ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 7: Wireless MAC & Interference Management

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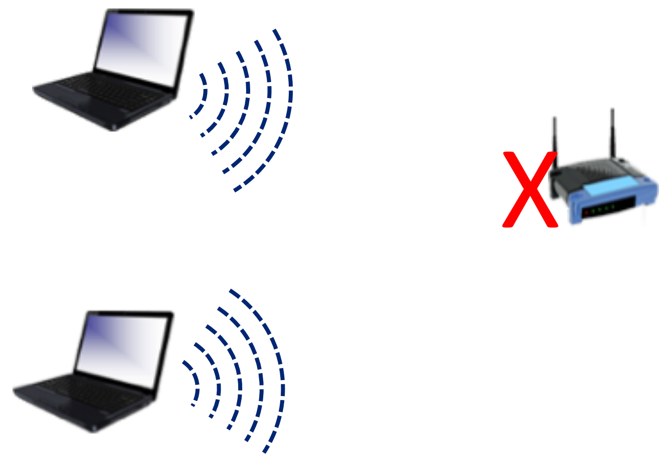
CSL: COORDINATED SCIENCE LAB

Wireless Is Shared Medium

- *interference from nodes in the network:*



- *interference from other sources:* standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors, microwaves, baby monitors, …) interfere as well

Wireless Interference

SNR is no longer the main metric!

$Interference\ to\ Noise\ Ratio$: $INR = \dfrac{Interference\ (I)}{Noise\ (N)}$

- $INR > 1 \rightarrow$ Interference limited
- $INR < 1 \rightarrow$ Noise limited

$Signal - to - Interference\ \&\ Noise\ Ratio$:

$$SINR = \frac{Received\ Signal\ Power\ (P_{Rx})}{Interference\ (I) + Noise\ (N)}$$

Multiple Access Protocols

- Single shared broadcast channel
- Two or more simultaneous transmissions by nodes: interference
  - *collision* if node receives two or more signals at the same time

Multiple Access Protocol

- distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination

MAC Protocol Should be:

Efficient:

No idle channels, Maximize utilization, No Collisions

→ No wasted resources

Fair:

No starvation, Equal distribution of resources

→ based on what? Need?

Ideal MAC Protocol

given: broadcast channel of rate R bps

desiderata:

1. when one node wants to transmit, it can send at rate R.
2. when M nodes want to transmit, each can send at average rate R/M
3. fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. simple

MAC Protocols

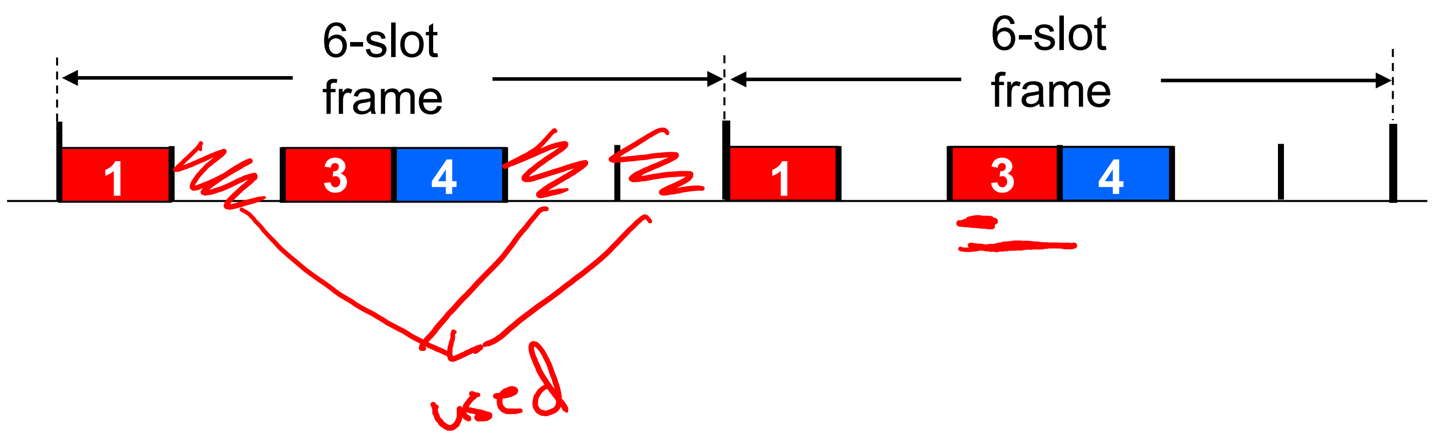
- ***Reservation Based:***
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - allocate piece to node for exclusive use

- ***Contention Based: (random access)***
  - channel not divided, allow collisions
  - "recover" from collisions

TDMA: Time Division Multiple Access

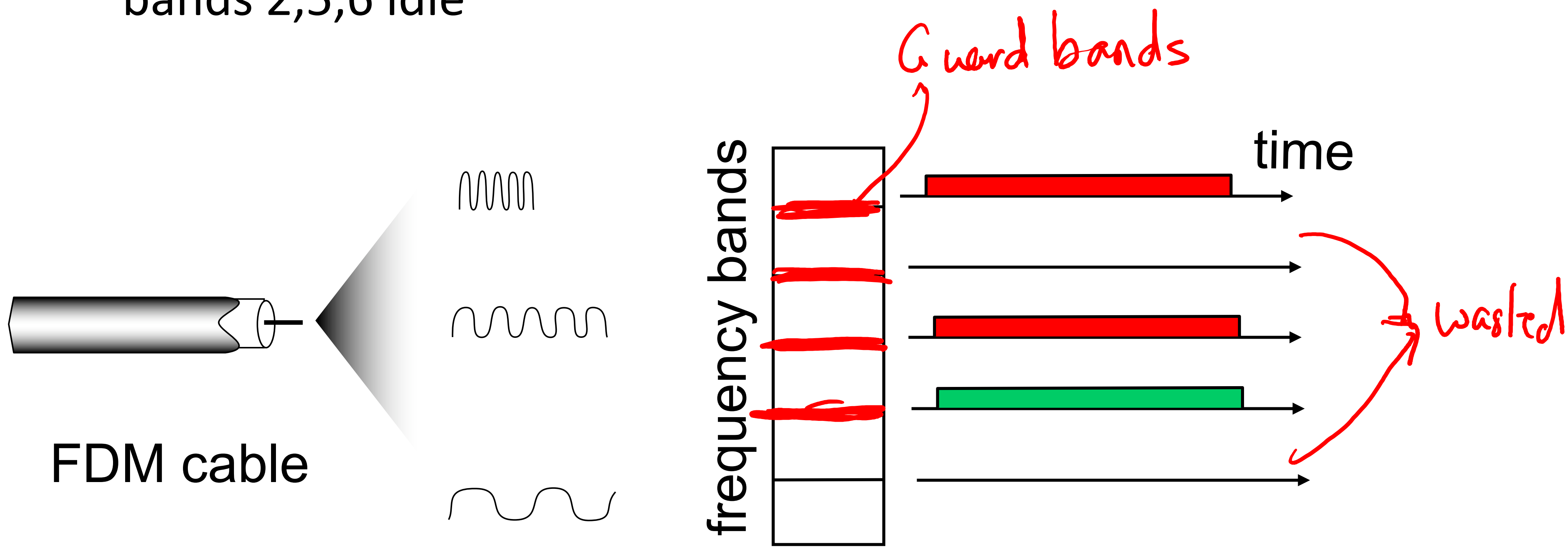
- access to channel in "rounds"
- each station gets fixed length slot (length = more packet transmission time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have packets to send, slots 2,5,6 idle

latency = $O(N)$



FDMA: Frequency Division Multiple Access

- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused transmission time in frequency bands go idle
- example: 6-station LAN, 1,3,4 have packet to send, frequency bands 2,5,6 idle



CDMA: Code Division Multiple Access

- unique “code” assigned to each user; i.e., code set partitioning
  - all users share same frequency, but each user has own “chipping” sequence (i.e., code) to encode data
  - allows multiple users to “coexist” and transmit simultaneously with minimal interference (if codes are “orthogonal”)
- encoded signal = (original data) X (chipping sequence)
- decoding: inner-product of encoded signal and chipping sequence
- Example codes: Gold Codes, Walsh Codes

CDMA: Code Division Multiple Access

Ideally, need codes to have good:

- Auto-correlation properties: $c_i(t) \cdot c_i(t) = 1$
- Cross-correlation properties: $c_i(t) \cdot c_j(t) = 0$ for $j \neq i$

$$\left(\sum_i h_i x_i(t)\, c_i(t)\right) \cdot c_i(t) = h_i x_i(t)$$

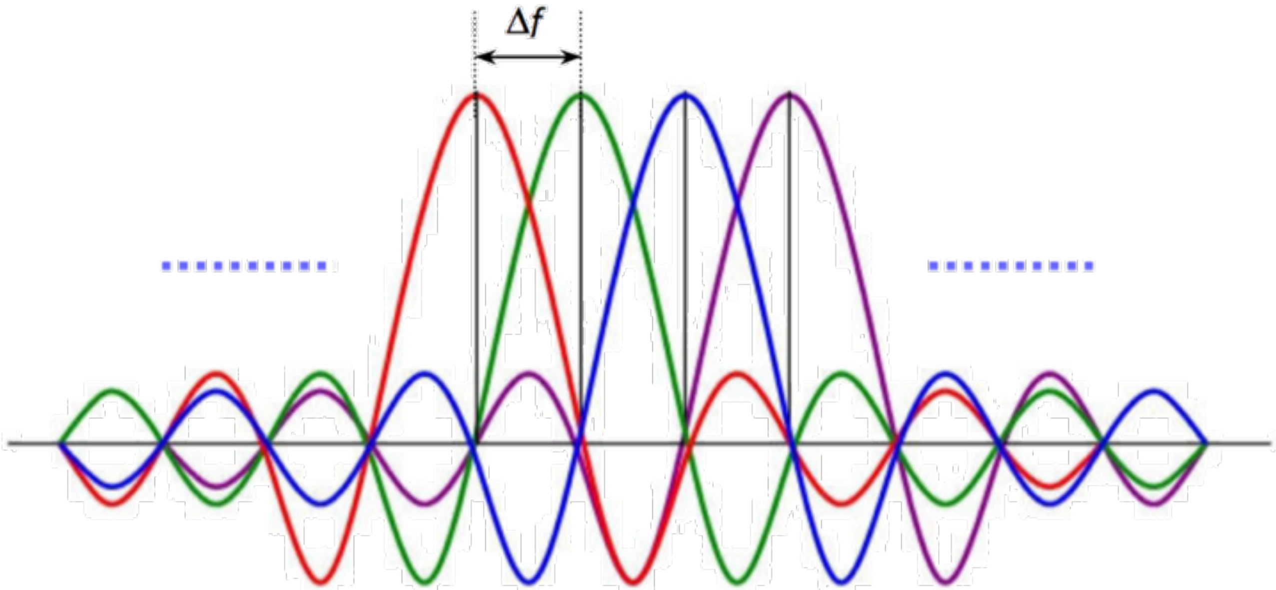
Need orthogonal codes:

- For N users, length of code is exponential in N → 2^{N-1}

- Near Far Effect Problem → need power management

OFDMA: Orthogonal Frequency Division Multiple Access

- Use OFDM: Assign different subcarriers to different users.
- More efficient than FDMA since no guard bands are needed
- Requires Time Synchronization



CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CSMA: listen before transmit:

if channel sensed idle: transmit entire frame

- if channel sensed busy, defer transmission

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

Contention Window (CW):

- (1) Sense, if channel idle, wait $DIFS \approx 50\mu s$
- (2) Pick random number m between 0— CW_{max} ← Random back-off
- (3) Wait m slots ($\approx 10\mu s$), then sense & transmit
- (4) Wait S$IFS \approx 10\mu s$ for an ACK
- → If Collision: $CW_{max} = 2{\times}CW_{max}$ ← exponential
- → If Success: $CW_{max} = 2$

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

Throughput Efficiency

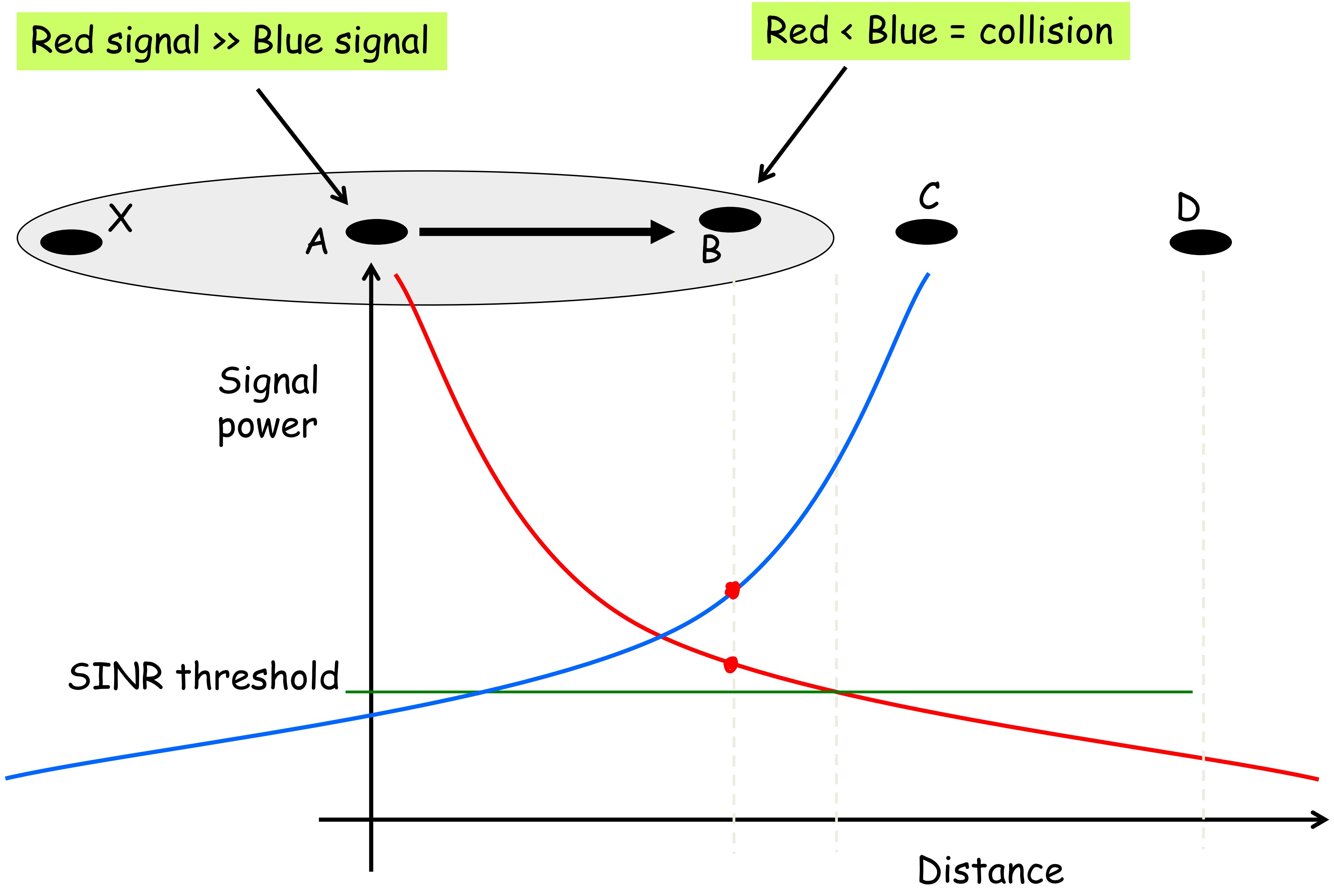
- Data: 1500 bytes = 12000 bits
- 802.11n advertised rate: 300 Mbps
- Data Packet Time $= \ 12000/300Mbps \ = \ 40\mu s$

- Overhead:

$$DIFS \ + \ SIFS \ + \ ACK \ + \ m\times slot = 50 + 10 + 30 + 7\times 10 = 160\mu s$$

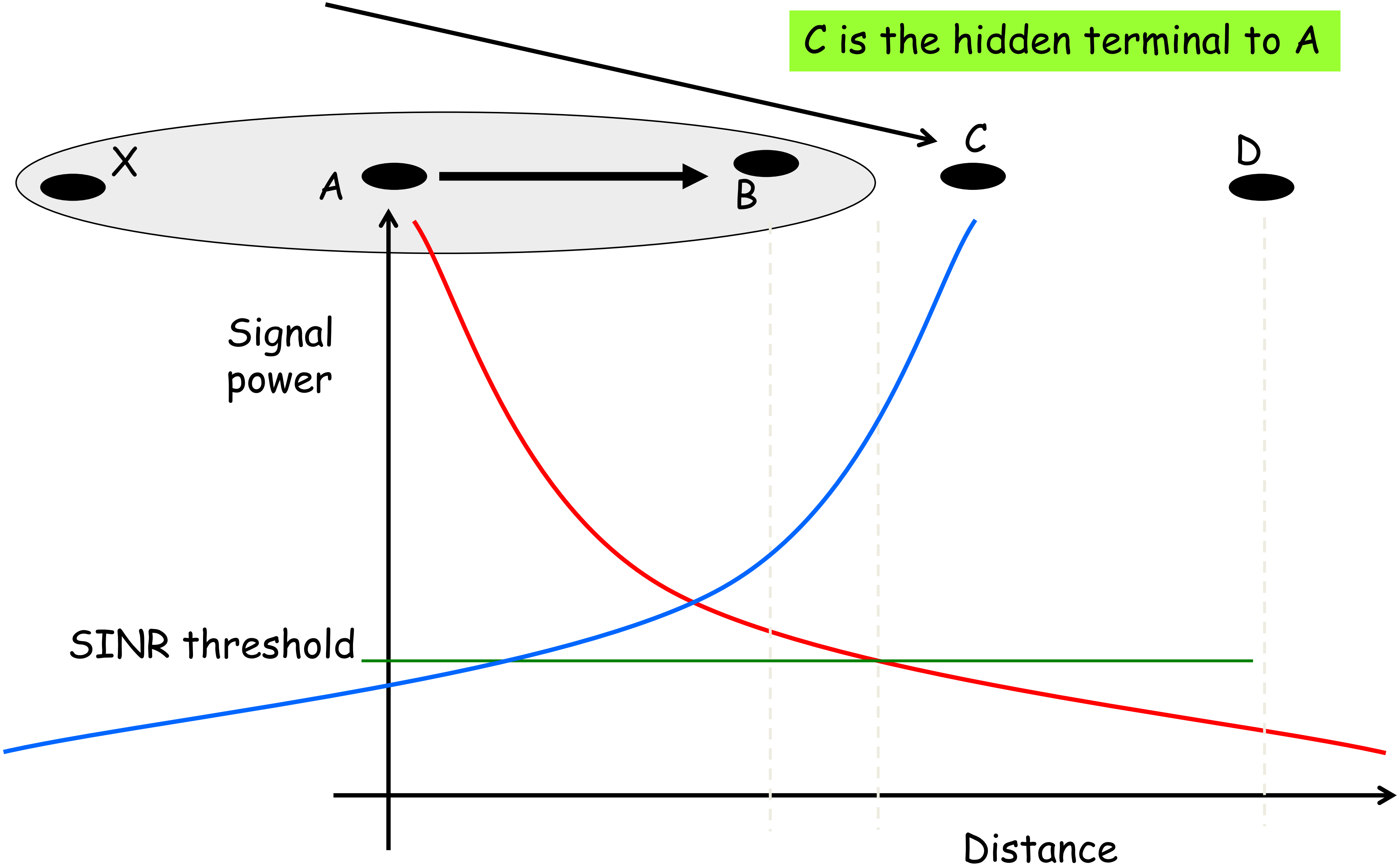
- Actual Throughput: $12000/(40 + 160) \ = 60Mbps$

- **80% Reduction in Throughput!!**


Red signal >> Blue signal
Red < Blue = collision
X
A
B
C
D
Signal power
SINR threshold
Distance

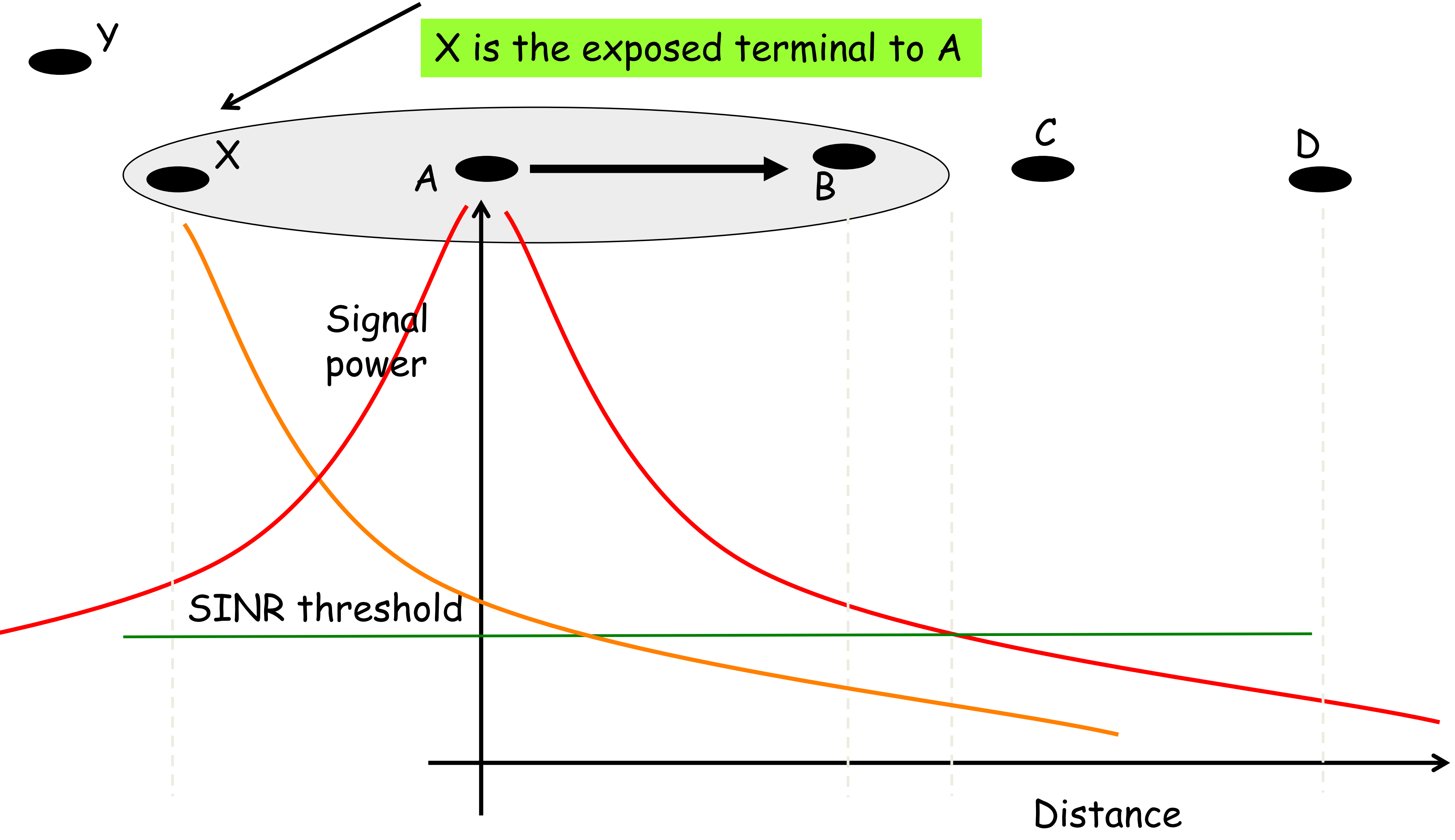
Important: C has not heard A, but can interfere at receiver B

C is the hidden terminal to A



Important: X has heard A, but should not defer transmission to Y

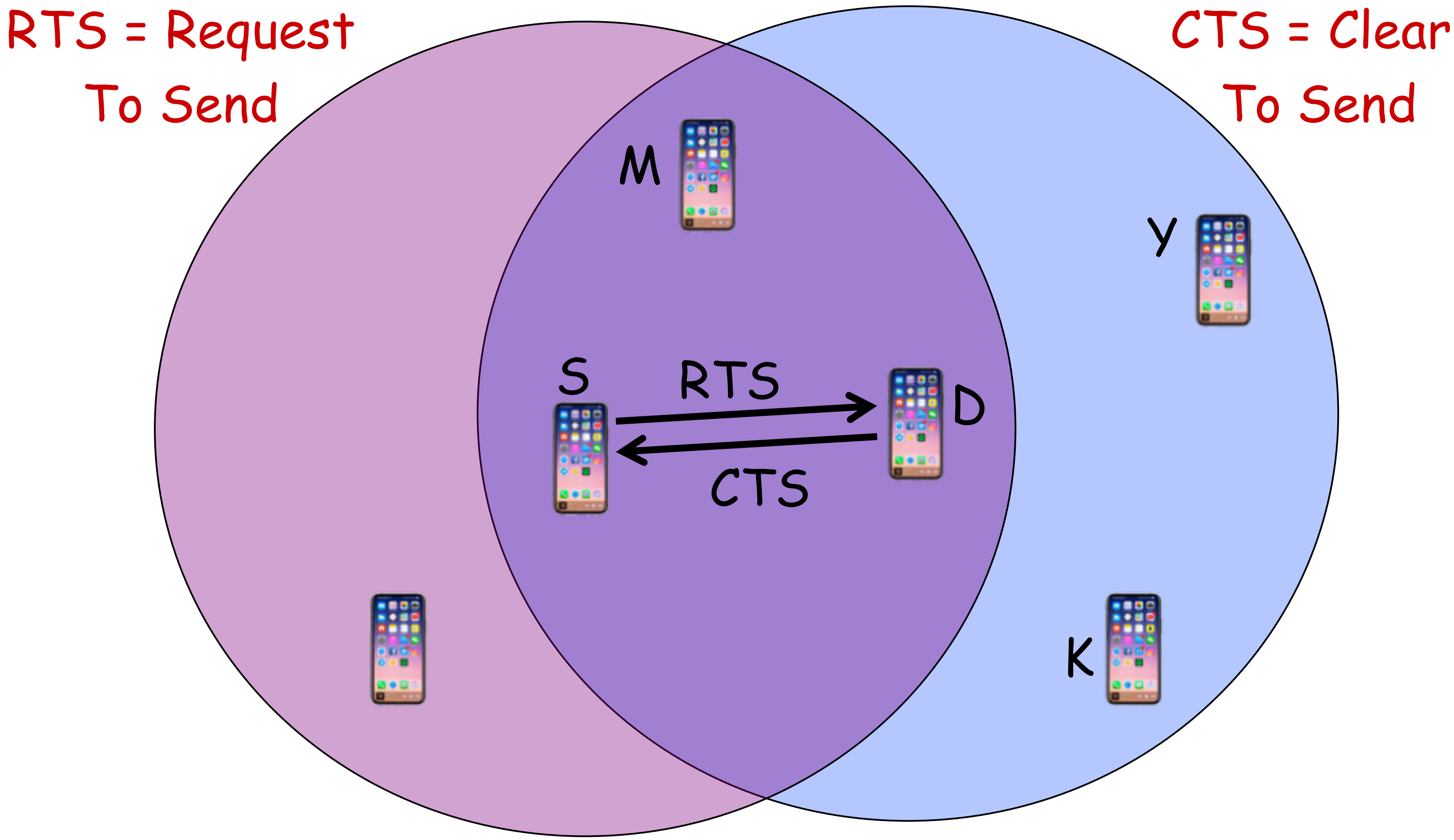
X is the exposed terminal to A



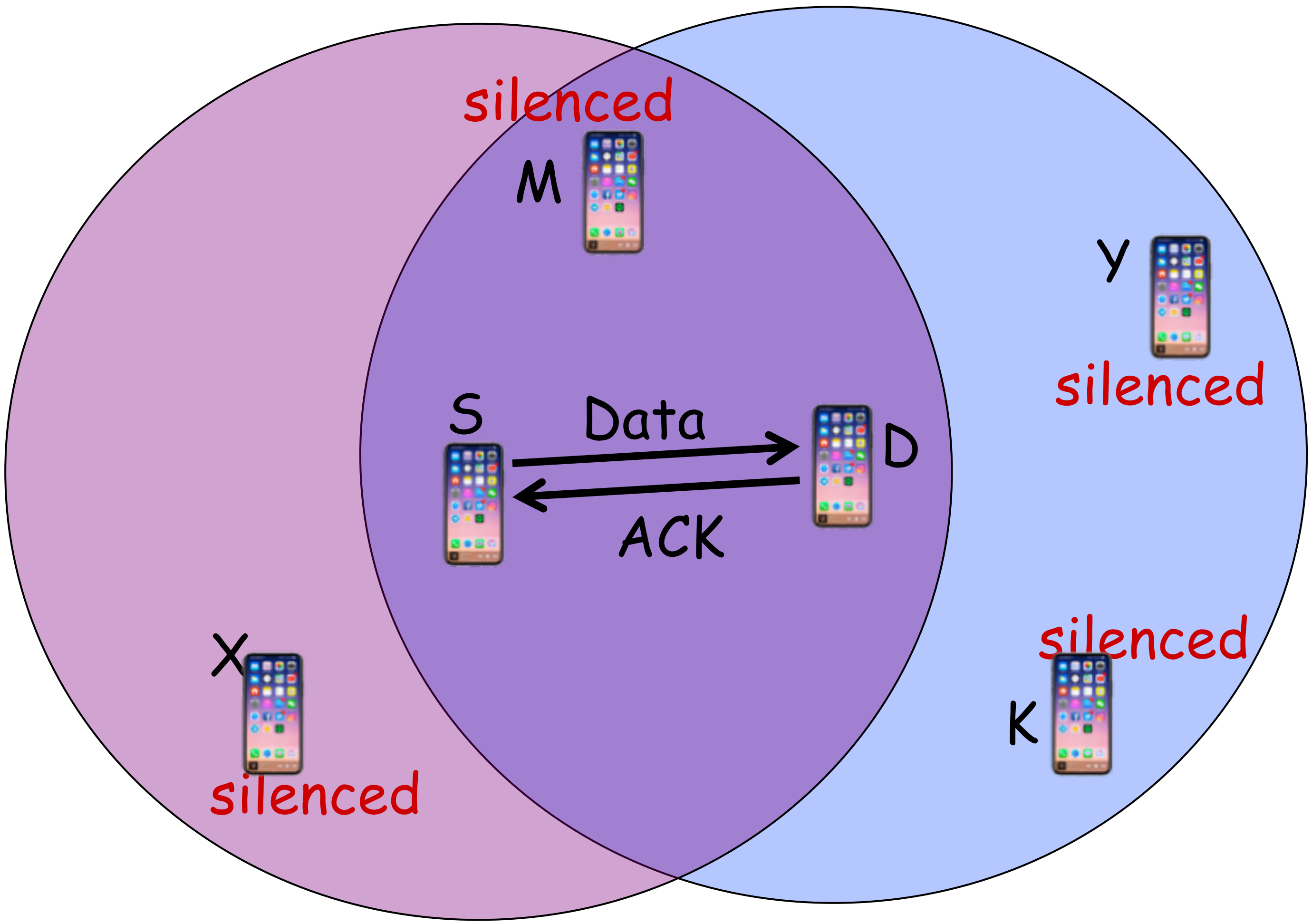
Hidden and Exposed Terminal Problems

Critical to wireless networks even today

IEEE 802.11



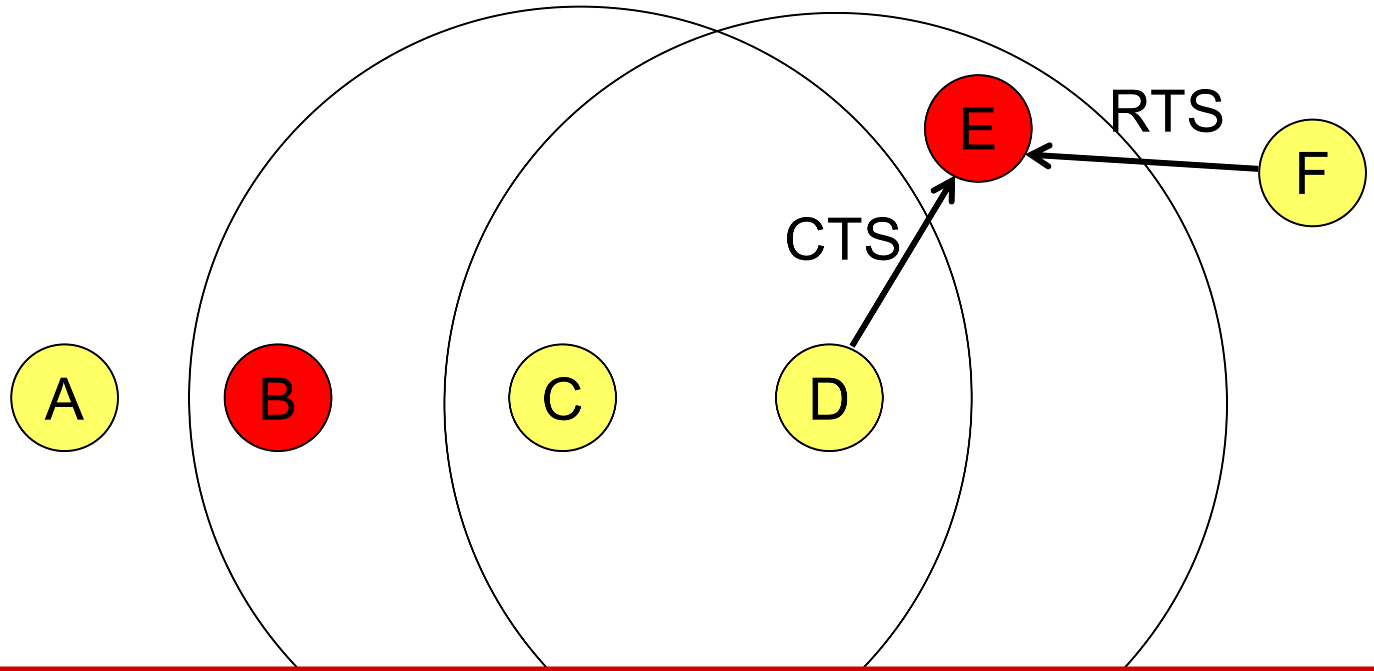
IEEE 802.11



But is that enough?

RTS/CTS

- Does it solve hidden terminals ?



E does not receive CTS successfully → Can later initiate transmission to D. Hidden terminal problem remains.

MAC Protocols: Pros and Cons

- ***Reservation Based:***
  + No Interference
  + Fair
  – Centralized
  – Wasted resources

- ***Contention Based: (random access)***
  + Distributed
  + Good for bursty traffic
  – Collisions
  – Overhead

Traditional Approach: Avoid Collisions

Can we decode collisions?

Channel Rate

- Single TX

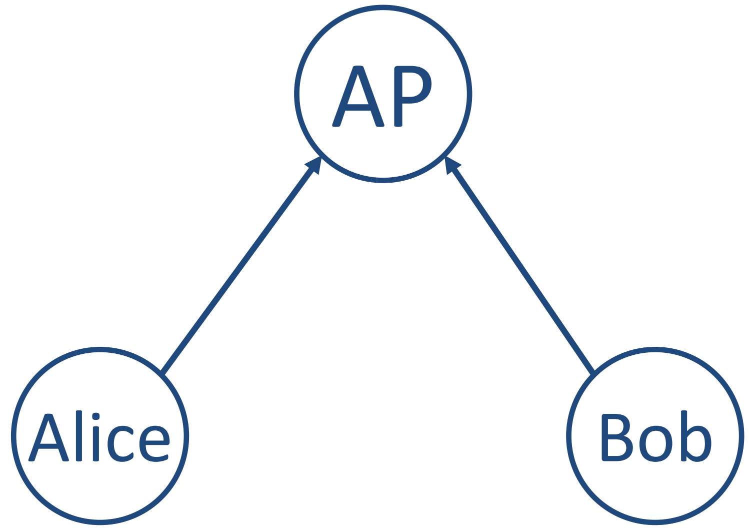
$$Max\ Achievable\ Rate = Capacity$$

$$= Bandwidth \times \log_2(1 + SNR)$$

$$= B \times \log_2\left(1 + \frac{P_{RX}}{N}\right)$$

Channel Rate

- Multiple TX



R_{max}

$$R_A \leq B\log_2(1 + SINR_A) = B\log_2\left(1 + \frac{P_A}{P_B + N}\right) \leq B\log_2\left(1 + \frac{P_A}{N}\right)$$

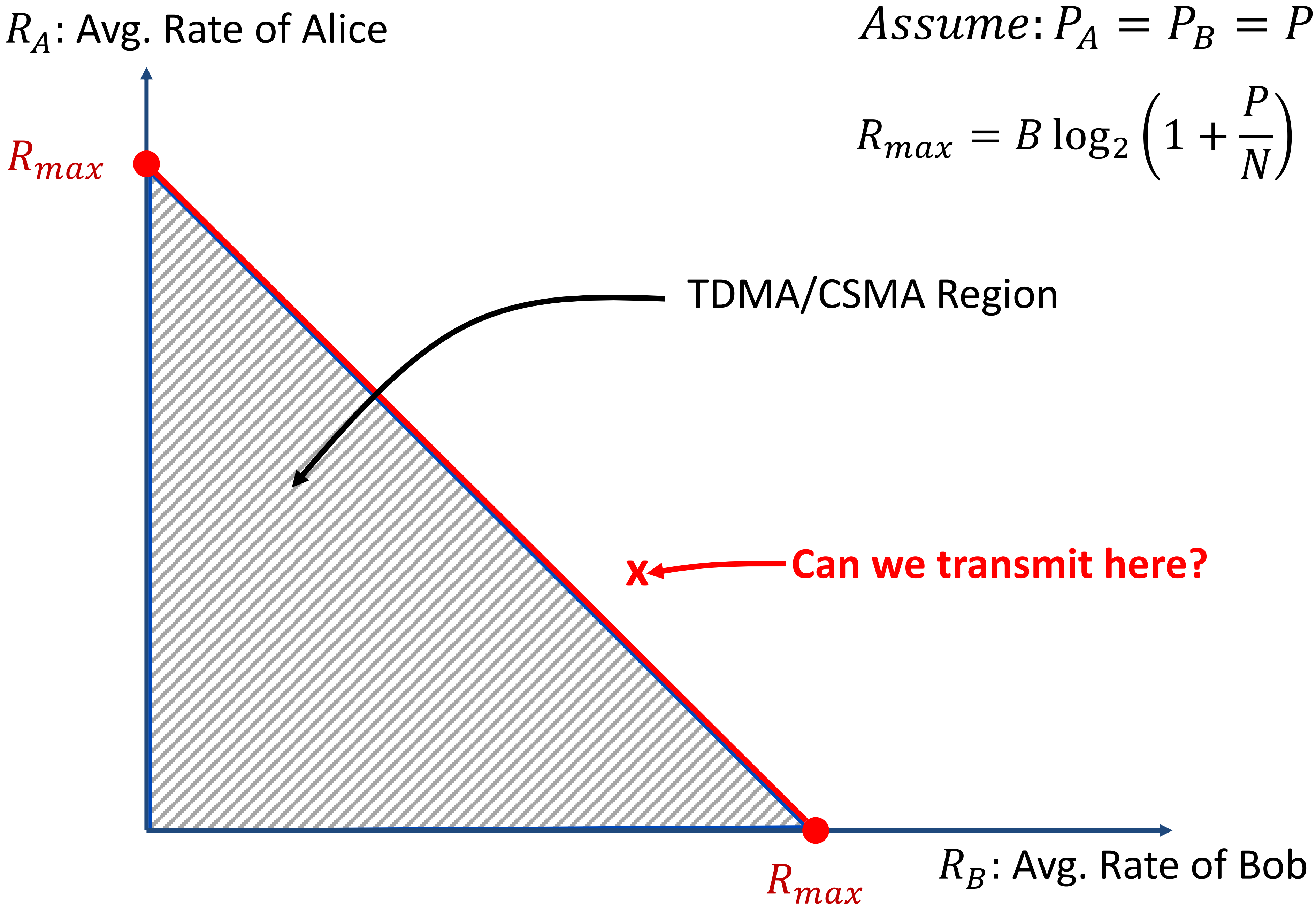
$$R_B \leq B\log_2(1 + SINR_B) = B\log_2\left(1 + \frac{P_B}{P_A + N}\right) \leq B\log_2\left(1 + \frac{P_B}{N}\right)$$

$$Total\ Rate = R_A + R_B$$

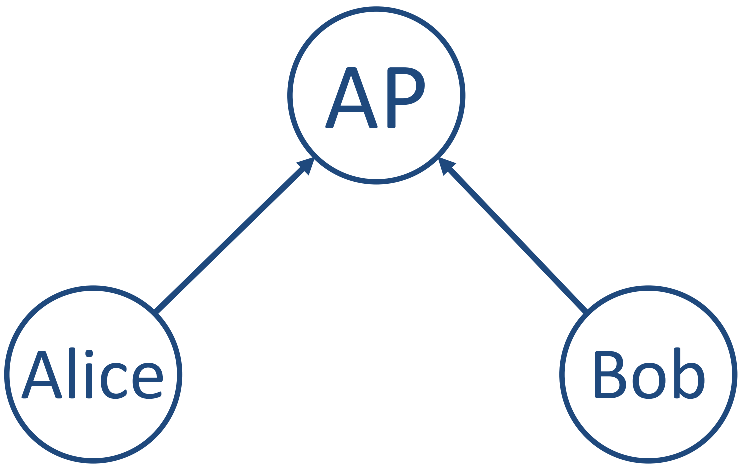
Rate Region

Assume: $P_A = P_B = P$

$$R_{max} = B\log_2\left(1 + \frac{P}{N}\right)$$



Interference Cancellation



AP gets: $y(t) = y_A(t) + y_B(t) + n(t)$

$n'(t)$

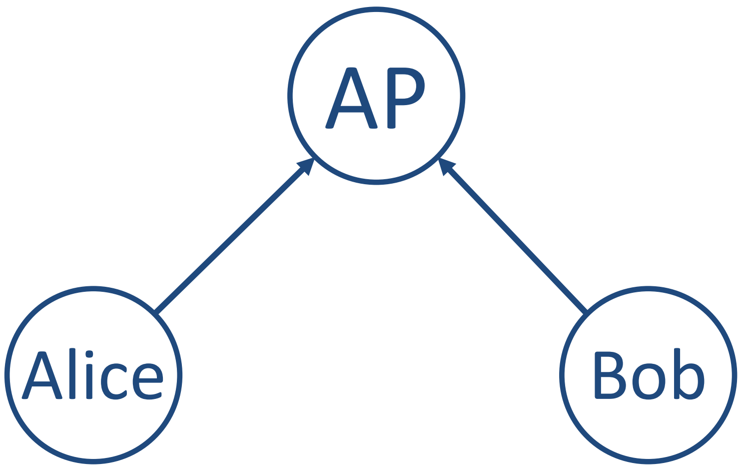
1. Decode Alice by treating Bob's signal as noise.
2. Now AP knows Alice's signal, subtract it out:

$$y(t) - y_A(t) = y_B(t) + n(t)$$

3. Decode Bob's signal
4. Iterate to improve robustness to noise: subtract Bob, decode Alice

SIC

Interference Cancellation



AP gets: $y(t) = y_A(t) + y_B(t) + n(t)$

To decode Alice, she must transmit at:

$$R_{IC} = B\log_2\left(1 + \frac{P}{P+N}\right)$$

Bob can TX at $R_{max} = B\log_2\left(1 + \frac{P}{N}\right)$

1. Decode Alice by treating Bob's signal as noise.
2. Now AP knows Alice's signal, subtract it out:

   $$y(t) - y_A(t) = y_B(t) + n(t)$$

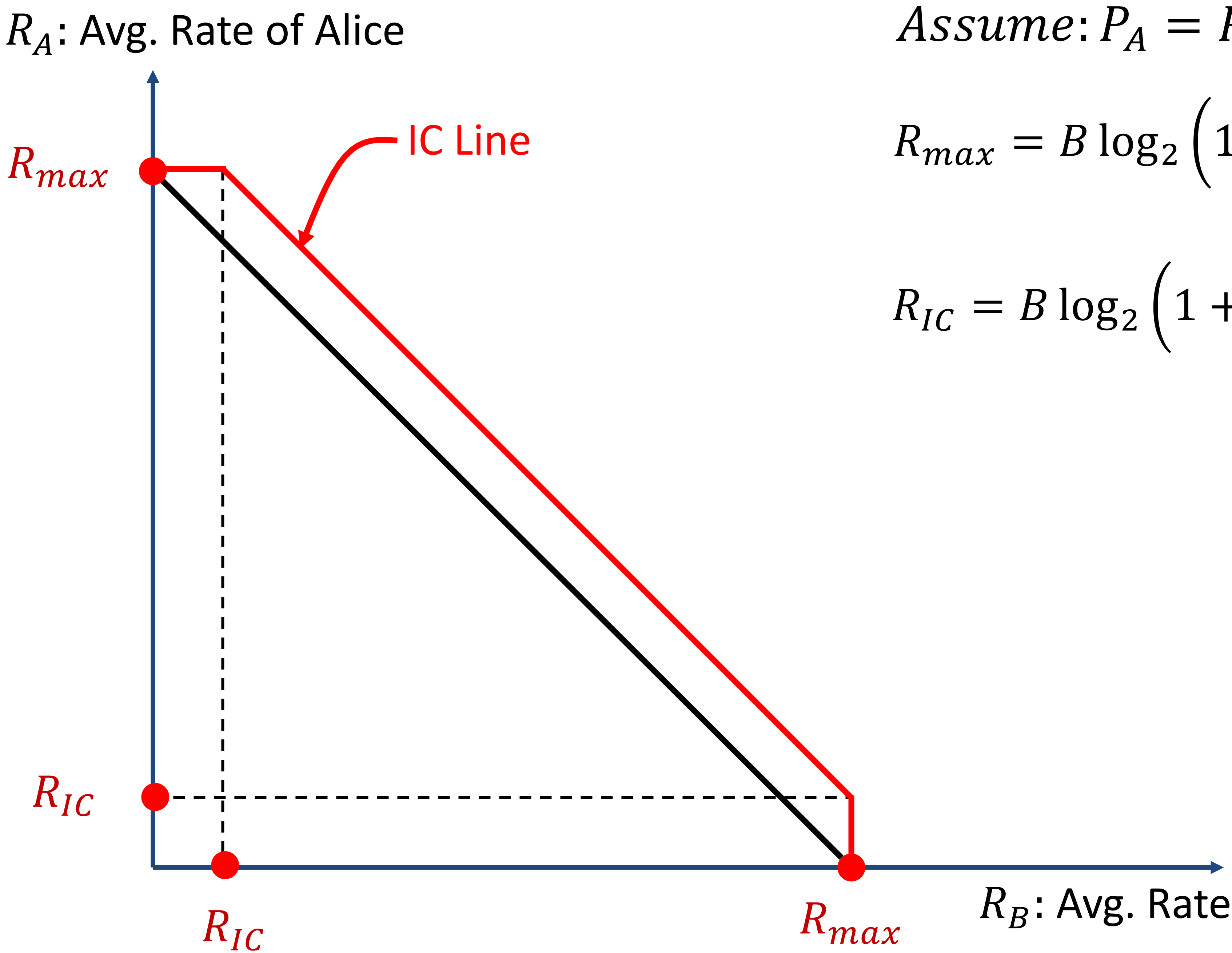
3. Decode Bob's signal
4. Iterate to improve robustness to errors: subtract Bob, decode Alice

Rate Region

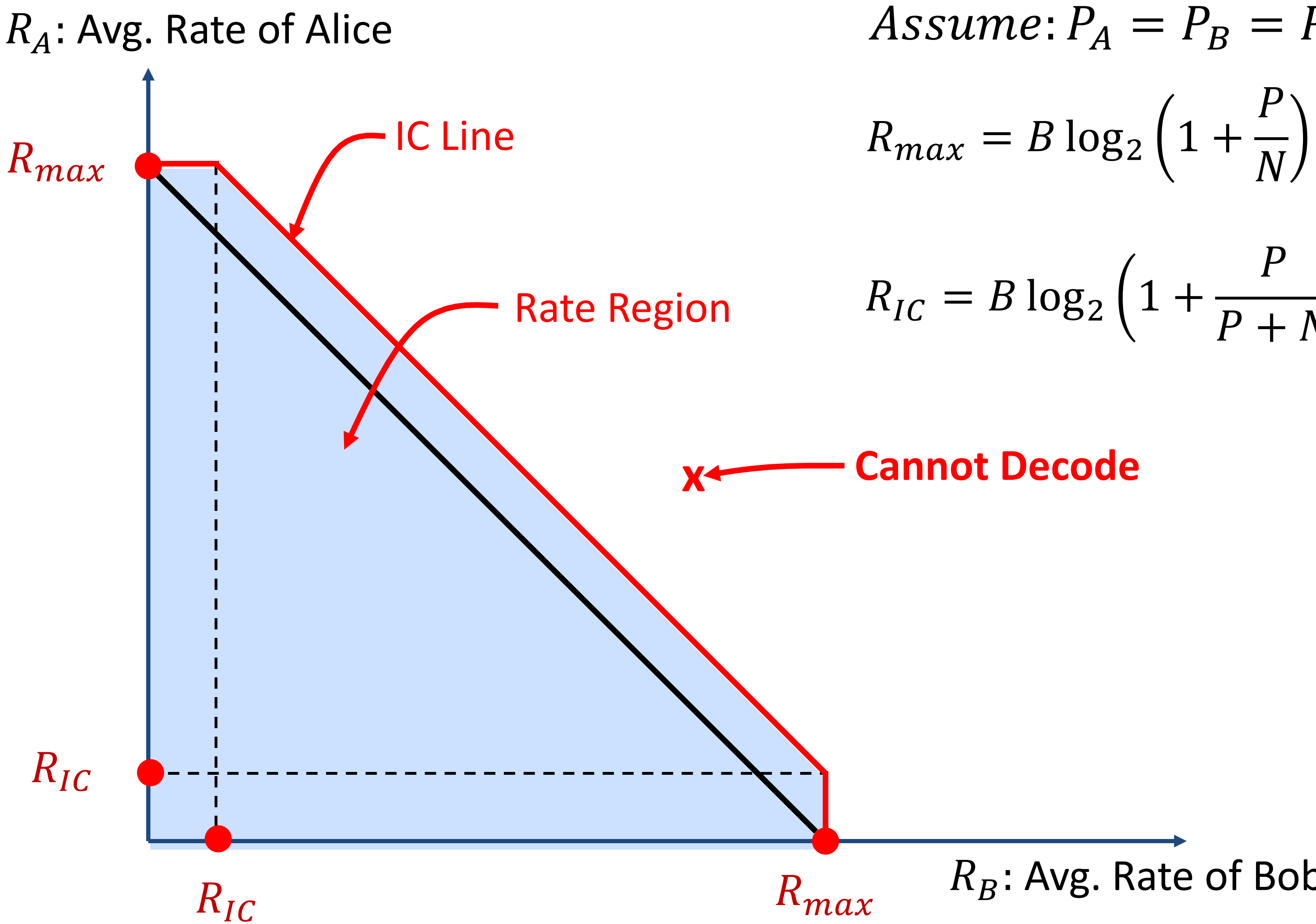
$Assume: P_A = P_B = P$

$$R_{max} = B \log_2\left(1 + \frac{P}{N}\right)$$

$$R_{IC} = B \log_2\left(1 + \frac{P}{P+N}\right)$$



Rate Region

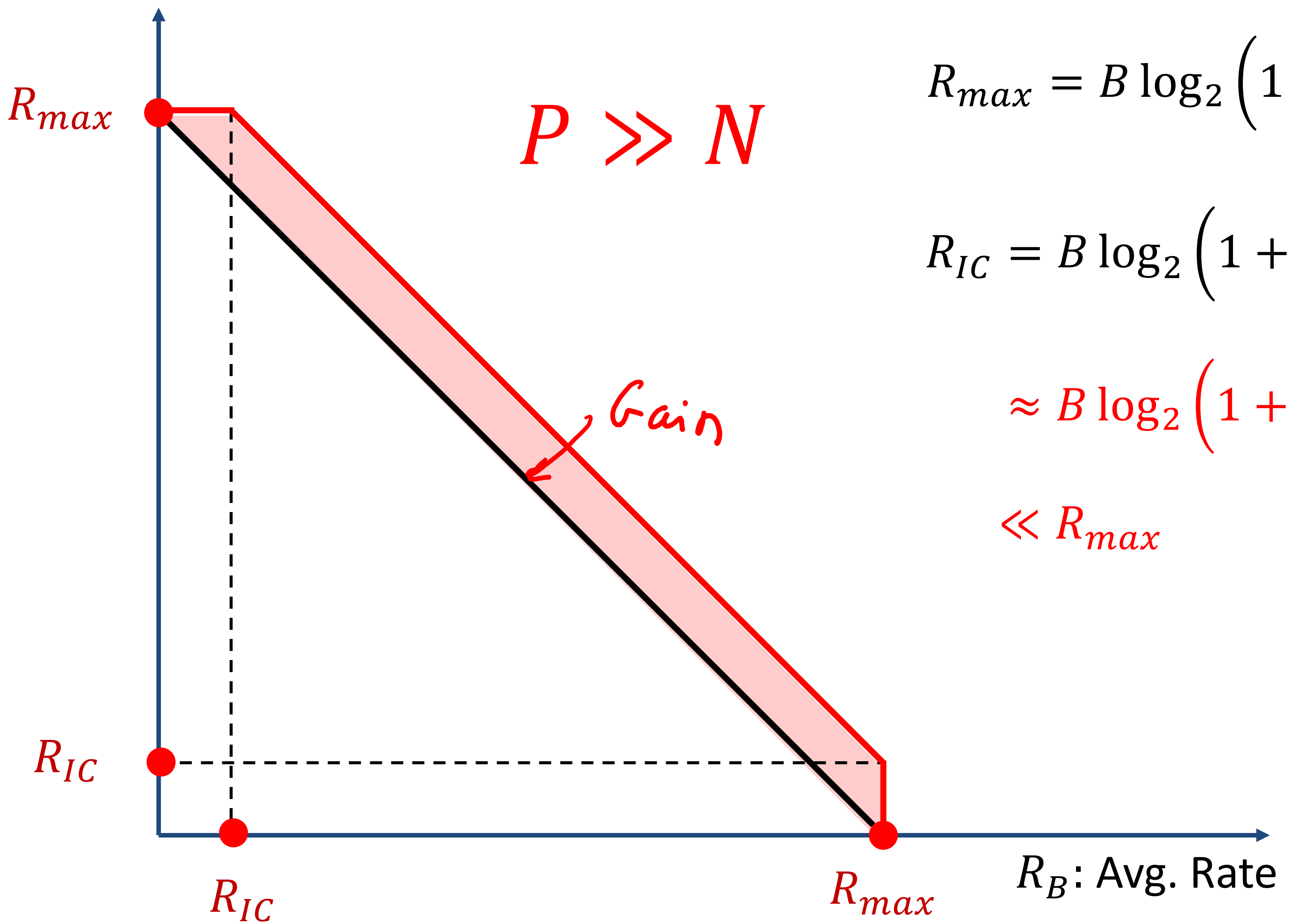


$Assume: P_A = P_B = P$

$$R_{max} = B \log_2\left(1 + \frac{P}{N}\right)$$

$$R_{IC} = B \log_2\left(1 + \frac{P}{P+N}\right)$$

Rate Region: Interference Limited



$Assume$: $P_A = P_B = P$

$$R_{max} = B \log_2\left(1 + \frac{P}{N}\right)$$

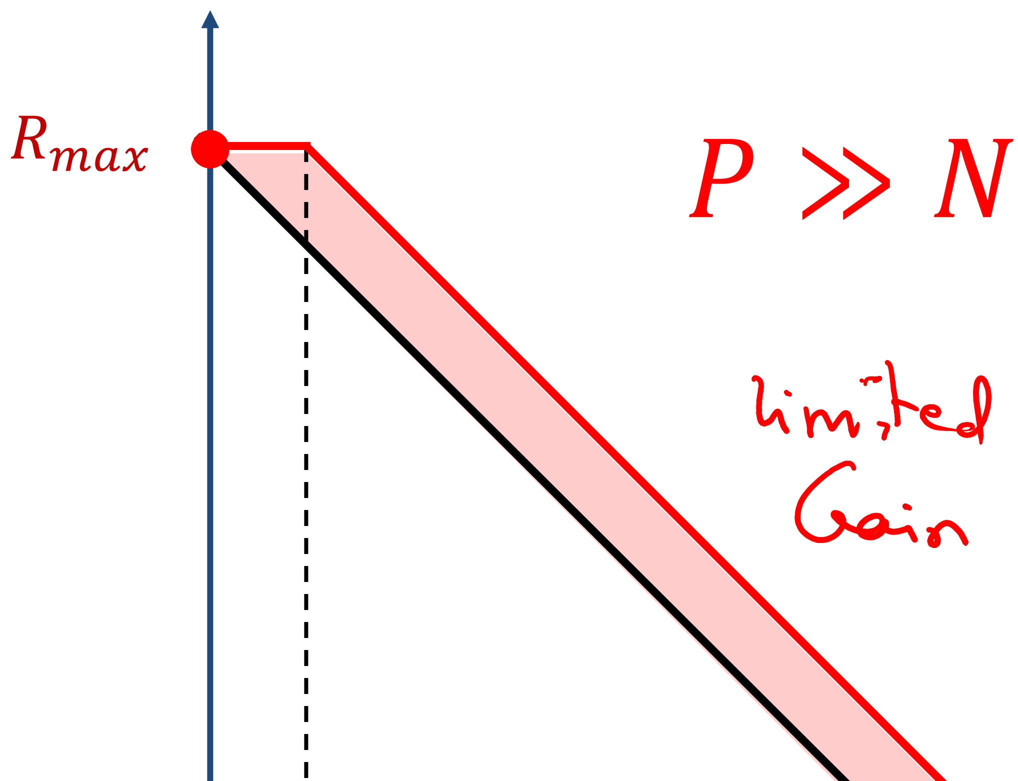
$$R_{IC} = B \log_2\left(1 + \frac{P}{P + N}\right)$$

$$\approx B \log_2\left(1 + \frac{P}{P}\right) = B$$

$$\ll R_{max}$$

Rate Region: Interference Limited

R_A: Avg. Rate of Alice



$Assume: P_A = P_B = P$

$$R_{max} = B\log_2\left(1 + \frac{P}{N}\right)$$

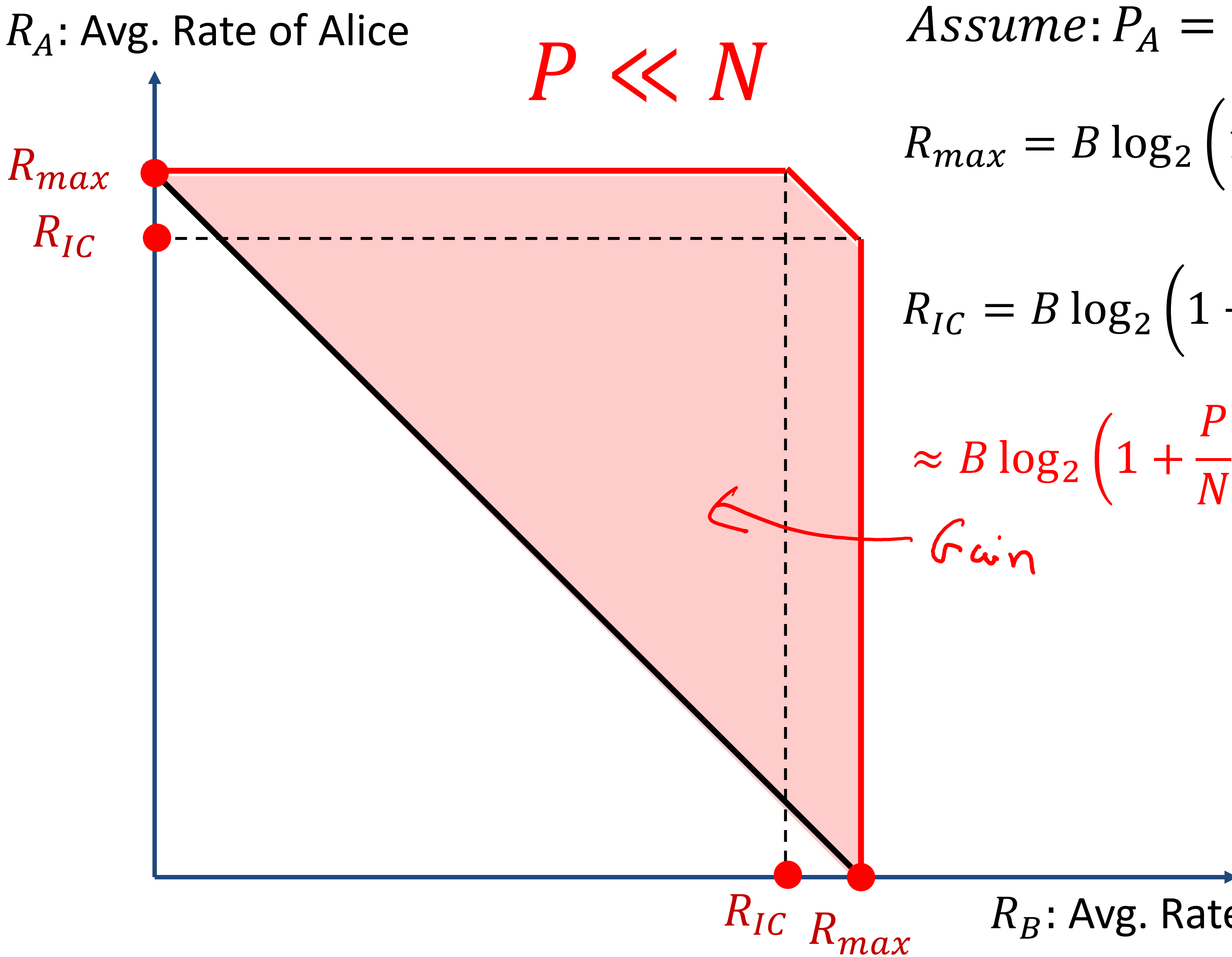
$$R_{IC} = B\log_2\left(1 + \frac{P}{P+N}\right)$$

$$\approx B\log_2\left(1 + \frac{P}{P}\right) = B$$

$$\ll R_{max}$$

$$R_{total} = R_{max} + R_{IC} = B\left(1 + \log_2\left(1 + \frac{P}{N}\right)\right)$$

Rate Region: Noise Limited



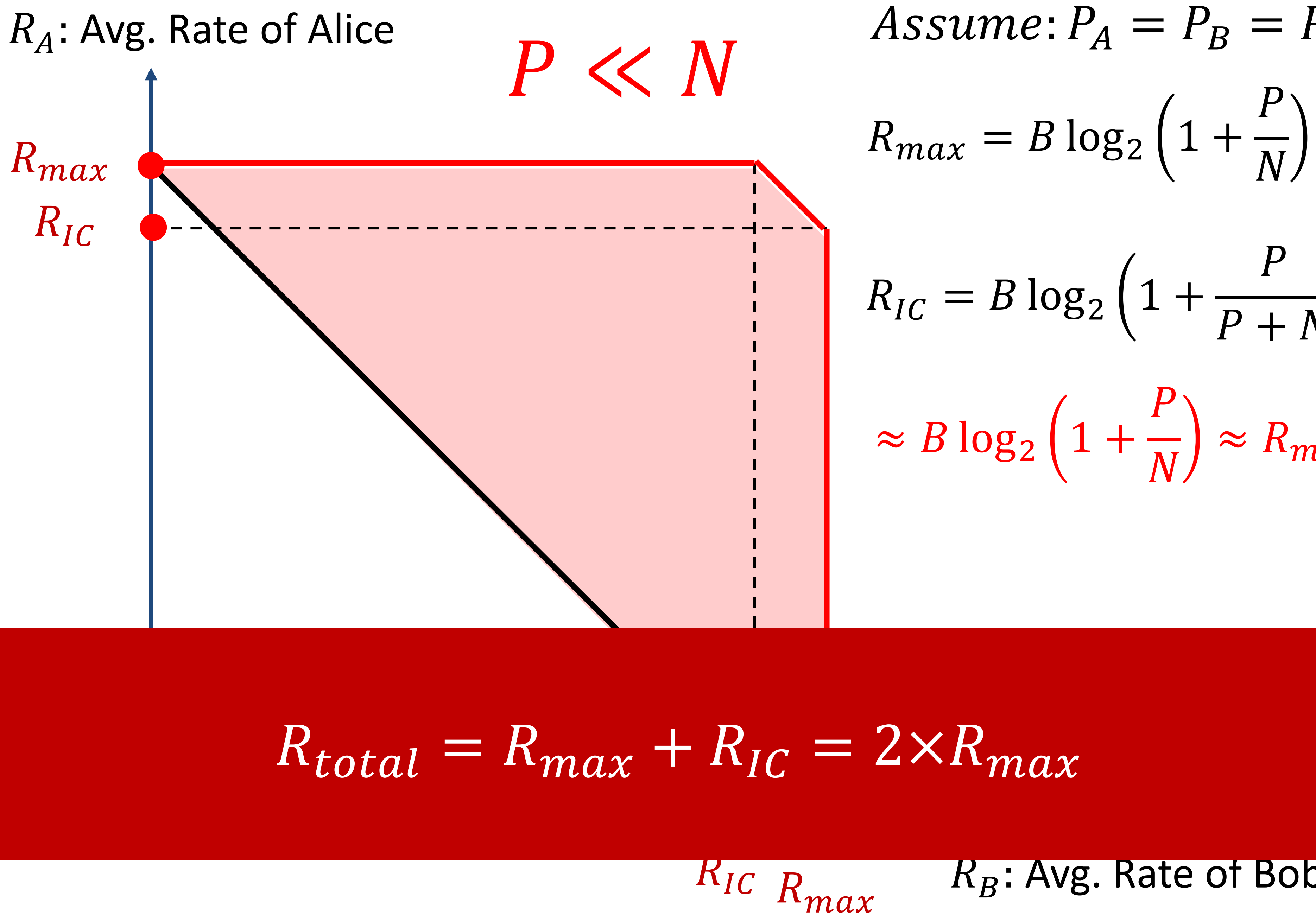
$Assume: P_A = P_B = P$

$$R_{max} = B\log_2\left(1+\frac{P}{N}\right)$$

$$R_{IC} = B\log_2\left(1+\frac{P}{P+N}\right)$$

$$\approx B\log_2\left(1+\frac{P}{N}\right) \approx R_{max}$$

Rate Region: Noise Limited



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$$R_{max} = B\log_2\left(1+\frac{P}{N}\right)$$

$$R_{IC} = B\log_2\left(1+\frac{P}{P+N}\right)$$

$$\approx B\log_2\left(1+\frac{P}{N}\right) \approx R_{max}$$

$$R_{total} = R_{max} + R_{IC} = 2\times R_{max}$$

802.11 does not use IC despite gains!

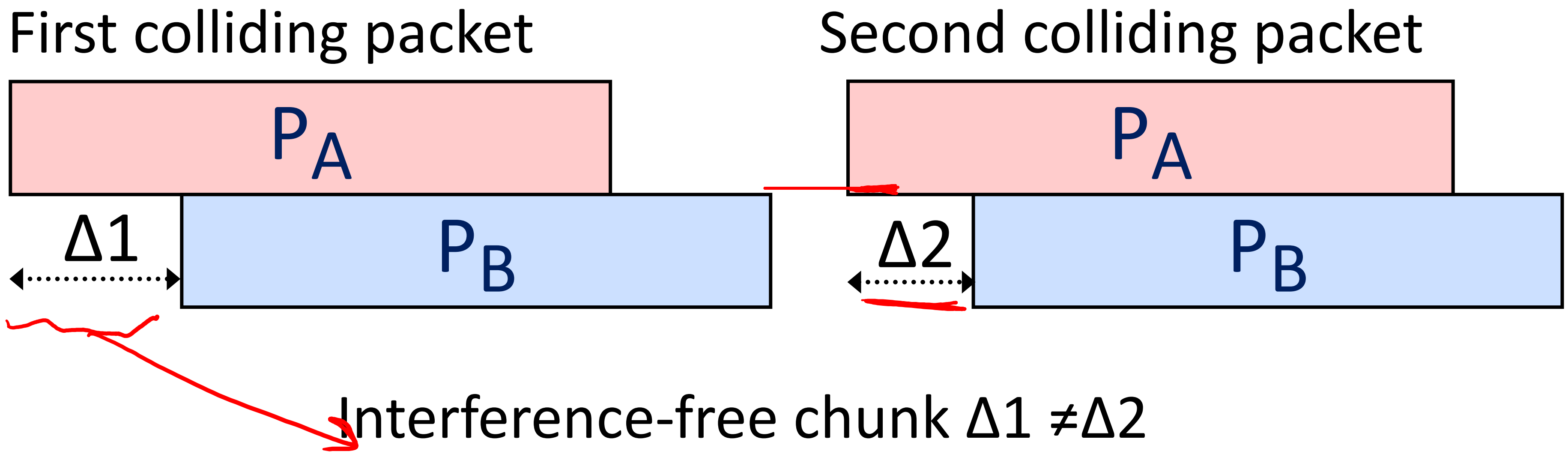
- Overhead of decoding
- Coordination between TXs to adjust the rate
- Assumes interference limited is the more common case→ limited gains.

ZigZag Decoding

- Problem:
  - Hidden Terminals

- Observations:
  - Packets that collide continue to collide. } start from small CW
  - Collision of packets has different offsets. } Random backoff

ZigZag Decoding

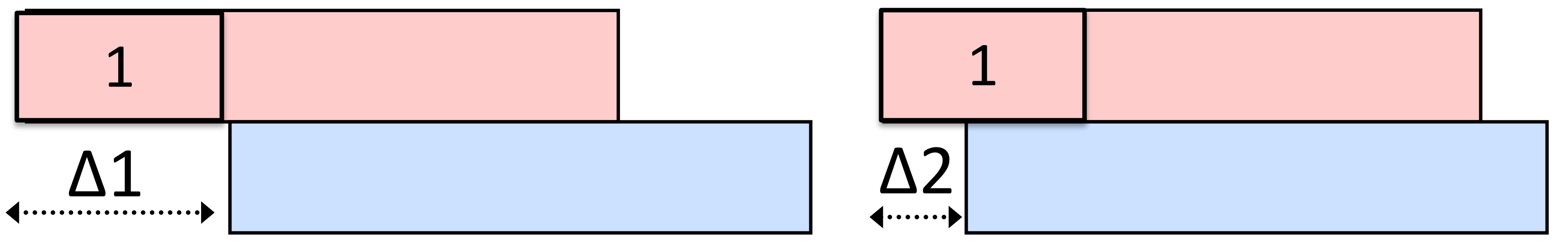


Interference-free chunk Δ1 ≠Δ2

(due to random backoff)

Interference-free chunk is exploited to bootstrap the decoding process

ZigZag Decoding

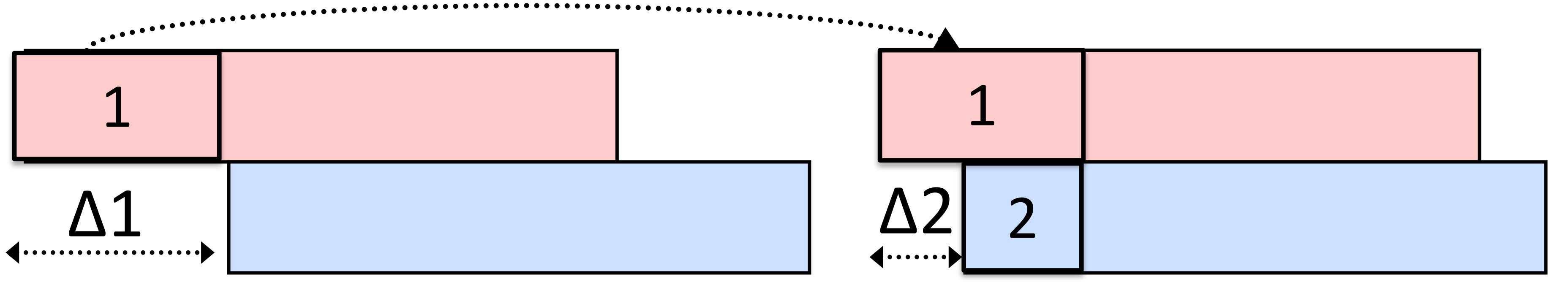


$\Delta 1 \neq \Delta 2$

Find a chunk that is interference-free in one collisions and has interference in the other

Subtract from the other collision

ZigZag Decoding



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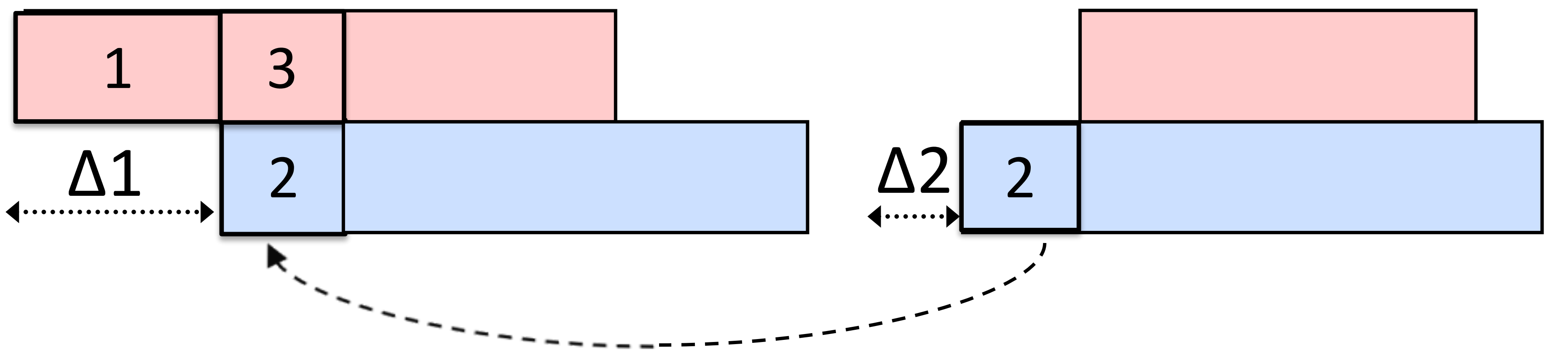

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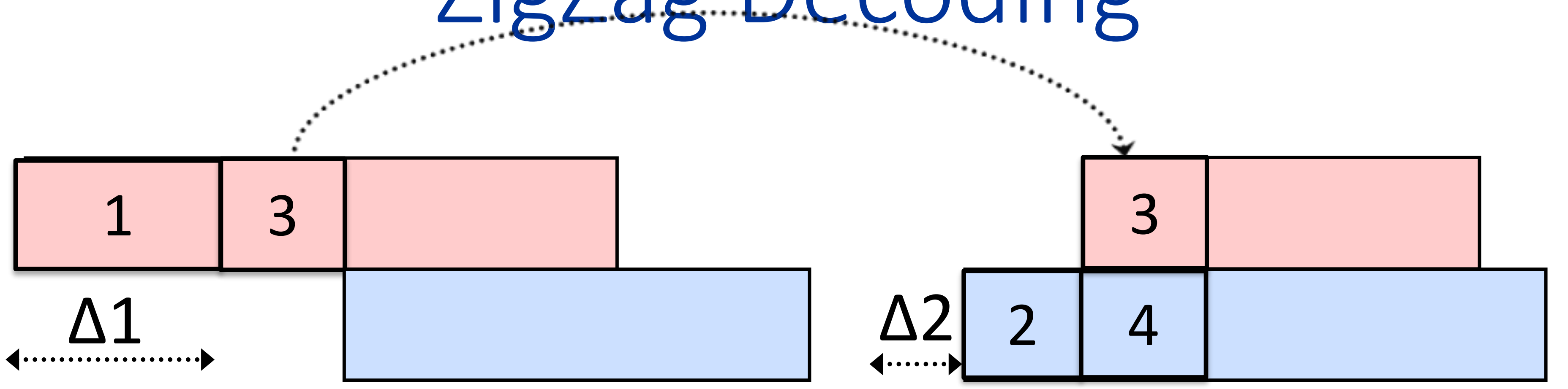

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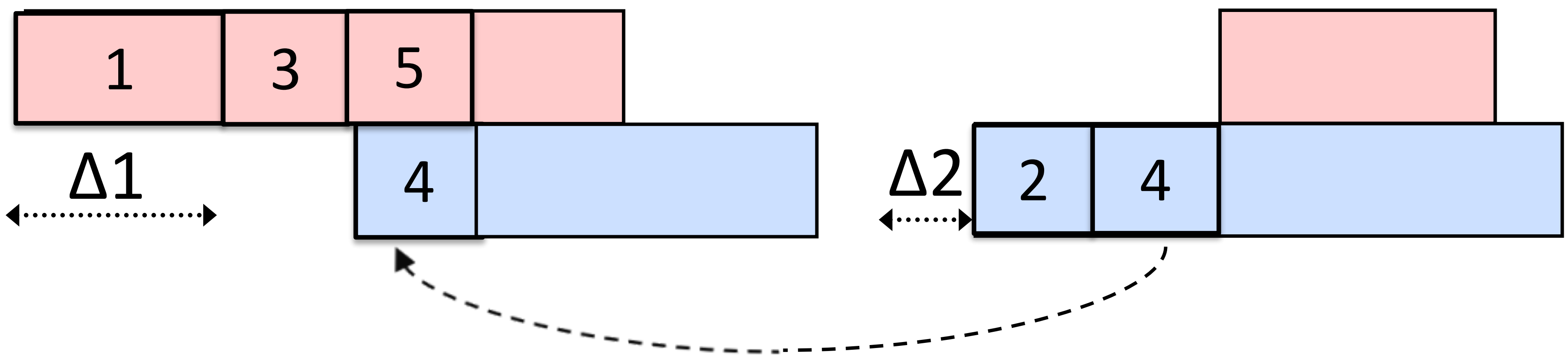
ZigZag Decoding



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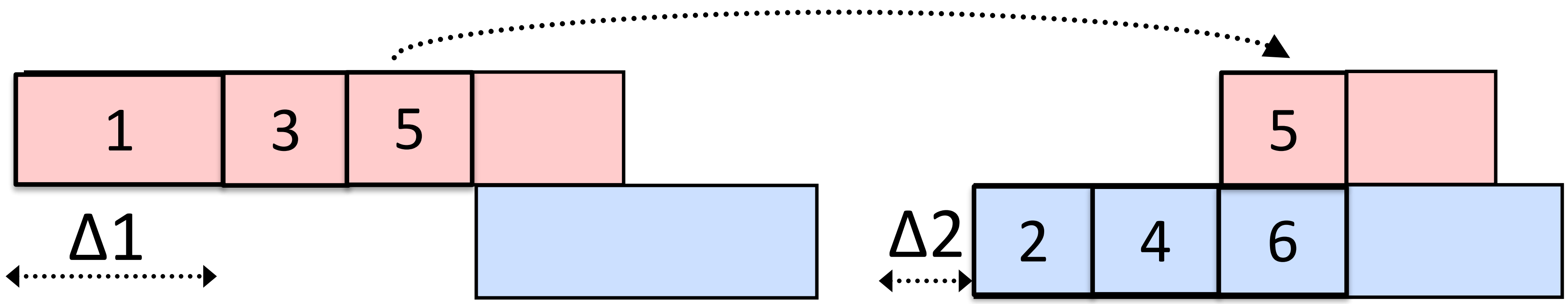
ZigZag Decoding



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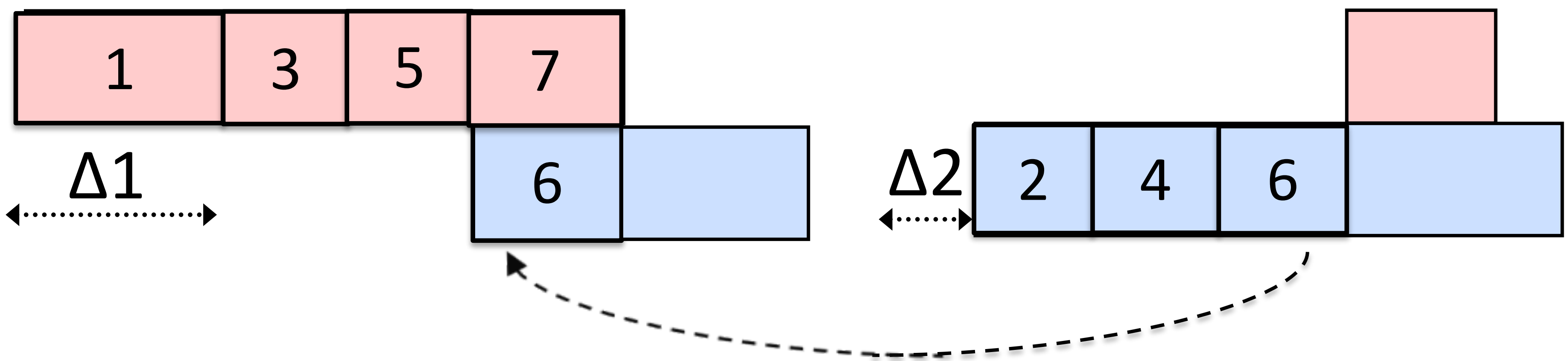
ZigZag Decoding



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Find a chunk that is interference-free in one collisions and has interference in the other

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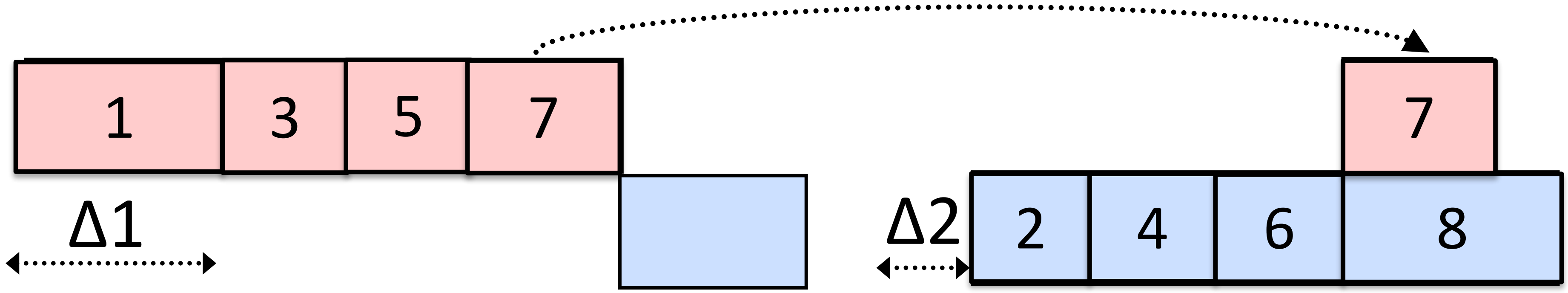
ZigZag Decoding



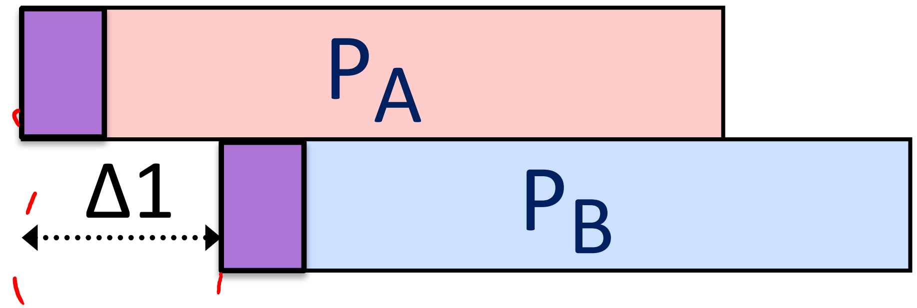
$\Delta 1 \neq \Delta 2$

Find a chunk that is interference-free in one collisions and has interference in the other

Subtract from the other collision

ZigZag Decoding

How do you compute Δ1?

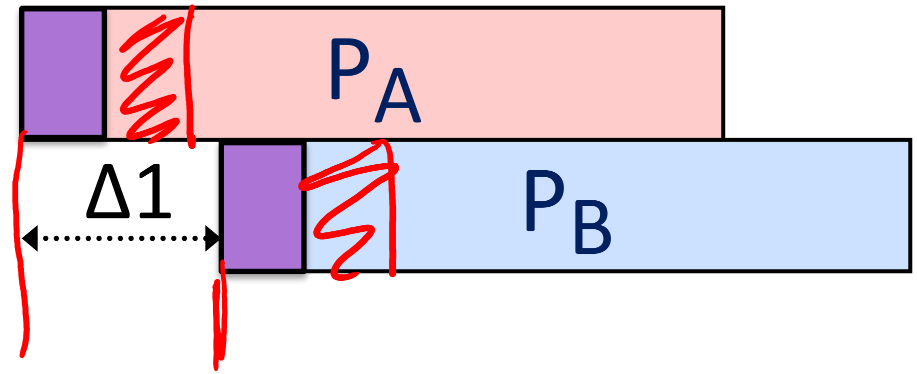


Correlate with Preamble

Correlation:

ZigZag Decoding

How do you compute Δ1?



Correlate with Preamble

Preamble: $x(t)$

Received signal: $y(t) = h_A x(t) + h_B x(t - \Delta 1) + n(t)$

Correlation: $\Gamma(\Delta) = \sum_{t=1}^{N} y(t) x^*(t - \Delta)$

$$= h_A \sum_{t=1}^{N} x(t) x^*(t - \Delta) + h_B \sum_{t=1}^{N} x(t - \Delta 1) x^*(t - \Delta) + 0$$

$$\Gamma(0) = h_A \sum_{t=1}^{N} |x(t)|^2 \quad e^{-j2\pi \Delta f_{c_A} t}$$

$$\Gamma(\Delta 1) = h_B \sum_{t=1}^{N} |x(t - \Delta 1)|^2 \quad e^{-j2\pi \Delta f_{c_B} t}$$

How to subtract chunks

Subtract interference free region in first collision from second collision!

- Channel changes between the two collisions
- CFO accumulates Phase
- Increase noise!

$$y_1(t) = y_A(t) + y_B(t - \Delta 1) + n_1(t) \rightarrow y_1(t) = y_A(t) + n_1(t)$$

$$y_2(t) = y_A(t) + y_B(t - \Delta 2) + n_2(t) - y_1(t)$$

$$= y_B(t - \Delta 2) + \underbrace{n_2(t) - n_1(t)}_{\text{Double noise}}$$

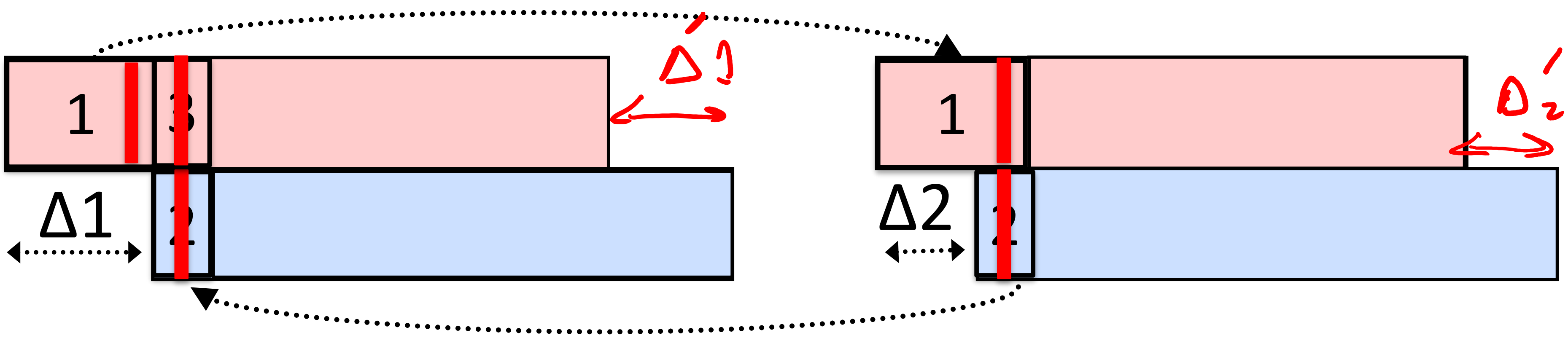
How to subtract chunks

1. Decode Interference free chunk
2. Re-encode the bits→ noise free signal
3. Apply channel h and CFO of 2^{nd} collision to it
4. Subtract it from 2^{nd} collision

Caveat: need Δ2 to be large to estimate h and CFO.

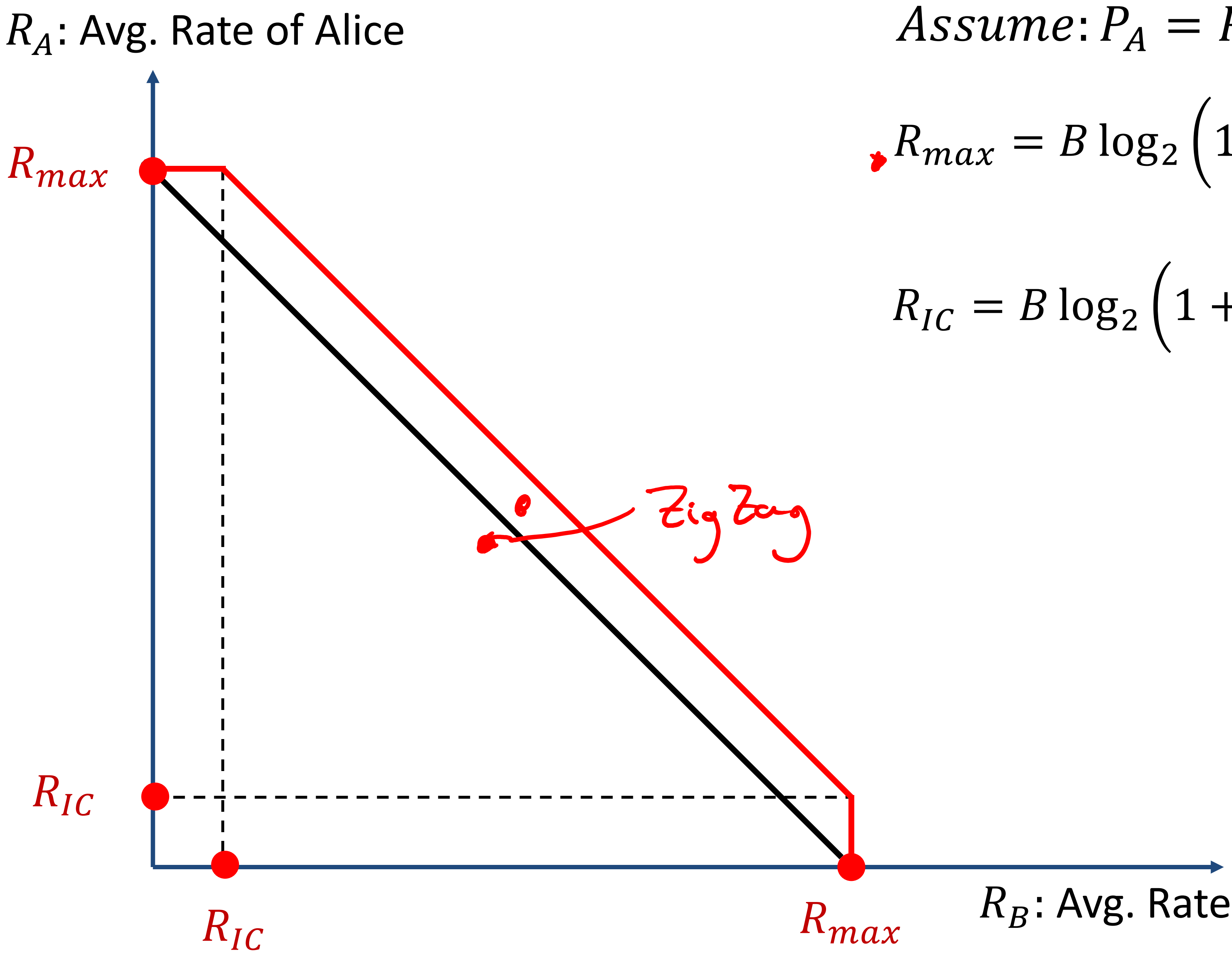
Error Propagates!

- If AP mistakenly decodes (1->0, 0->1), an error is propagated during ZigZag decoding



- AP decodes Backwards as well as Forwards
- AP picks the decoding that has a higher PHY confidence: SoftPHY!

Rate Region: ZigZag



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