Multimedia Communications
@CS.NCTU

Lecture 14: Wireless Basics

Instructor: Kate Ching-Ju Lin (林靖茹)

Outline

- **SNR and capacity**
- Channel fading and path loss
- Modulation and coding scheme
- Rate adaptation
- Wireless multicasting

SNR

- Wireless channel

$$y = x + n$$

received signal (y), transmitted signal (x), noise (n)

- Signal-to-noise ratio (SNR)

$$\frac{\text{Power of the signal}}{\text{Power of the noise}} = \frac{\mathbb{E}[x^2]}{\mathbb{E}[n^2]} = \frac{P}{N_0}$$

  - Unit of the power: watt

SNR in decibels

$$
\begin{aligned}
P_{\text{dBm}} &= 10\log_{10} P \\
N_{\text{dBm}} &= 10\log_{10} N_0 \\
\Rightarrow \qquad SNR_{\text{dB}} &= 10\log_{10} \frac{P}{N_0} \\
&= 10log_{10}P - 10\log_{10} N_0 \\
&= P_{\text{dBm}} - N_{\text{dBm}}
\end{aligned}
$$

- dBm: unit of power
- dB: unit of power difference
- Example: noise = -90dBm, signal = -70 dBm
  - SNR_{dB} = -70dBm – (-90dBm) = 20dB
- Why using decibel?
  - Many signals have a wide dynamic ranges

SINR

- Signal-to-noise-plus-interference ratio

$$\text{SINR} = \frac{P}{I + N_0}$$

$$\text{SINR}_{\text{dB}} = 10 \log_{10} \frac{P}{I + N_0}$$

- Example: if there exist two interferers

$$y = x + i_1 + i_2 + n$$

$$\Rightarrow \text{SINR} = \frac{\mathbb{E}[x^2]}{\mathbb{E}[(i_1 + i_2 + n)^2]}$$

$$= \frac{\mathbb{E}[x^2]}{\mathbb{E}[i_1^2] + \mathbb{E}[i_2^2] + \mathbb{E}[n^2]}$$

If i_1, i_2, n are i.i.d

Channel Capacity

- Derived by Claude E. Shannon during World War II
- Assume that we have an additive white Gaussian noise (AWGN) channel with bandwidth B Hz

$$\text{Capacity (bit/s)} = B\log_2(1 + SNR)$$

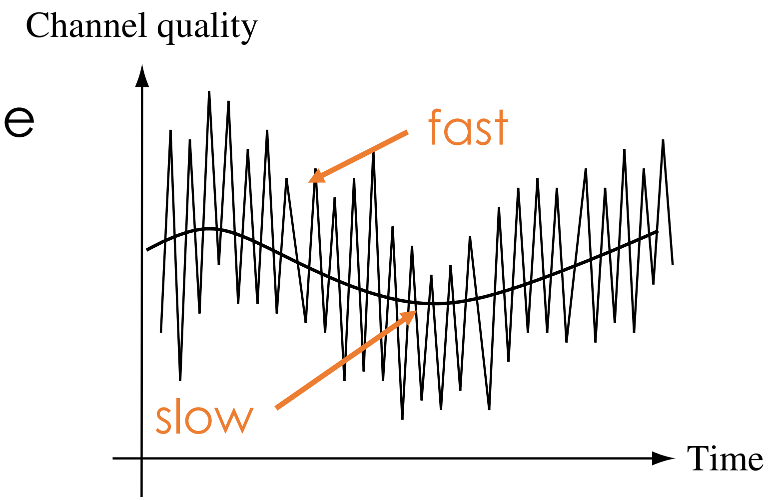
- Also known as Shannon capacity
- SNR is expressed as a power ratio, not in decibel (dB)

Outline

- SNR and capacity
- **Channel fading and path loss**
- Modulation and coding scheme
- Rate adaptation
- Wireless multicasting

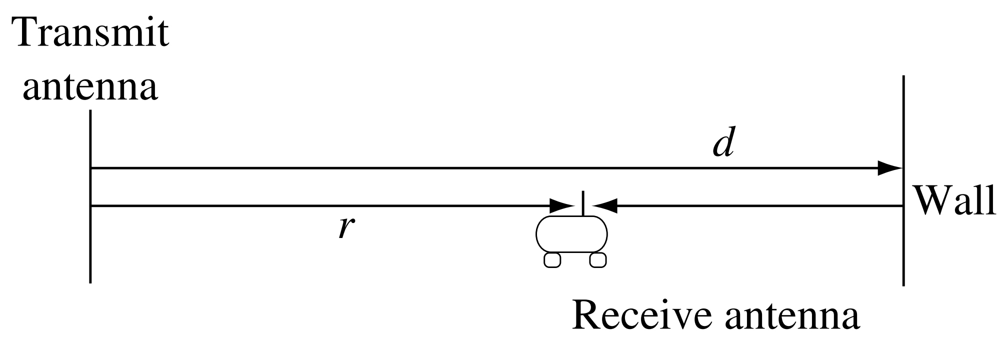
Channel fading

- Coherence time
  - The time over which a propagating wave may be considered coherent
- Fading
  - Variation of attenuation of a signal due to environmental dynamics, such as time, location, radio frequency and/or multi-path propagation
- Slow and fast fading
  - <u>fast fading</u>: if the coherence time is much shorter than the delay requirement of the application
  - <u>slow fading</u>: if the coherence time is longer.



Channel Fading

- Fast fading usually caused by
  - High mobility (Doppler spread)
  - Multipath effects



- Slow fading usually caused by
  - Small/slow mobility
  - Shadowing (signal power fluctuates due to obstacles)

Path Loss

- Signal attenuation as the wave propagates over the air

$$\text{PL} = \frac{P_{\text{rx}}}{P_{\text{tx}}}$$

$$\Rightarrow P_{\text{rx, dBm}} = P_{\text{tx, dBm}} + \text{PL}_{\text{dB}}$$

- Example: assume the transmit power is 15dBm and the path loss is -90 dB
  - What is the receive power?
    → 15dBm + (-90dB) = -75dBm
  - What is the SNR if noise level is -90dBm?
    → -75dBm – (-90dBm) = 15dB

Simple Path Loss Model

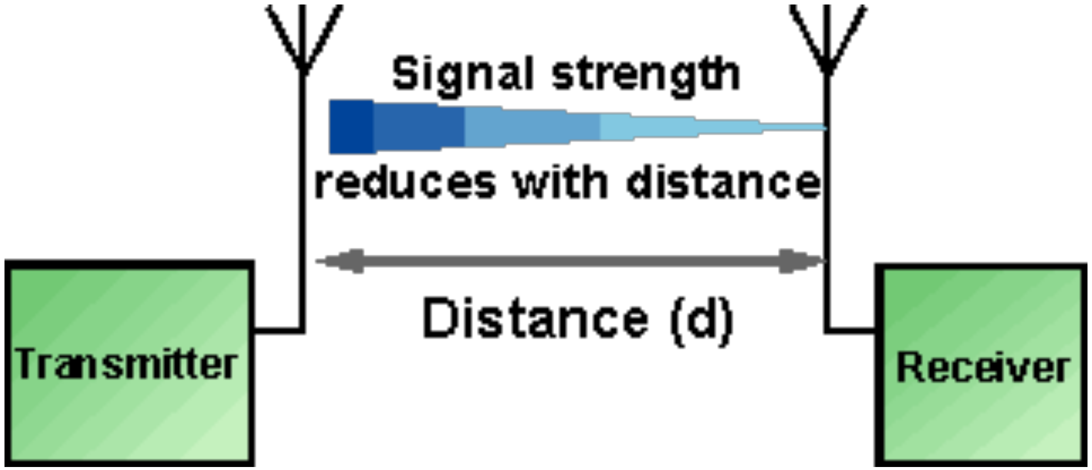
- Friis transmission equation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

  - Gt: gain of the transmit antenna
  - Gr: gain of the receive antenna
  - d: distance between the transmitter and receiver
  - λ: wavelength (= light speed/frequency)

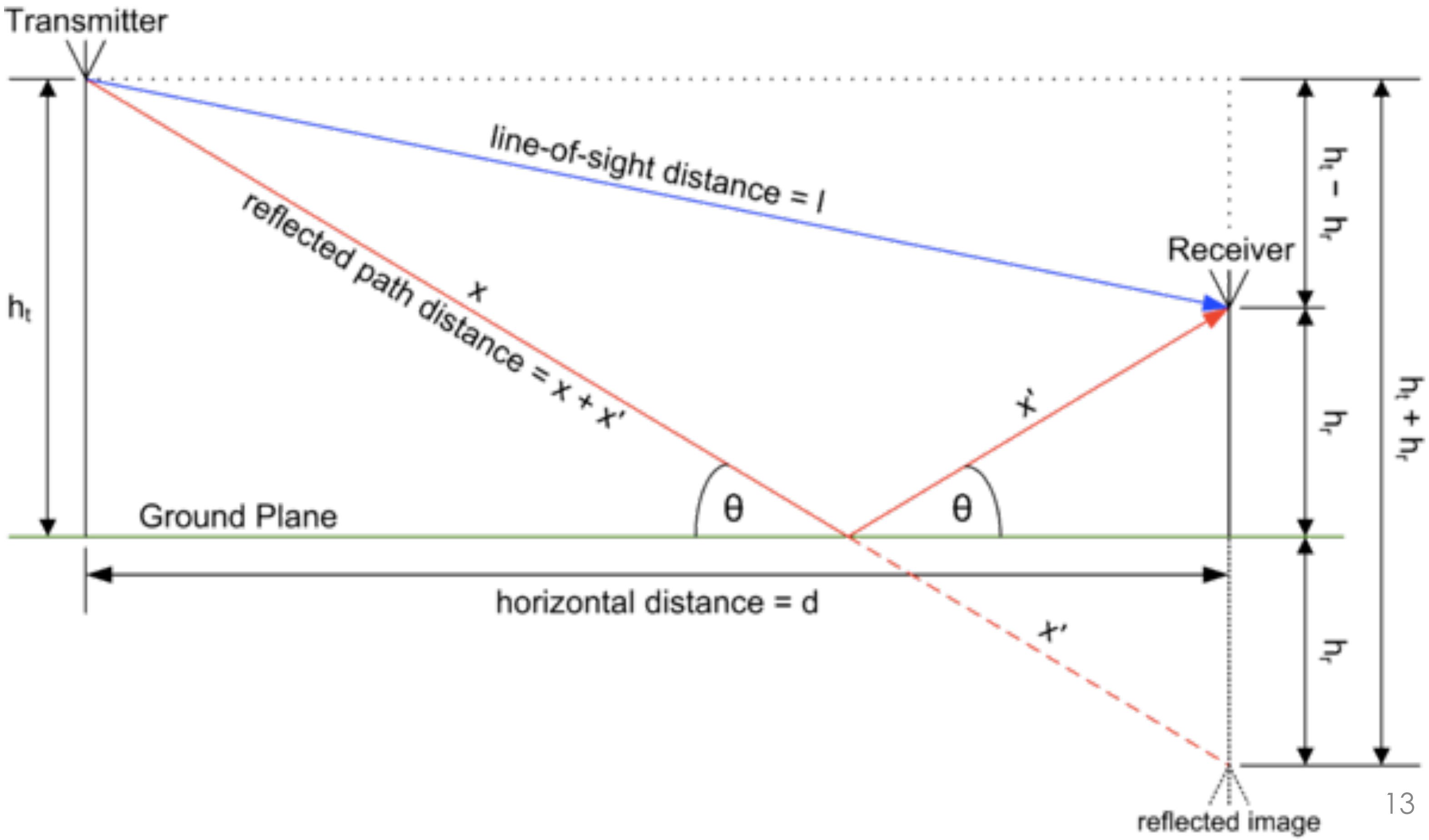
Free-Space Path Loss model

- Only consider the loss resulting from the line-of-sight (LOS) path



Two-ray Ground-Reflection Model

- Only consider the losses from the LOS path and the path reflected by the ground



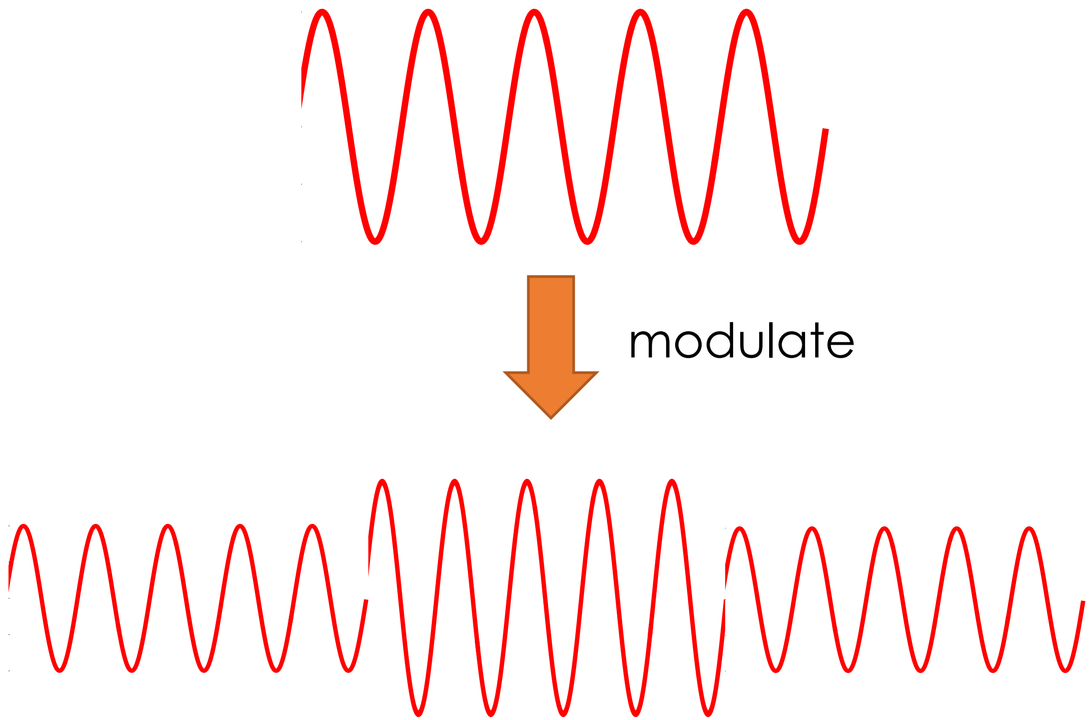
Outline

- SNR and capacity
- Channel fading and path loss
- **Modulation and coding scheme**
- Rate adaptation
- Wireless multicasting

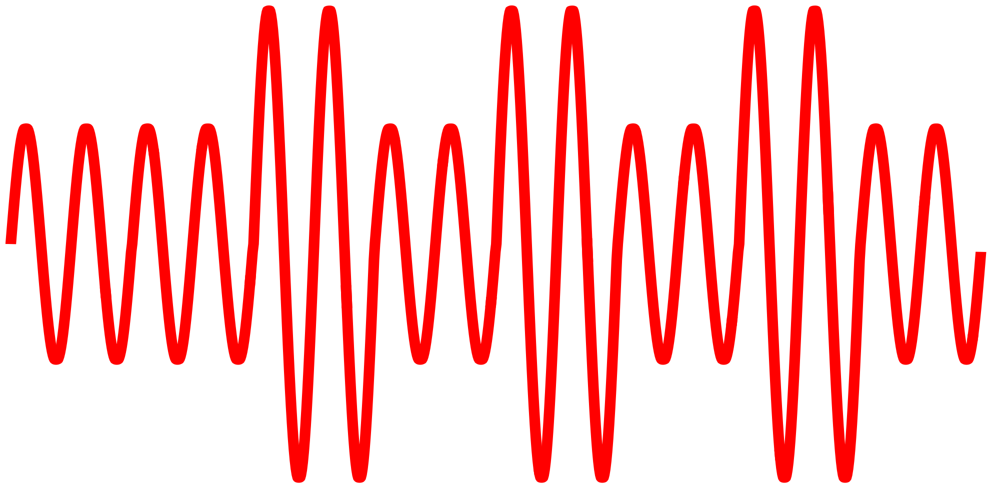
Modulation

From Wikipedia:

The process of varying one or more properties of a periodic waveform with a modulating signal that typically contains information to be transmitted.



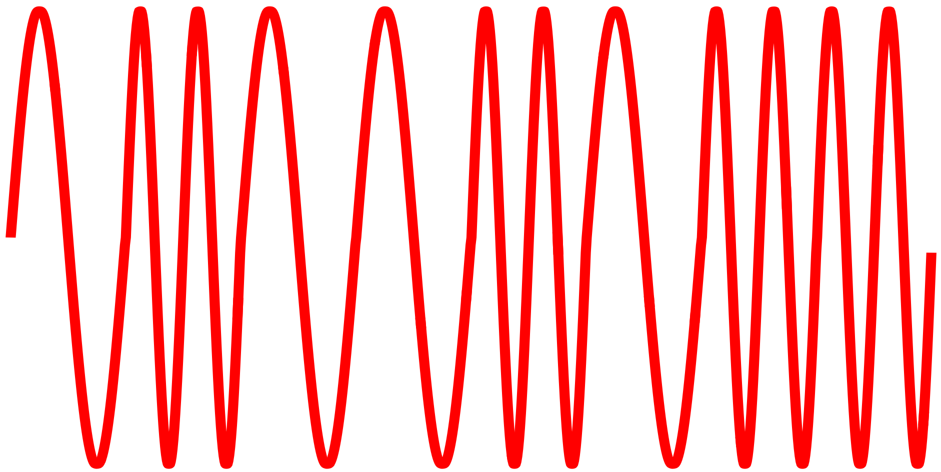
Example 1



= bit-stream?

(a) 10110011 (b) 00101010 (c) 10010101

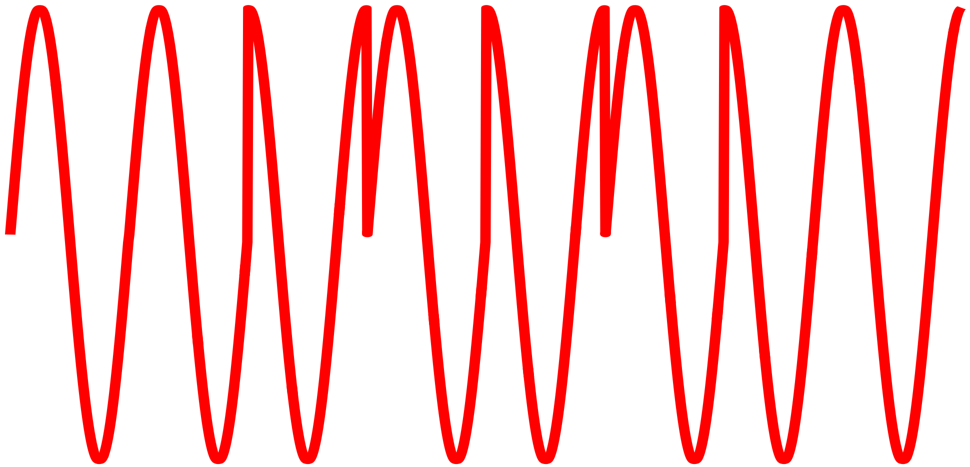
Example 2



= bit-stream?

(a) 01001011 (b) 00101011 (c) 11110100

Example 3



= bit-stream?

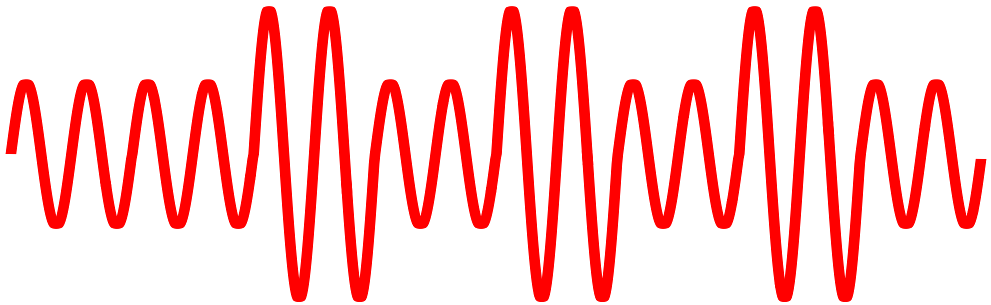
(a) 11010100

(b) 00101011

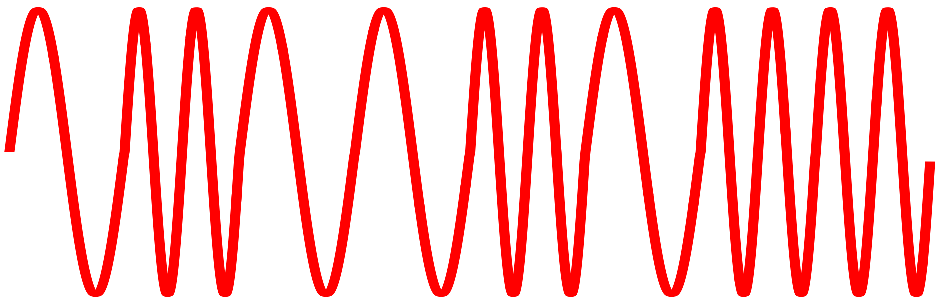
(c) 01010011

(d) 11010100 or 00101011

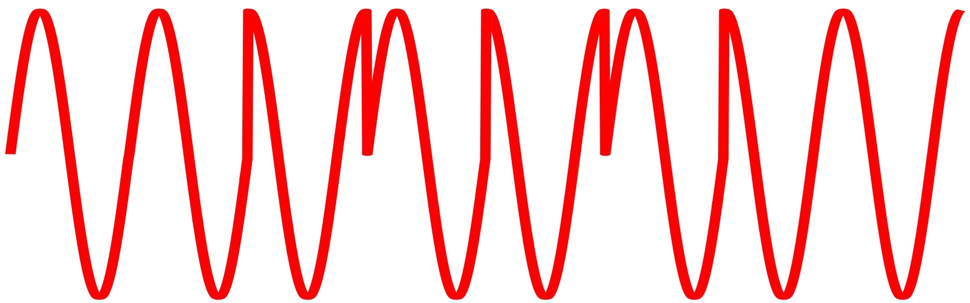
Types of Modulation



Amplitude
ASK



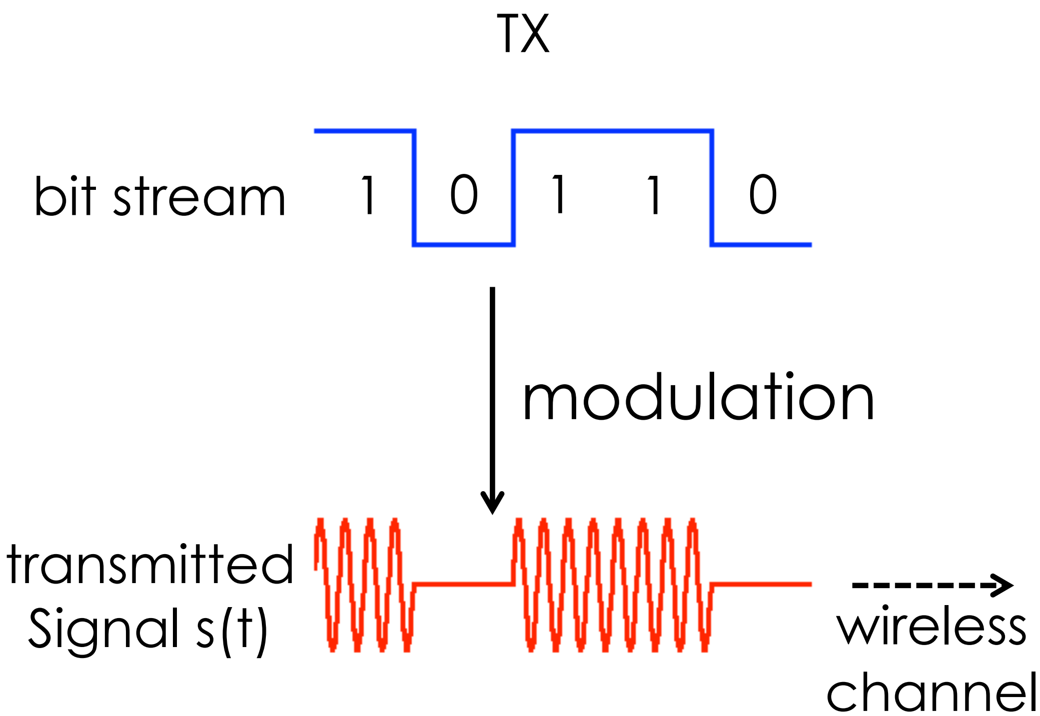
Frequency
FSK



Phase
PSK

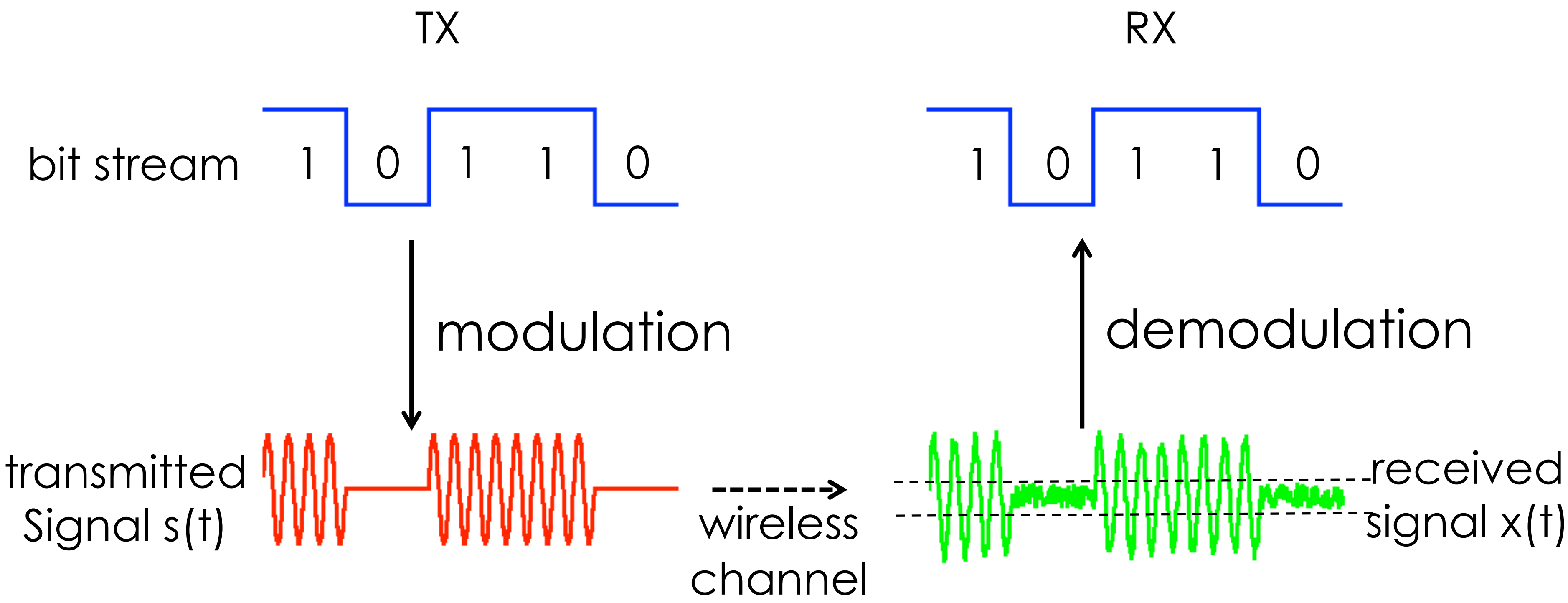
Modulation

- Map bits to signals



Demodulation

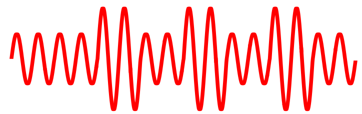
- Map signals to bits



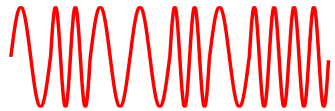
Types of Modulation

$$s(t) = A\cos(2\pi f_c t + \phi)$$

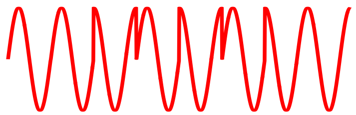
- Amplitude
  - M-ASK: Amplitude Shift Keying



- Frequency
  - M-FSK: Frequency Shift Keying



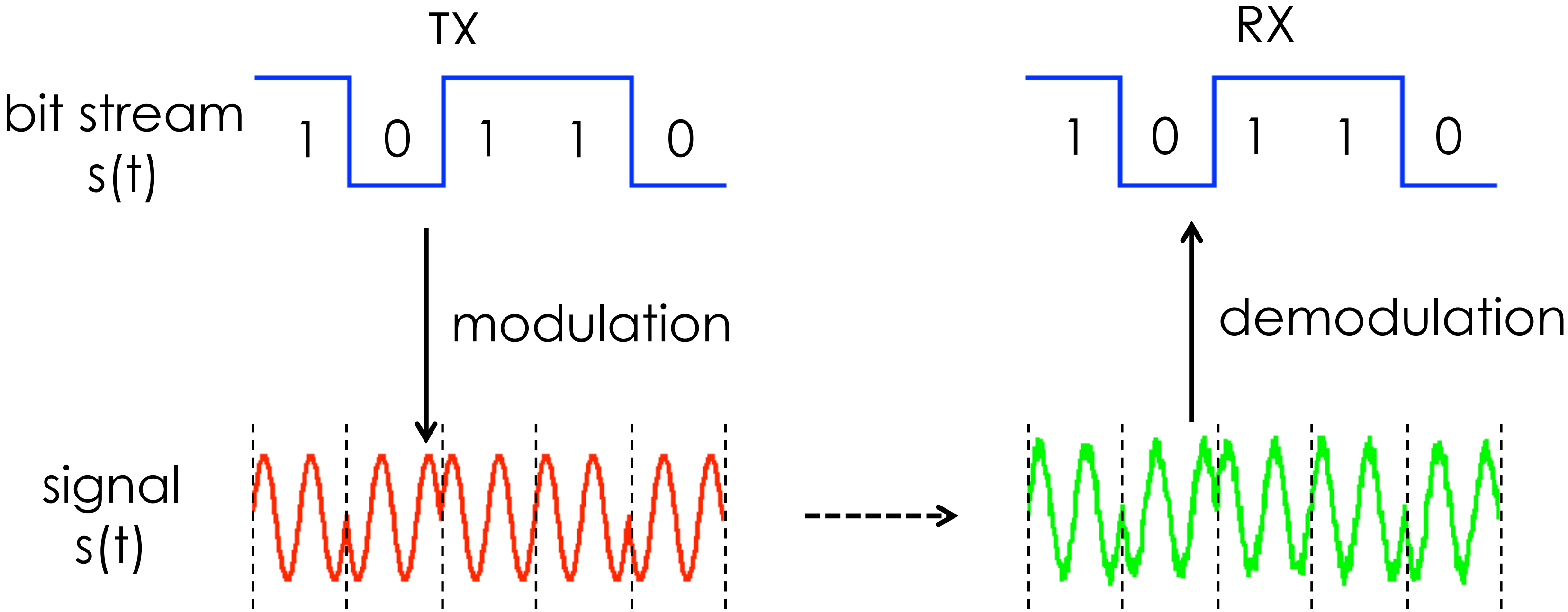
- Phase
  - M-PSK: Phase Shift Keying



- Amplitude + Phase
  - M-QAM: Quadrature Amplitude Modulation

Phase Shift Keying (PSK)

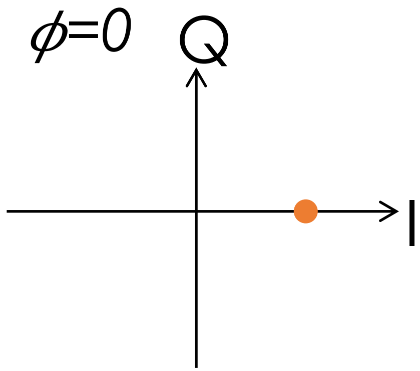
- A bit stream is encoded in the phase of the transmitted signal
- Simplest form: Binary PSK (BPSK)
  - ‘1’→ϕ=0, ‘0’→ϕ=π



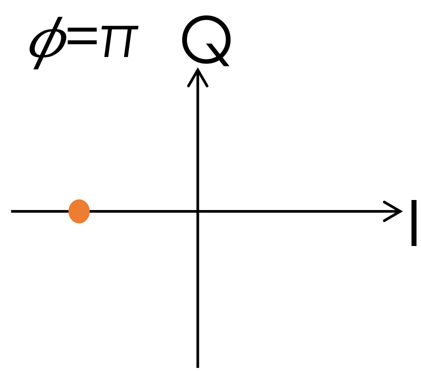
Constellation Points for BPSK

- '1' → $\phi=0$
- $\cos(2\pi f_c t+0)$
  $= \cos(0)\cos(2\pi f_c t) - \sin(0)\sin(2\pi f_c t)$
  $= s_I \cos(2\pi f_c t) - s_Q \sin(2\pi f_c t)$

- '0' → $\phi=\pi$
- $\cos(2\pi f_c t+\pi)$
  $= \cos(\pi)\cos(2\pi f_c t) - \sin(\pi)\sin(2\pi f_c t)$
  $= s_I \cos(2\pi f_c t) - s_Q \sin(2\pi f_c t)$



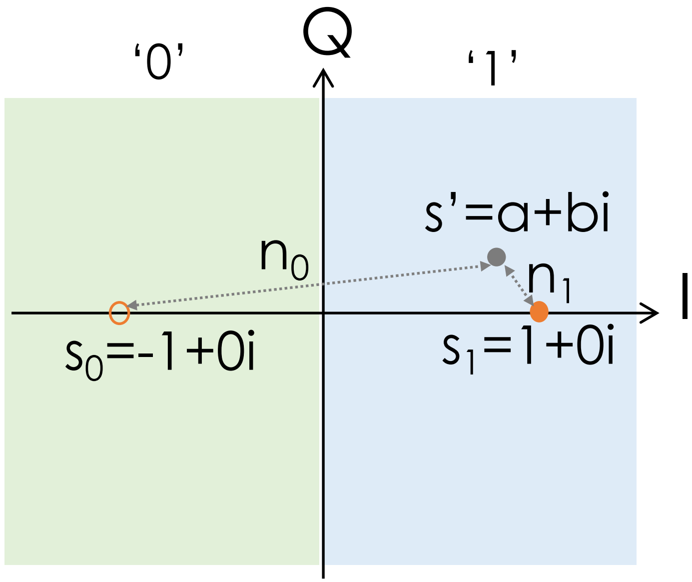
$(s_I, s_Q) = (1, 0)$
'1' → $1+0i$



$(s_I, s_Q) = (-1, 0)$
'0' → $-1+0i$

Demodulate BPSK

- Map to the closest constellation point
- Quantitative measure of the distance between the received signal *s'* and any possible signal *s*
  - Find |s'-s| in the I-Q plane



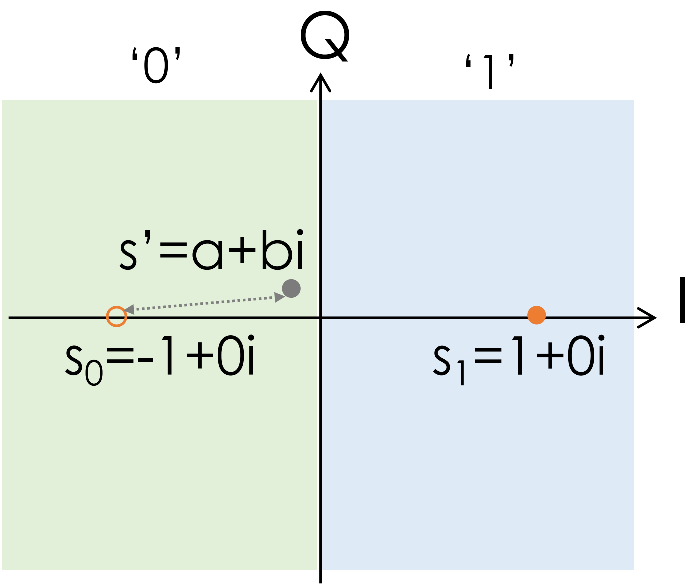
$n_1 = |s' - s_1| = |s' - (1+0i)|$

$n_0 = |s' - s_0| = | \ |s' - (-1+0i)|$

since $n_1 < n_0$, map *s'* to (1+0i)→'1'

Demodulate BPSK

- Decoding error
  - When the received signal is mapped to an incorrect symbol (constellation point) due to a large error
- Symbol error rate
  - P(mapping to a symbol s_j, $j \neq i$ | s_i is sent)



Given the transmitted symbol s_1
→ incorrectly map s' to s_0=(-1+0)→'0', when the error is too large

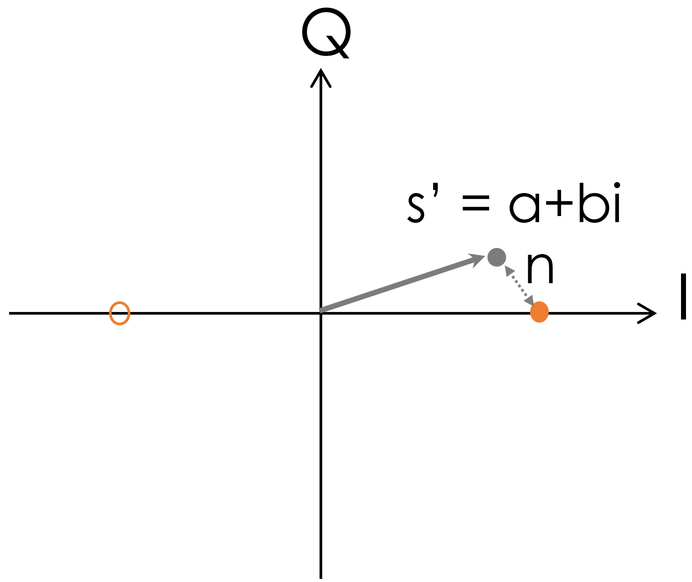
SNR of BPSK

- SNR: Signal-to-Noise Ratio

$$SNR = \frac{|s|^2}{n^2} = \frac{|s|^2}{|s' - s|^2}$$

$$= \frac{|1 + 0i|^2}{|(a + bi) - (1 + 0i)|^2}$$

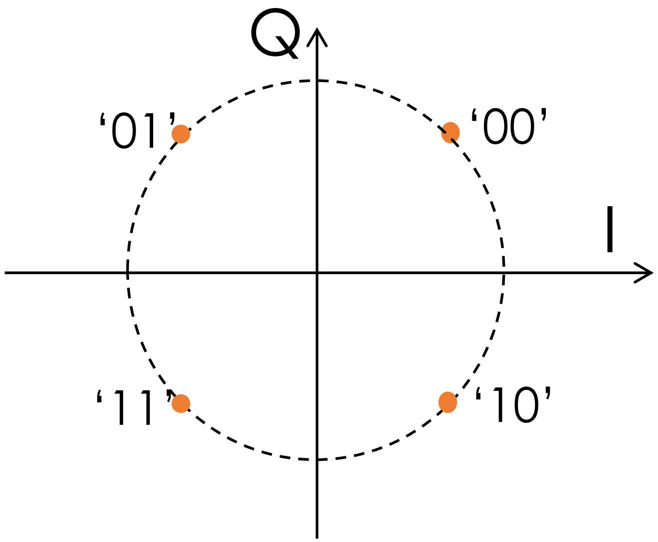
$$SNR_{dB} = 10 \log_{10}(SNR)$$



- Example:
  - Say Tx sends (1+0i) and Rx receives (1.1 – 0.01i)
  - SNR?
- Bit error rate: $P_b = Q(\sqrt{\frac{E_b}{N_0}})$

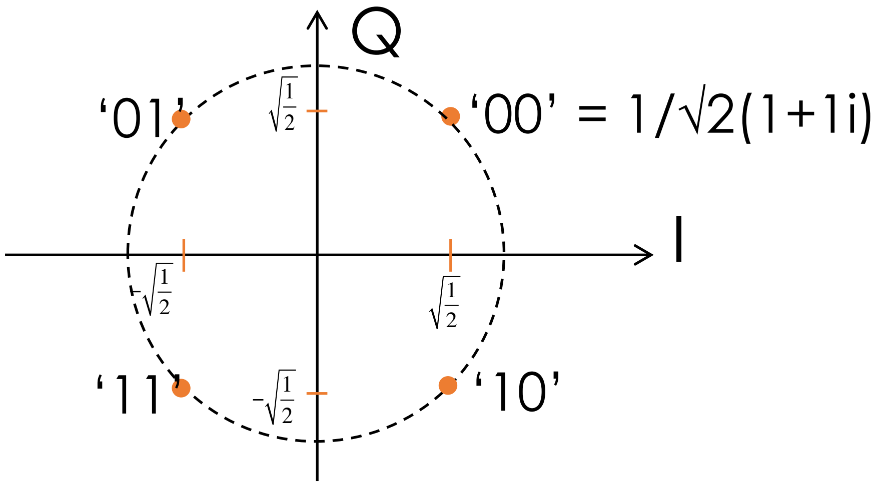
Quadrature PSK (QPSK)

- Use 2 degrees of freedom in I-Q plane
- Represent two bits as a constellation point
  - Rotate the constellations by π/2
  - Demodulation by mapping the received signal to the closest constellation point
  - Double the bit-rate
- No free lunch:
  - Higher error probability (Why?)



Quadrature PSK (QPSK)

- Maximum power is bounded
  - Amplitude of each constellation point should still be 1



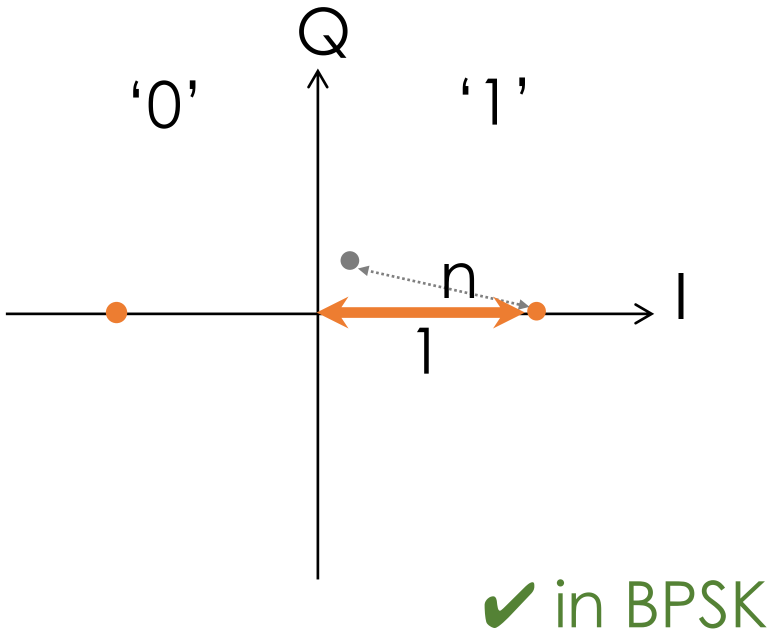
Bits	Symbols
'00'	1/√2+1/√2i
'01'	-1/√2+1/√2i
'10'	1/√2-1/√2i
'11'	-1/√2-1/√2i

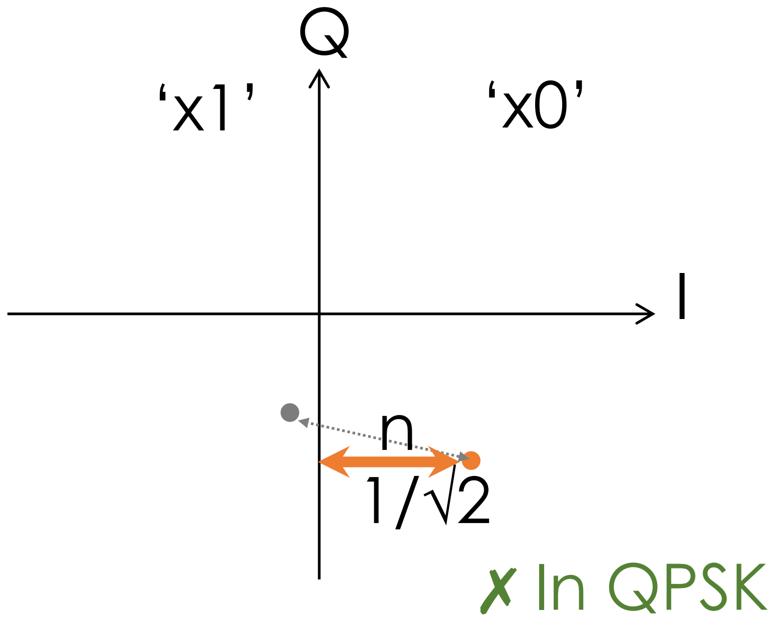
- Bit error rate:

$$P_b = 2Q\left(\sqrt{\frac{2E_b}{N_0}}\right)\left[1 - \frac{1}{2}Q\sqrt{\frac{2E_b}{N_0}}\right]$$

Higher Error Probability in QPSK

- For a particular error *n*, the symbol could be decoded correctly in BPSK, but not in QPSK
  - Why? Each sample only gets half power



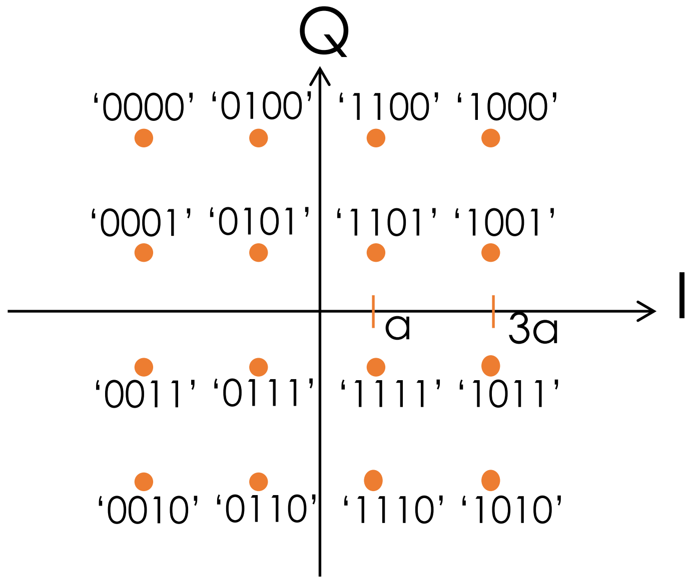


Trade-off between Rate and SER

- Trade-off between the data rate and the symbol error rate
- Denser constellation points
  - More bits encoded in each symbol
  - Higher data rate
- Denser constellation points
  - Smaller distance between any two points
  - Higher decoding error probability

Quadrature Amplitude Modulation

- Change both amplitude and phase
- $s(t)=A\cos(2\pi f_c t+\phi)$



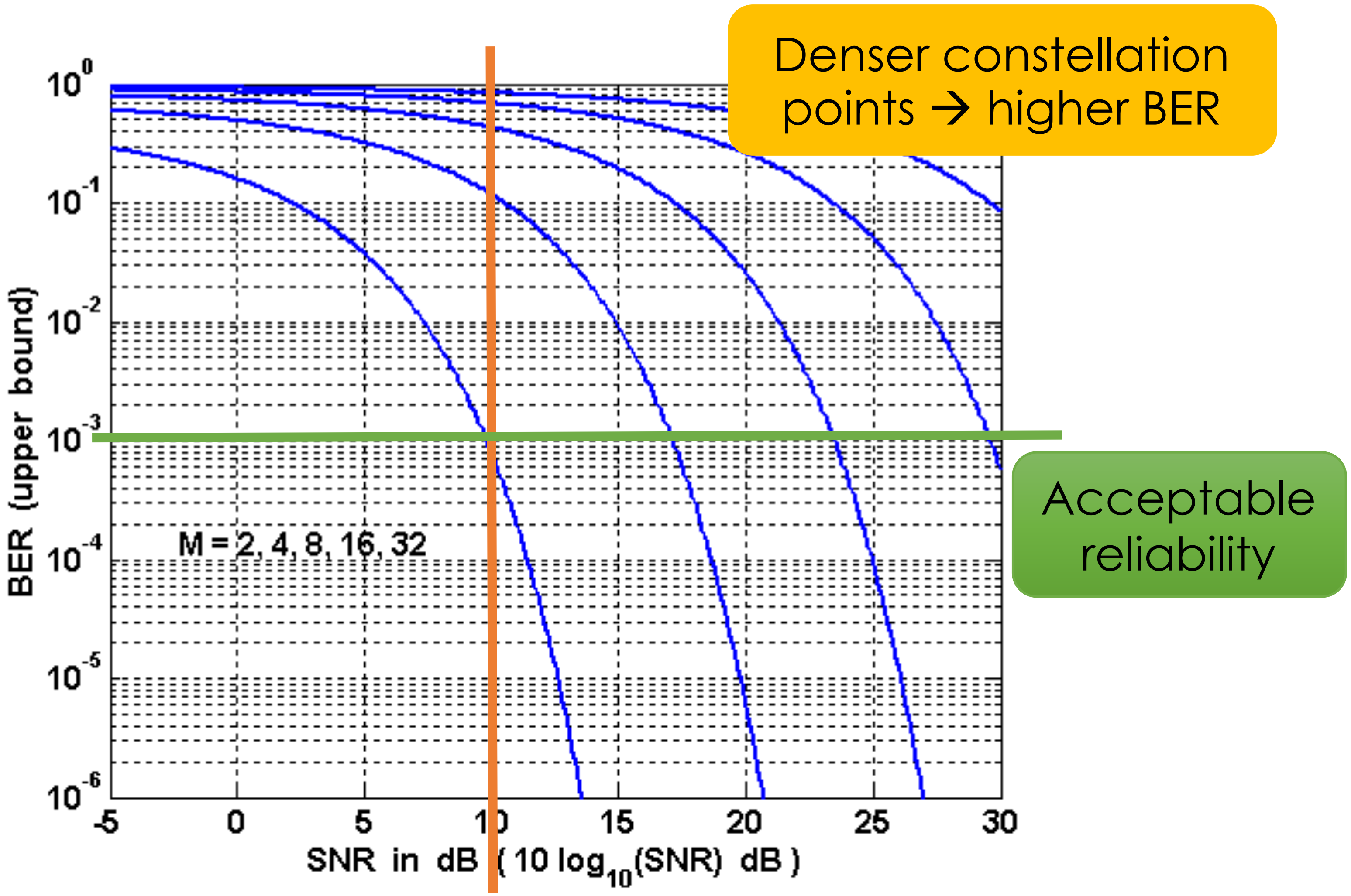
16-QAM

Bits	Symbols
'1000'	$s_1=3a+3ai$
'1001'	$s_2=3a+ai$
'1100'	$s_3=a+3ai$
'1101'	$s_4=a+ai$

expected power: $E\left[\left|s_i\right|^2\right]=1$

- 64-QAM: 64 constellation points, each with 8 bits

M-QAM BER versus SNR



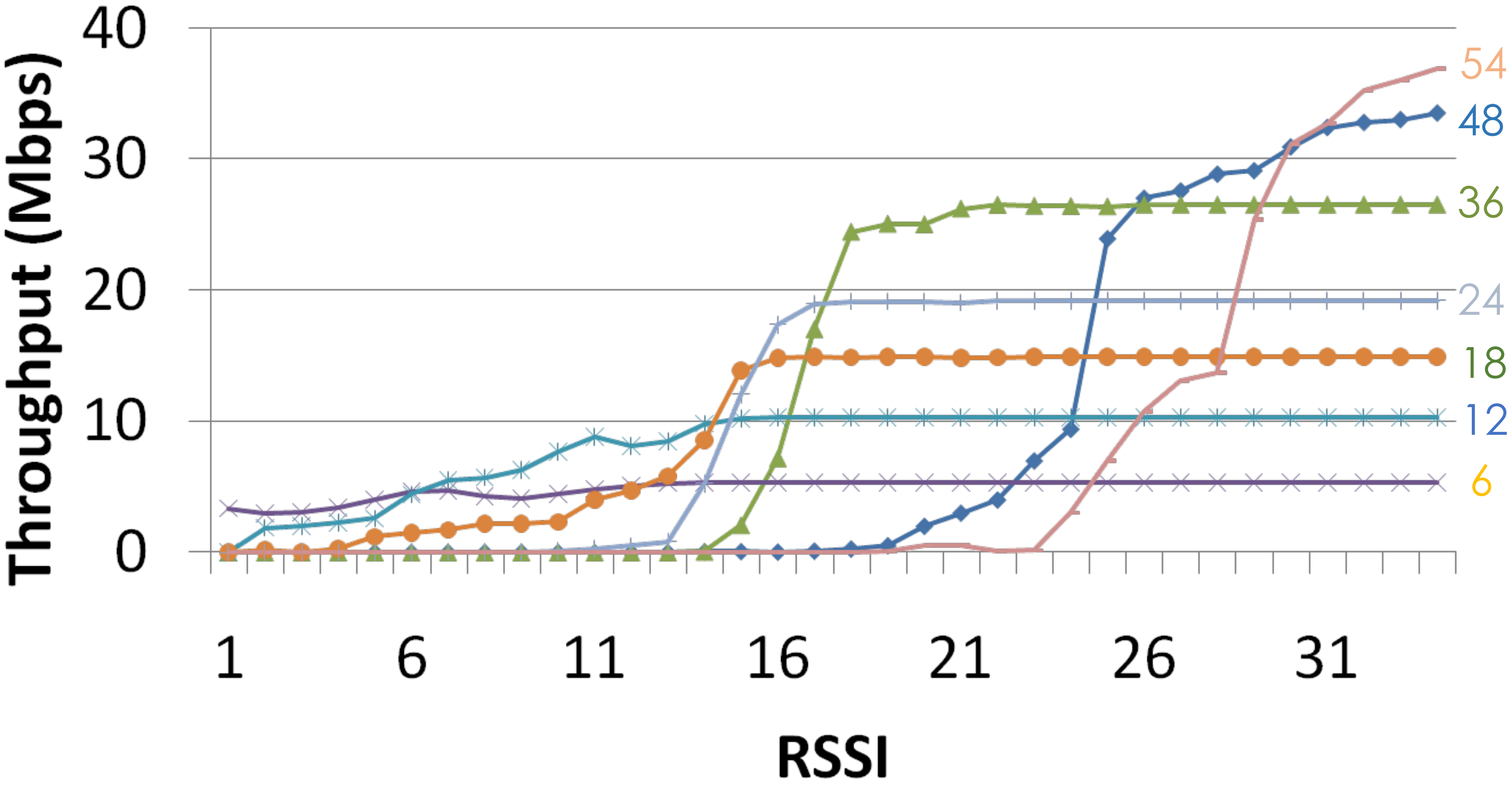
Modulation in 802.11

- 802.11a
  - 6 mb/s: BPSK + ½ code rate
  - 9 mb/s: BPSK + ¾ code rate
  - 12 mb/s: QPSK + ½ code rate
  - 18 mb/s: QPSK + ¾ code rate
  - 24 mb/s: 16-QAM + ½ code rate
  - 36 mb/s: 16-QAM + ¾ code rate
  - 48 mb/s: 64-QAM + ⅔ code rate
  - 54 mb/s: 64-QAM + ¾ code rate
- FEC (forward error correction)
  - k/n: k-bits useful information among n-bits of data
  - Decodable if any k bits among n transmitted bits are correct

Outline

- SNR and capacity
- Channel fading and path loss
- Modulation and coding scheme
- **Rate adaptation**
- Wireless multicasting

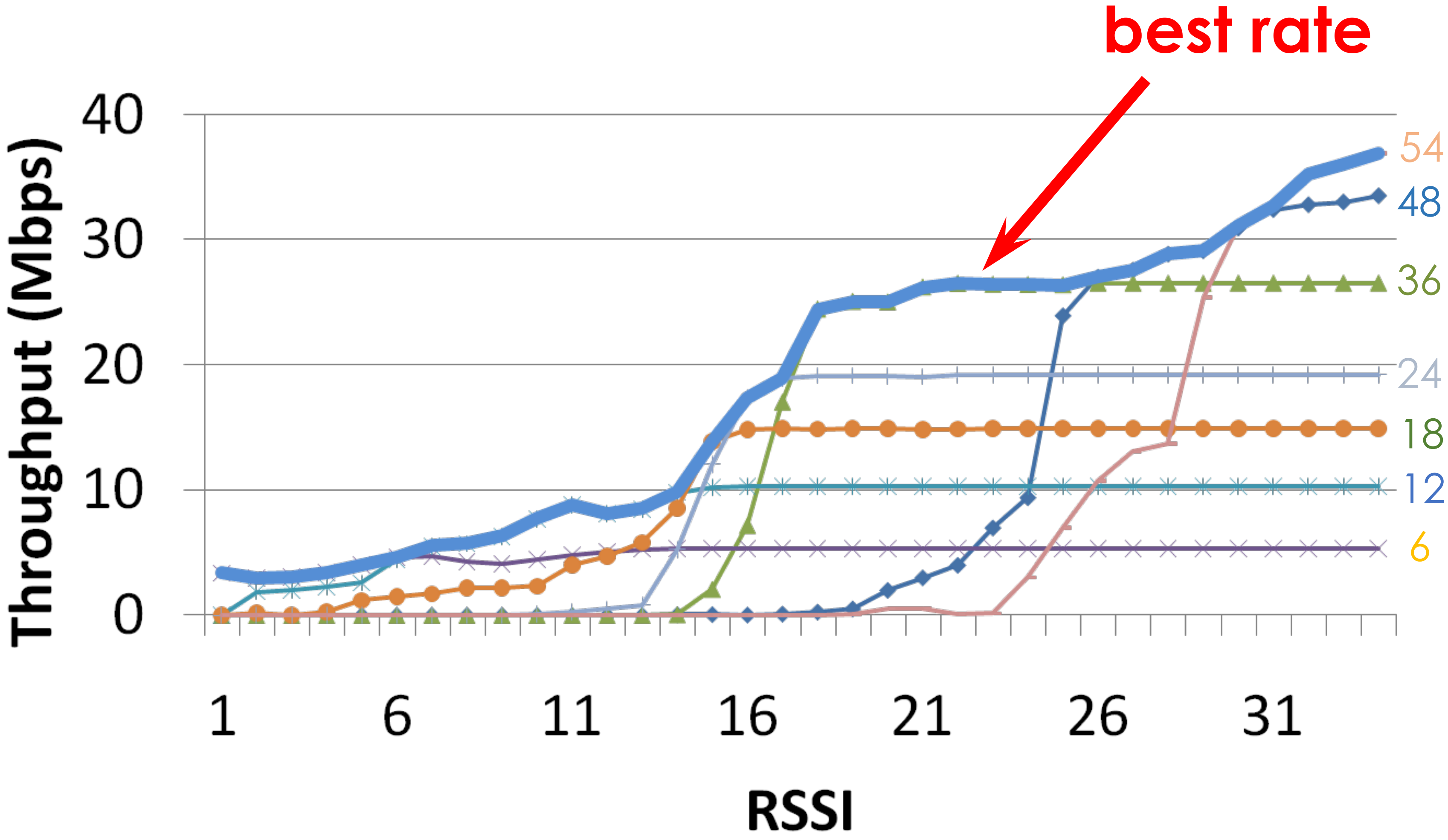
Bit-Rate Selection



$$\text{throughput} = (1\text{-}PER_{r,SNR}) * r = (1\text{-}BER_{r,SNR})^N * r$$

$$r^* = \arg\max \text{throughput}_r$$

Bit-Rate Selection



Adapt bit-rate to dynamic RSSI

Difficulties with Rate Adaptation

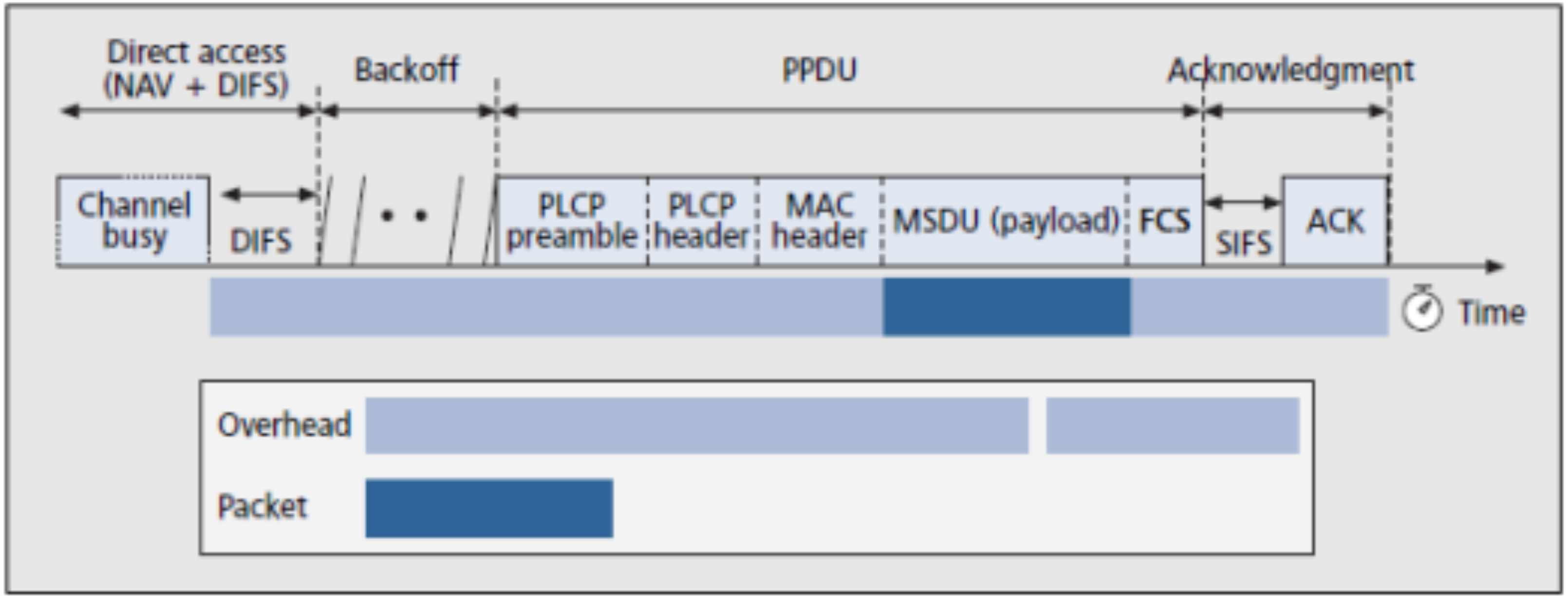
- Channel quality changes very quickly
  - Especially when the device is moving
- Can't tell the difference between
  - poor channel quality due to noise/interference/collision (high |noise|)
  - poor channel quality due to long distance (low |signal|)

Ideally, we want to decrease the rate due to low signal strength, but not interference/collisions

Types of Auto-Rate Adaptation

	Transmitter-based	**Receiver-Based**
SNR-based		RBAR, OAR, ESNR
ACK-based	ARF, AARF, ONOE	
Throughput-based	**SampleRate, RRAA**	
Partial packet		ZipTx
Soft information		SoftRate

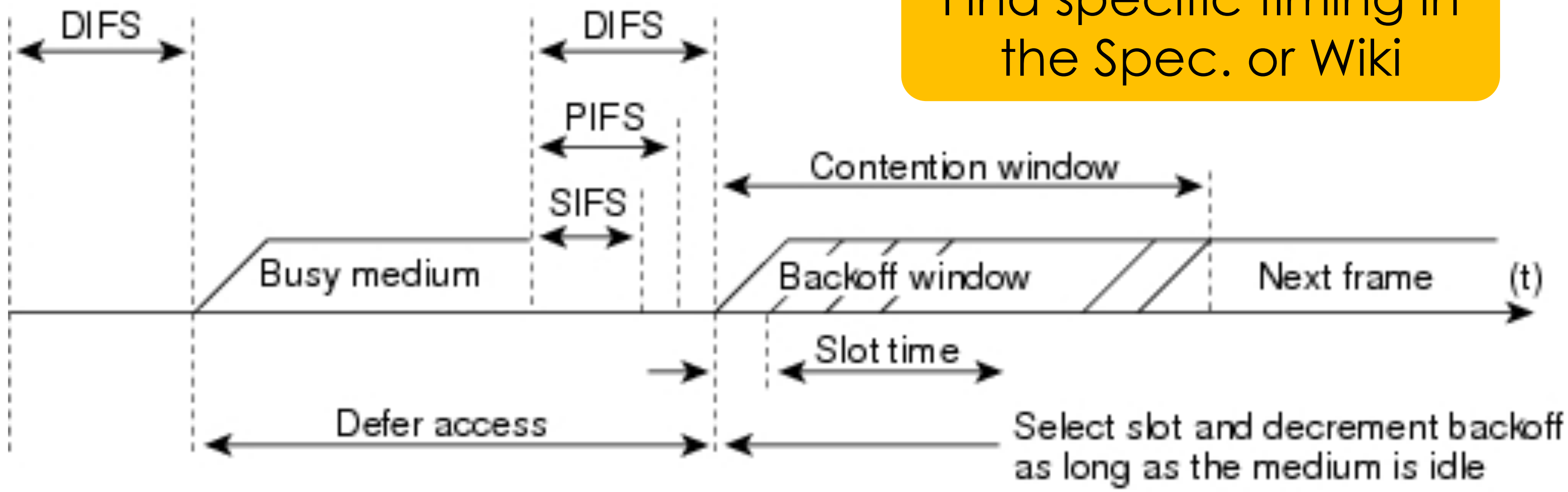
802.11 MAC



- Start contention after the channel keeps idle for DIFS
- Avoid collisions via random backoff
- AP responds ACK if the frame is delivered correctly (i.e., passing the CRC check) → No NACK
- Retransmit the frame until the retry limit is reached

Prioritized Interframe Spacing

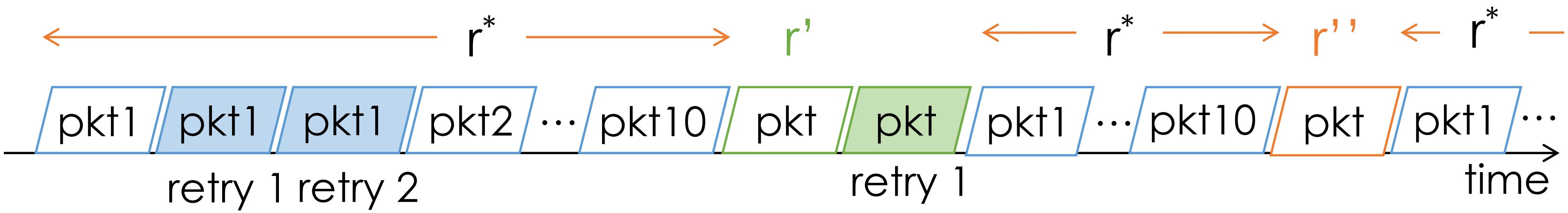
Find specific timing in the Spec. or Wiki



- Latency: SIFS < PIFS < DIFS
  Priority: SIFS > PIFS > DIFS
- SIFS (Short interframe space): control frames, e.g., ACK and CTS
- PIFS (PCF interframe space): CF-Poll
- DIFS (DCF interframe space): data frame

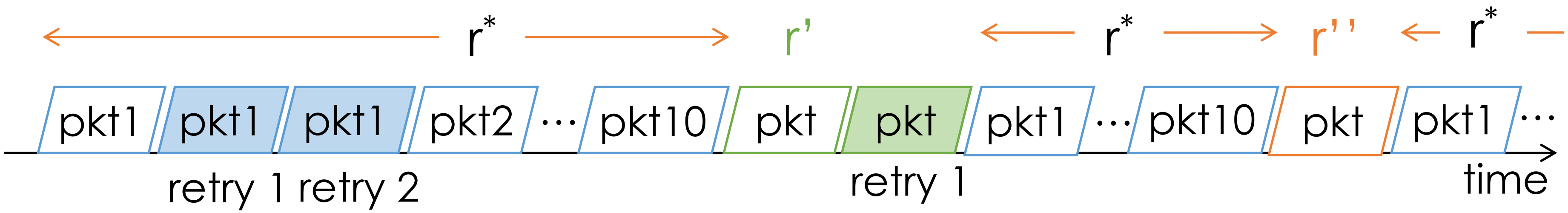
SampleRate – Tx-based Adaptation

- Default in Linux
- Periodically send packets at a randomly-sampled bit-rate other than the current bit-rate
  - Let r^* be the current best rate
  - After sending 10 packets at the best rate, send a packet at a randomly-sampled rate
  - Estimate the achievable throughput of the sampled rates



J. Bicket, "Bit-rate Selection in Wireless Networks," Ph.D Thesis, MIT, 2005

SampleRate – Throughput Estimation



- How to estimate the effective throughput of a rate?
  - Calculate the transmission time of a L-bit packet
  - Consider packet length (*l*), bit-rate (*r*), number of retries (n), backoff time

$$T_{tx}(r,n,l) = T_{\text{DIFS}} + T_{\text{back off}}(n) + (n+1)(T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{header}} + l/r)$$

- Select the rate that has the smallest measured average transmission time to deliver a *L*-bit packet

$$r^* = \min_r T_{tx}(r,n,L)$$

SampleRate

- Do not sample the rates that
  - Have failed four successive times
  - Are unlikely to be better than the current one
- Is thought of the most efficient scheme for static environments
  - SNR, and thereby BER and best rate, do not change rapidly over time
- Waste channel time for sampling if the channel is very stable

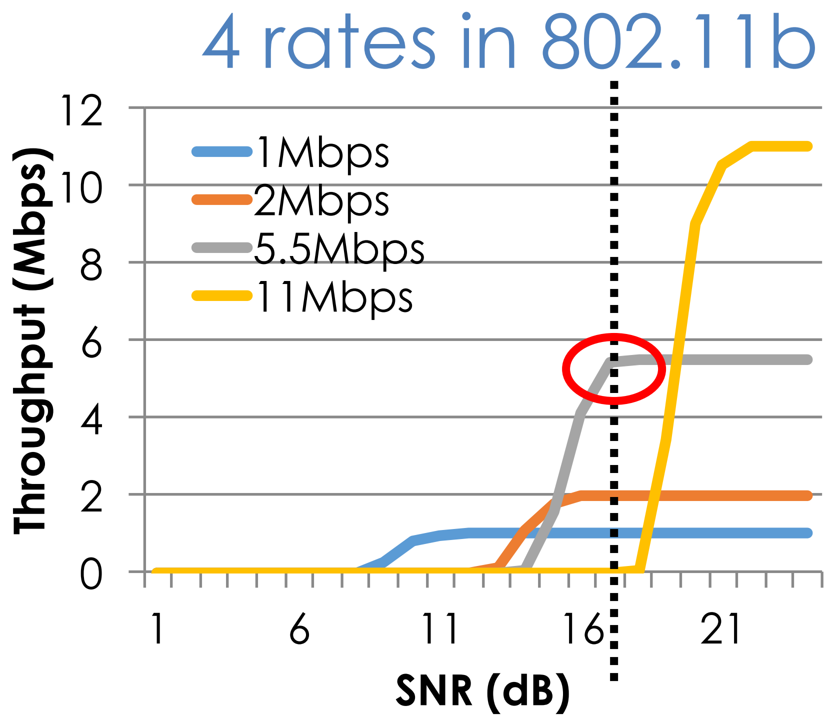
Outline

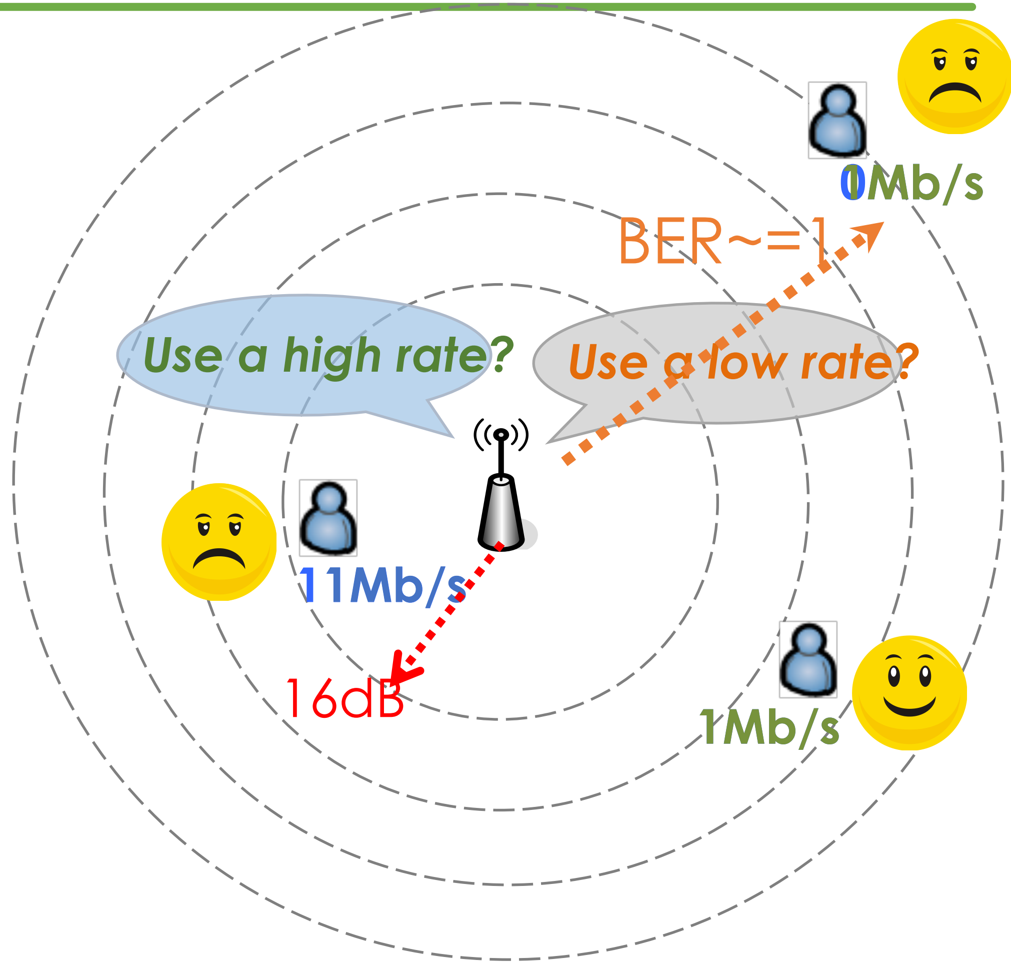
- SNR and capacity
- Channel fading and path loss
- Modulation and coding scheme
- Rate adaptation
- **Wireless multicasting**

Wireless Multicast

- Achieve a higher throughput
- Packets are randomly lost on a noisy wireless channel
- Link reliability decreases with the link distance
- Different receivers may lose different packets

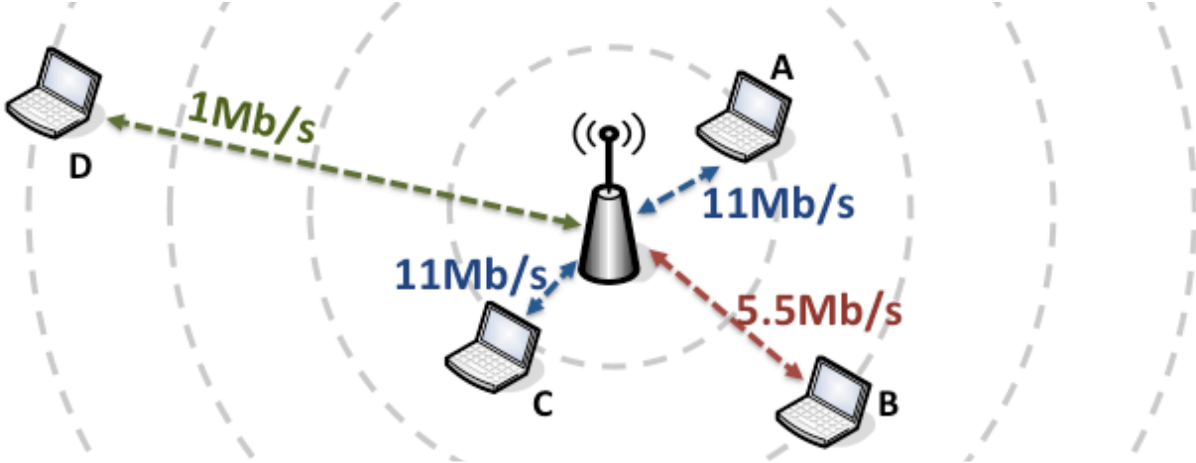
Heterogeneous Channel Conditions





Higher rates provide a higher throughput, but a shorter coverage range

Rate Adaptation for Multicast



- Why it is difficult?
  - Can only assign a single rate to each packet
  - But the channel conditions of clients are different
- Possible Solutions
  - For reliable transmission: select the rate based on the worst node
  - For non-reliable transmission: provide clients heterogeneous throughput

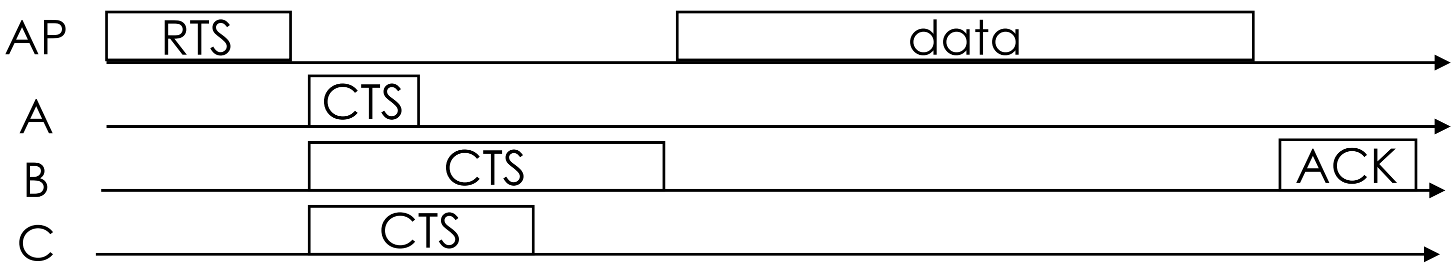
Reliable Multicast Protocol

- Before rate adaptation, we should first ask:
  - How to efficiently collect ACK from multicast clients?
- Leader-based Protocol (LBP)
  - Select one of the receivers as the leader to reply ACK
  - Leader
    if receive successfully, send ACK
    otherwise, send NACK
  - Others
    if receive successfully, do nothing
    otherwise, send NACK
  - Retransmit if the AP receives any NACK

J. Kuri and S. Kasera, "Reliable Multicast in Multi-Access Wireless LANs," IEEE INFOCOM, Mar. 1999.

Rate Adaptation for Data Multicast

- Rate Adaptive Reliable Multicast (RAM)
  - Should pick the bit-rate based on the channel of the worst receiver
- Say we have three receivers A, B, and C
  - Each receiver feedbacks CTS at its optimal rate chosen based on its SNR
  - The AP detects the lowest rate by measuring the longest channel time occupied by CTS



A. Basalamah, H. Sugimoto, and T. Sato, "Rate Adaptive Reliable Multicast MAC Protocol for WLANs," Proc. IEEE VTC-Spring, May 2006.