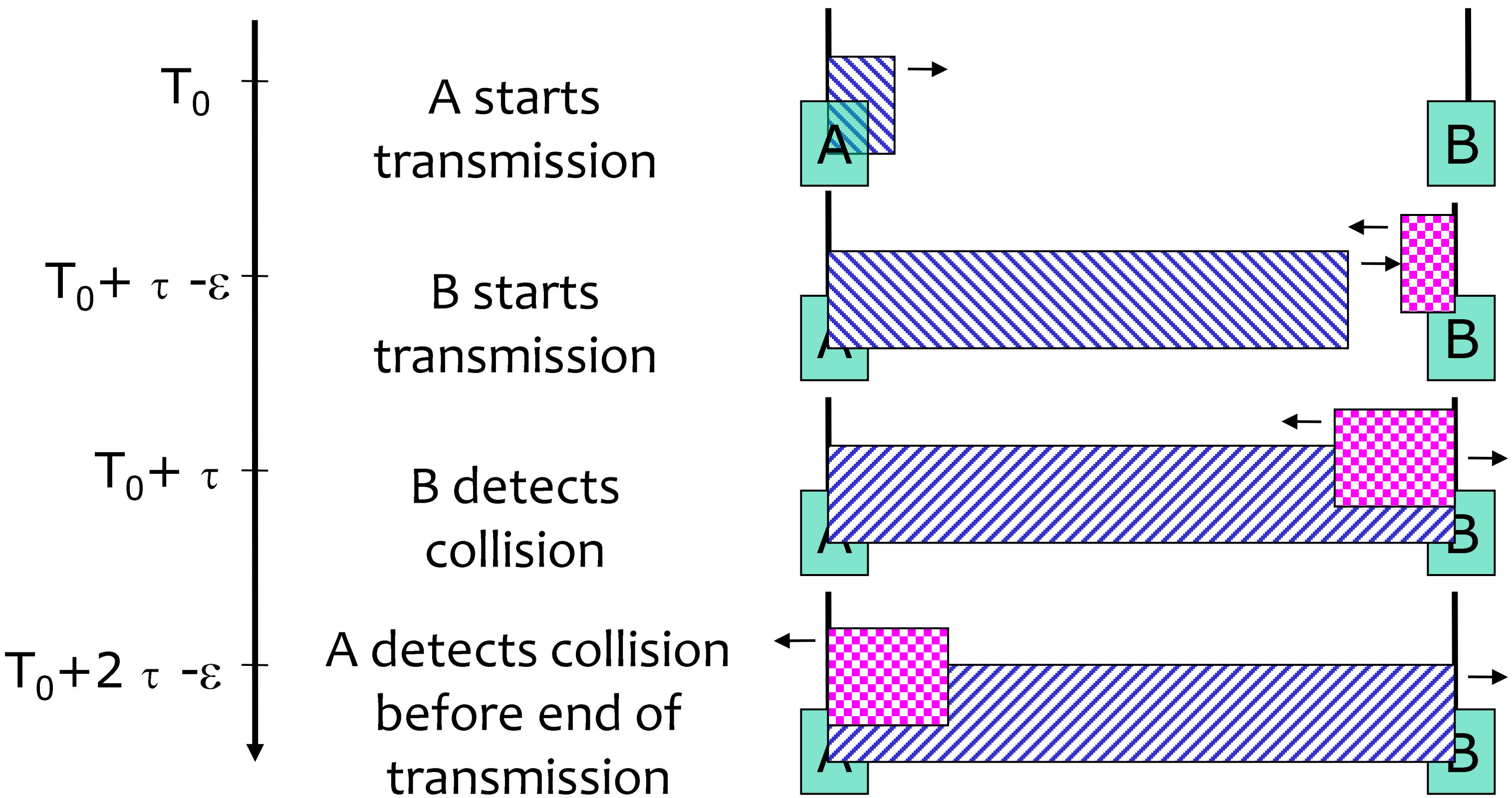


Contention period

- **Wait randomly after collision**
- **Contention periods alternate with free and busy periods**
- **How long does it take to detect?**
  - **Depends on propagation time τ**

- **It is true that after τ, the channel is considered busy by all?**
  - **No, it takes 2 τ**

CSMA/CD detection example



Why CSMA/CD works?

1. Sender can send and listen at the same time

    if (send == listen) then success

2. Signal is almost the same at Tx and Rx

SENDER can detect <u>if and when</u> a collision is produced

Cost of collision = ~ 2τ (minumum frame 64bytes in Ethernet)

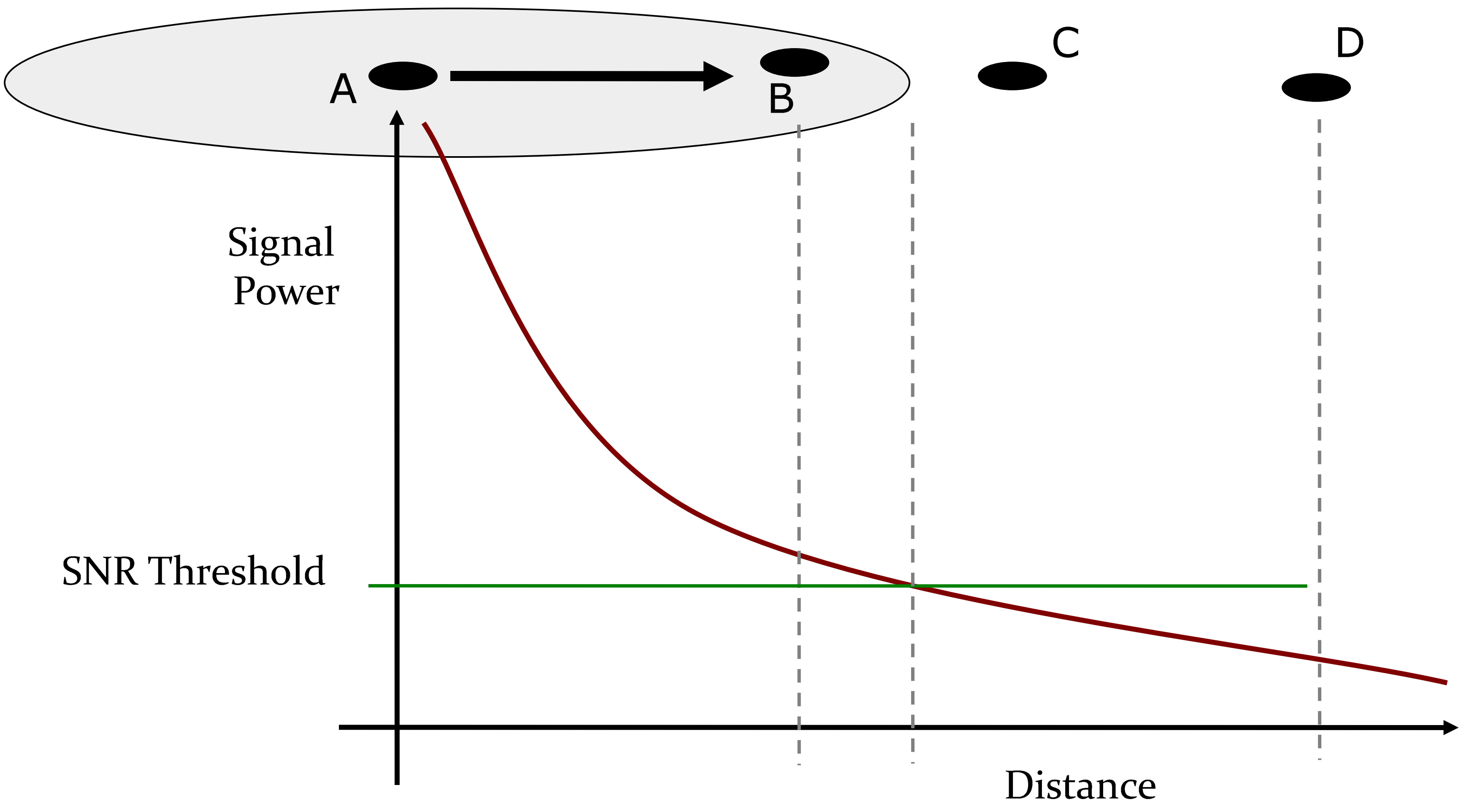
unfortunately…

None of the two holds for wireless :-(

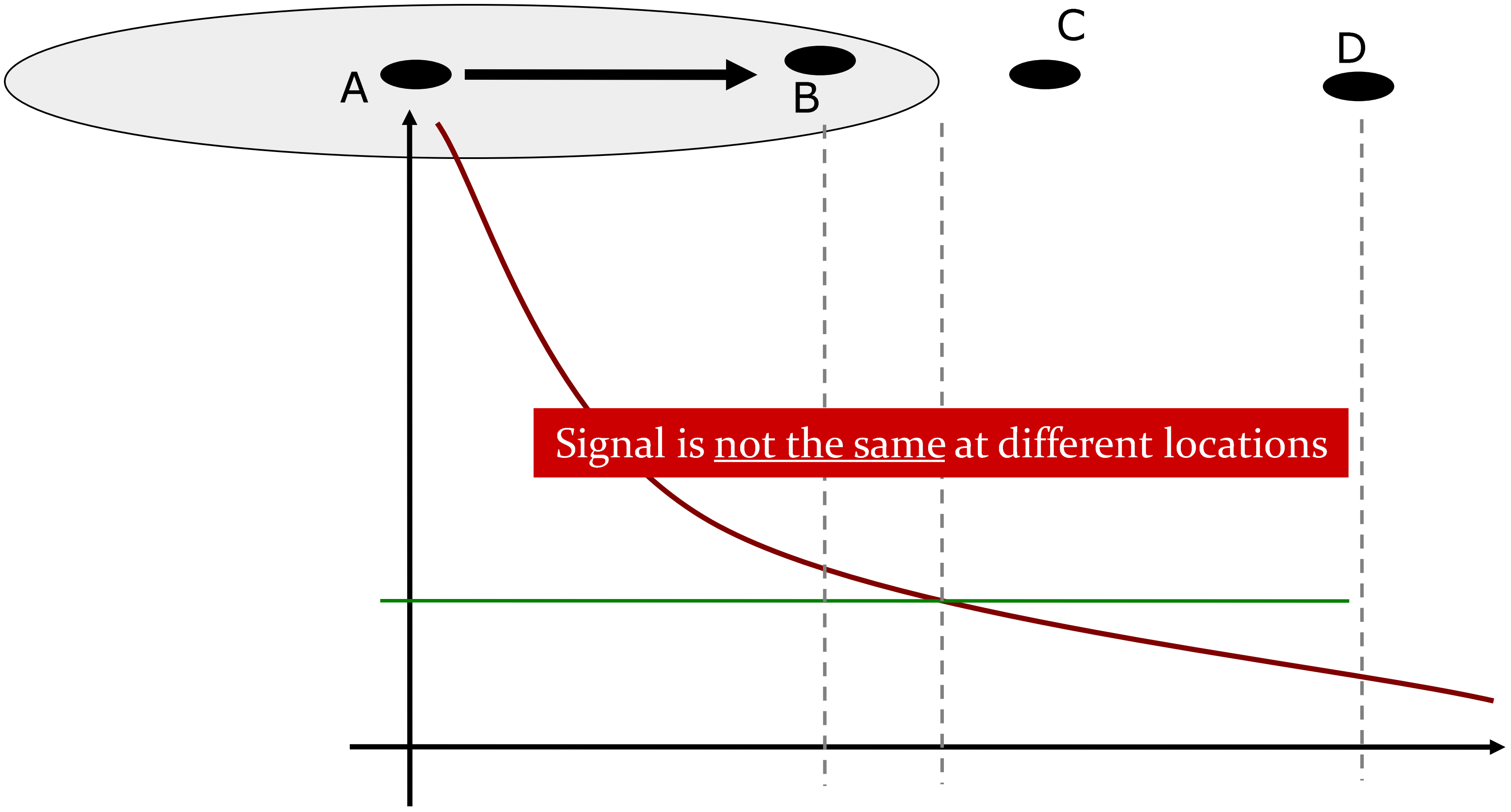
wired == wireless?

- **Similarities with Ethernet:**
  - » wireless is a shared medium
  - » Interference between senders
  - » CSMA (carrier sense multiple access)
    - – Sender can detect carrier of another sender
    - – “listen before talking”
    - – wishes: at most one station to send at any time

- **Differences:**
  - » CD ~~is difficult~~ impossible
    - – one channel, simplex communication
  - » Weak channels: low BER, highly variable in space/time
  - » Hidden terminals, exposed terminals
  - » Cost of collision: entire frame + retries

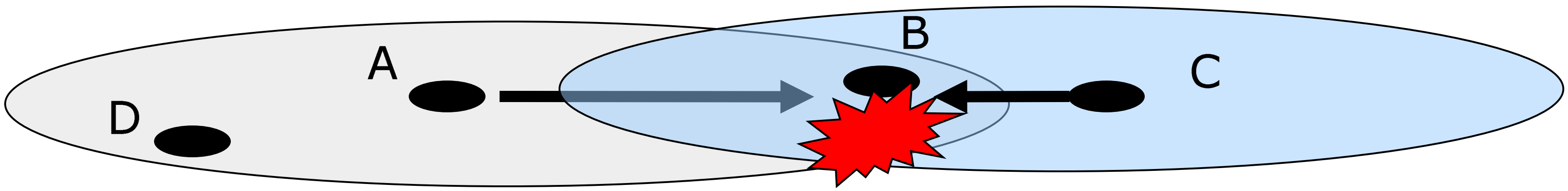

A
B
C
D
Signal Power
SNR Threshold
Distance

A cannot send and receive at the same time



Signal is not the same at different locations

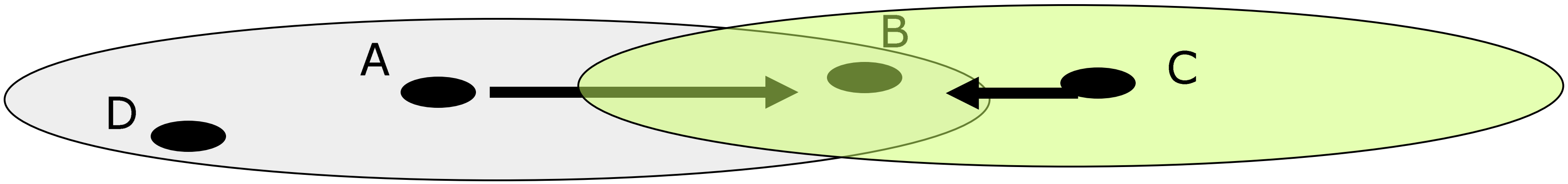
CD is difficult



Signal reception based on SINR

- **Sender only hears himself**
- **Cannot estimate signal quality at the receiver**

SINR computation



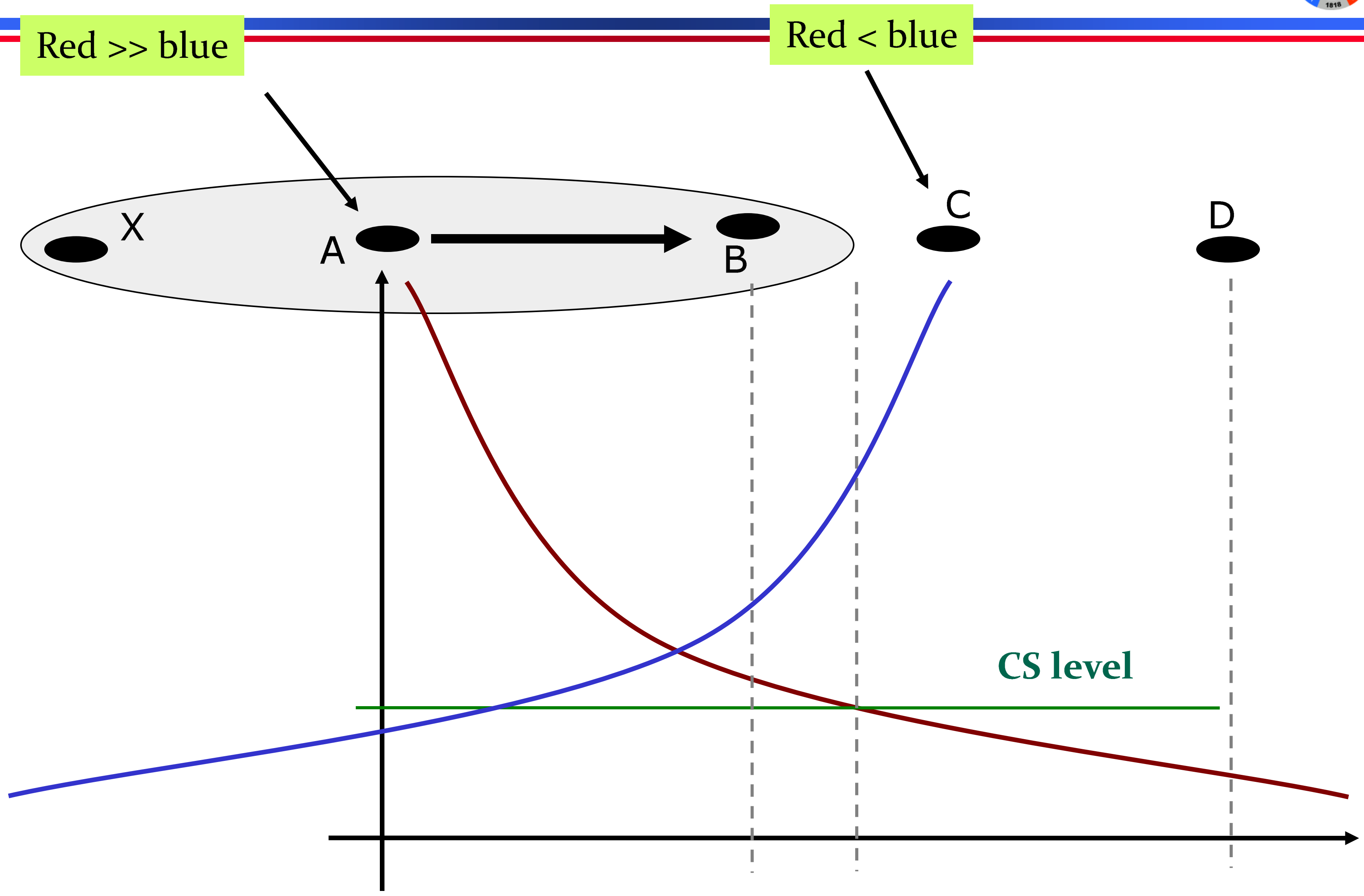
$$SINR = \frac{Semnal(S)}{Interferenta(I) + Zgomot(N)}$$

$$S_B^A = \frac{P^A_{transmit}}{d_{AB}^{\alpha}}$$

$$I_B^C = \frac{P^C_{transmit}}{d_{CB}^{\alpha}}$$

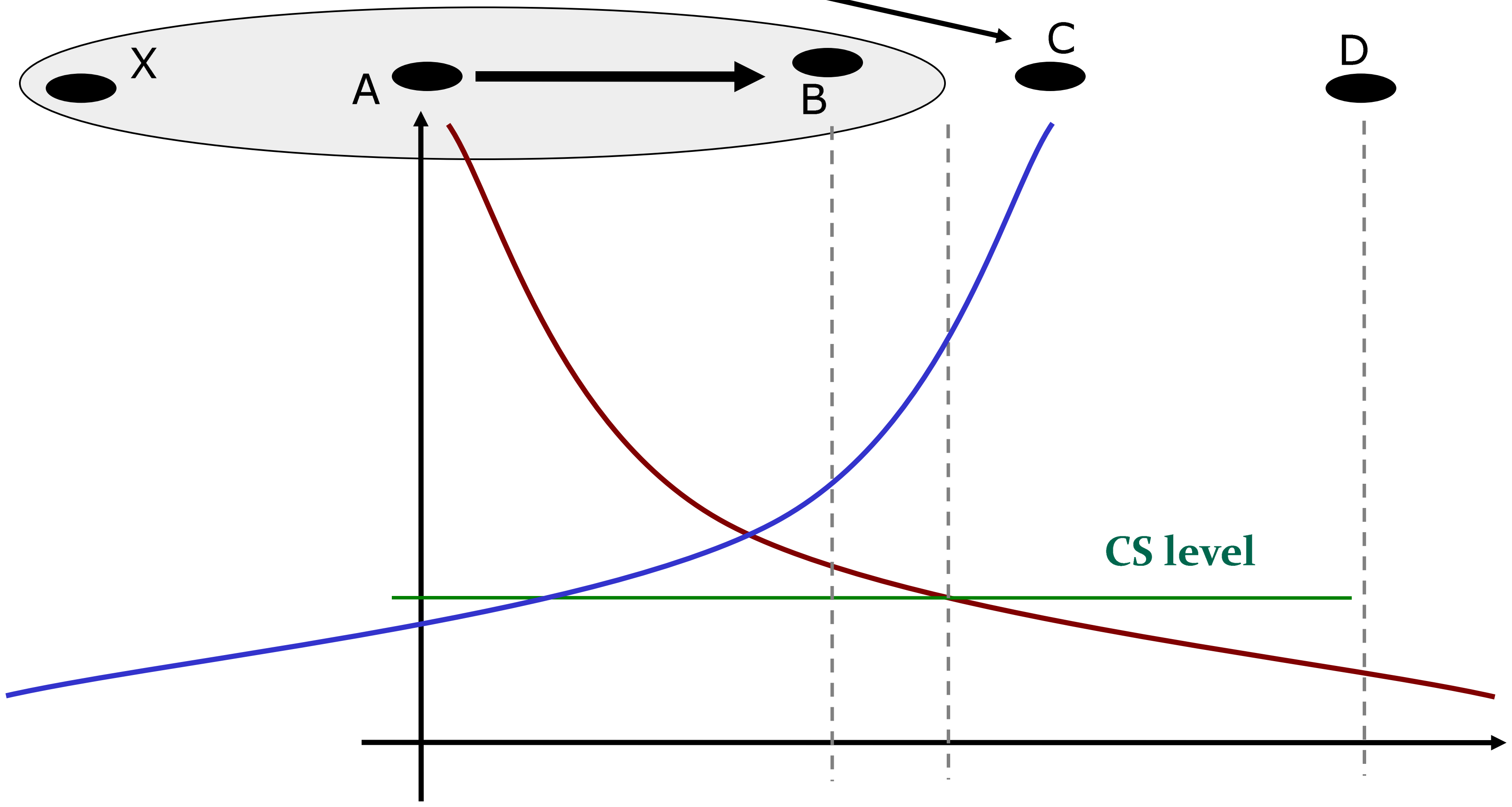
$$\longrightarrow$$

$$SINR_B^A = \frac{\dfrac{P^A_{transmit}}{d_{AB}^{\alpha}}}{N + \dfrac{P^C_{transmit}}{d_{CB}^{\alpha}}}$$


Red >> blue
Red < blue
X
A
B
C
D
CS level

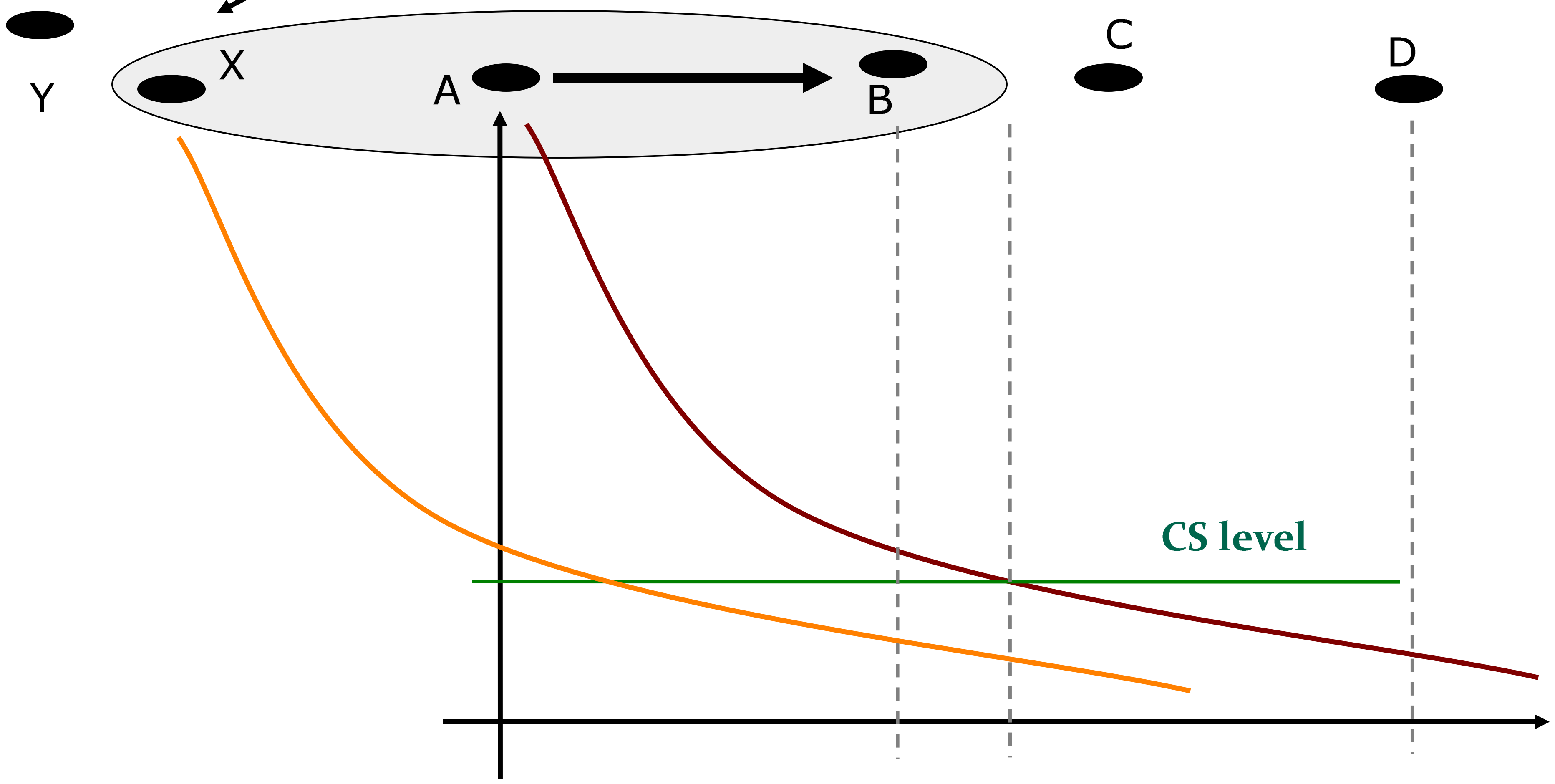
Important: C doesn't hear A, creates interference at B

C is a hidden terminal for A



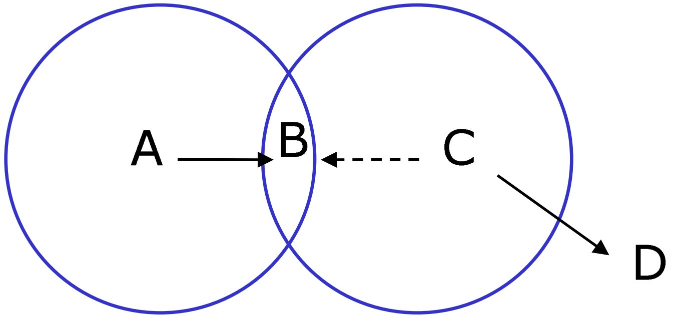
Important: X hears A, but doesn't really need to yield access (because he speaks to Y)

X is an exposed terminal for A

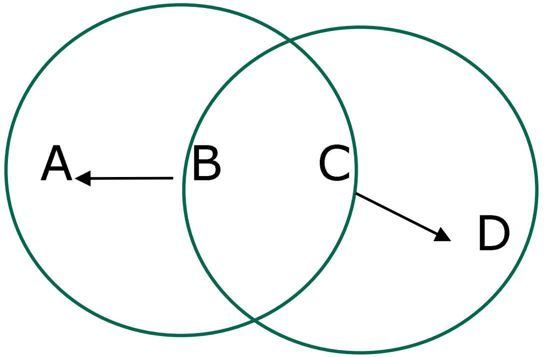


hidden & exposed terminals

- **Hidden terminal (HT)**
  - » **A and C can send at the same time**

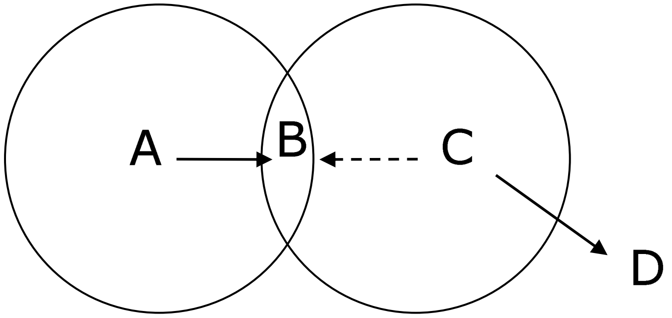


- **Exposed terminal (ET)**
  - » **B and C cannot send at the same time**

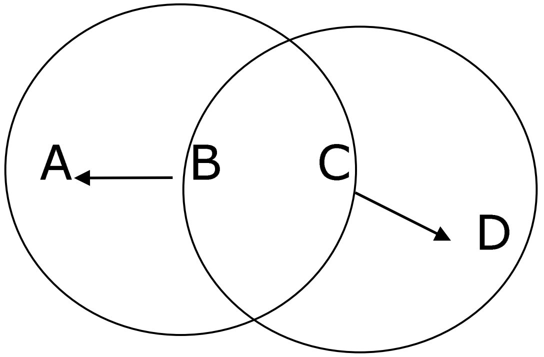


hidden & exposed terminals

- Real situations are rarely clean HT/ET
  - asymmetric channels
  - different hardware
  - combinations of HT, ET



- Asymmetrical ET:
  - only B hears C
  - unfairness between B->A, C->D



summary access methods

- Fixed access: TDMA, FDMA, CDMA
  - Limited scalability, granularity
  - near-far terminals, power control

- Random access
  - Aloha, CS, CSMA/CD

- Problems in wireless networks
  - power control
  - signal strength decreases with $1/d^n$
  - sender applies CS, but <u>collisions happen at the receiver</u>
  - sender cannot hear the collision =>CD does not work
  - hidden terminal => CS might not work
  - exposed terminal => CS works when it shouldn’t
  - near-far terminal => close terminals are too ‘loud’