Wireless Networking
Fundamentals and Applications

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Agenda

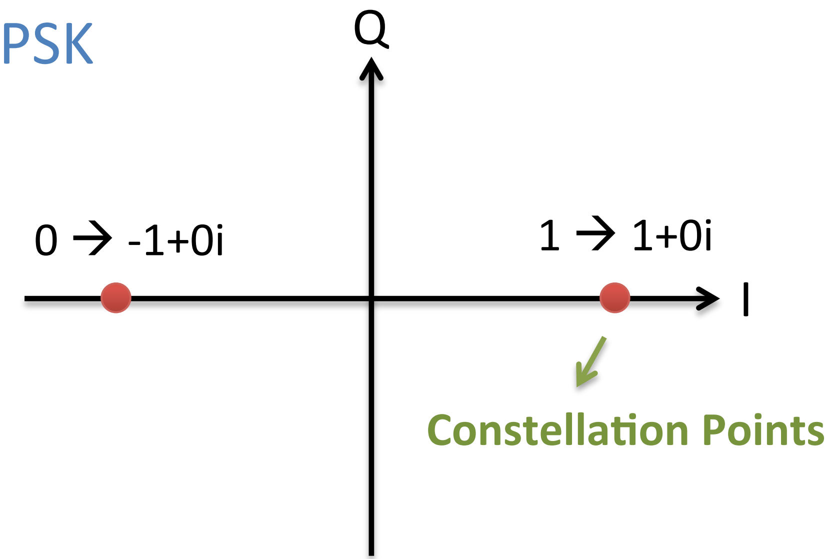
- Auto Rate Adaptation
- Orthogonal Frequency Division Modulation (OFDM)
- Multi-Input Multi-Output Systems (MIMO)

Auto Rate Adaptation

- Modulations and bit-rates
- SNR and bit-error rate
- Bit-rate selection algorithms

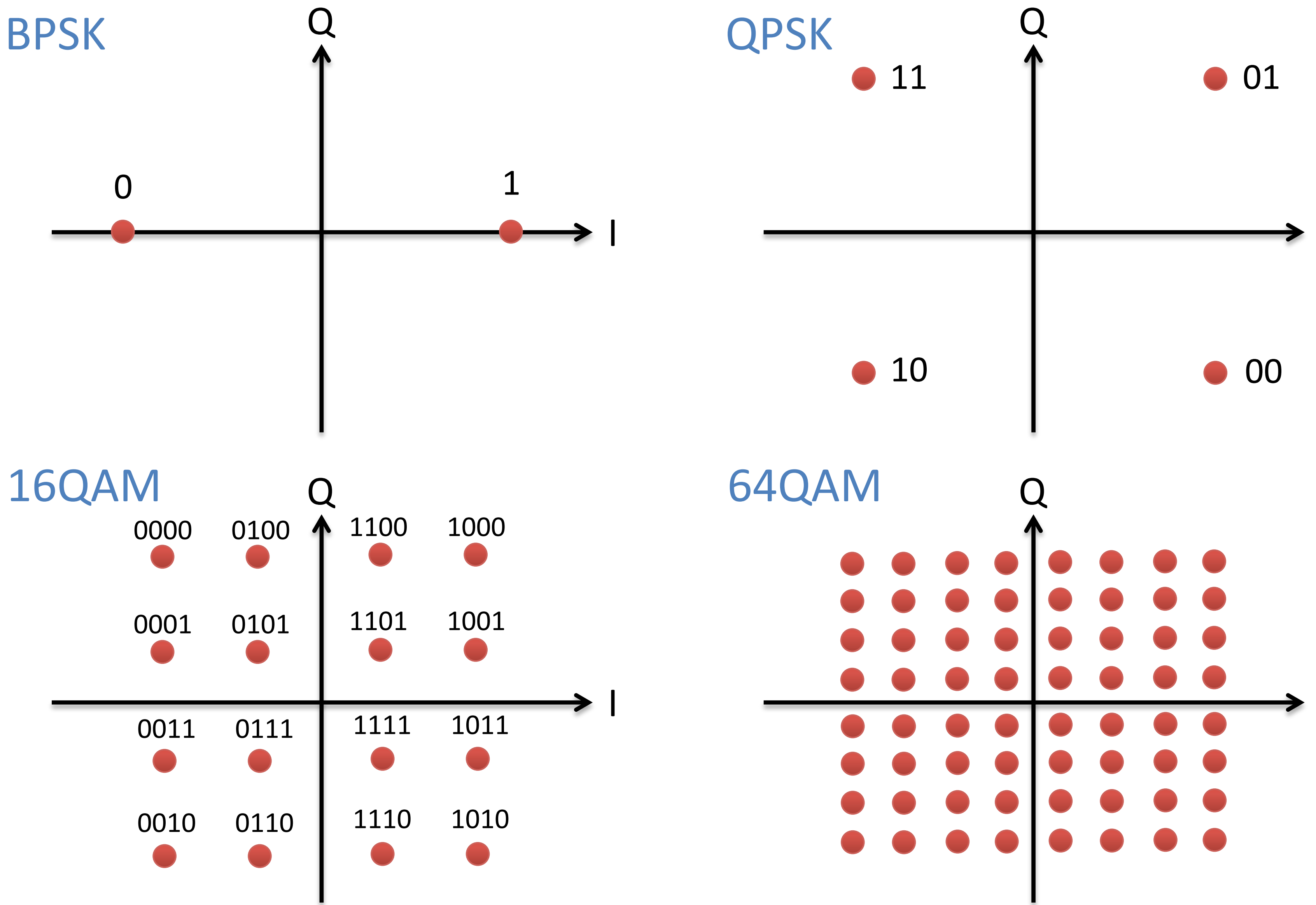
Modulations

BPSK



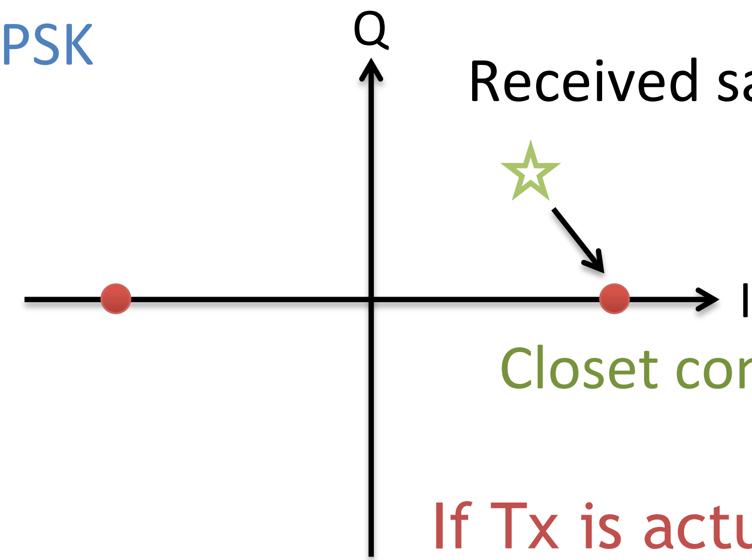
Modulate digital bits
to a complex number (sample)

Modulations



Demodulation

BPSK



If Tx is actually sending ‘0’, bit error occurs

Map the received complex number back to digital bits

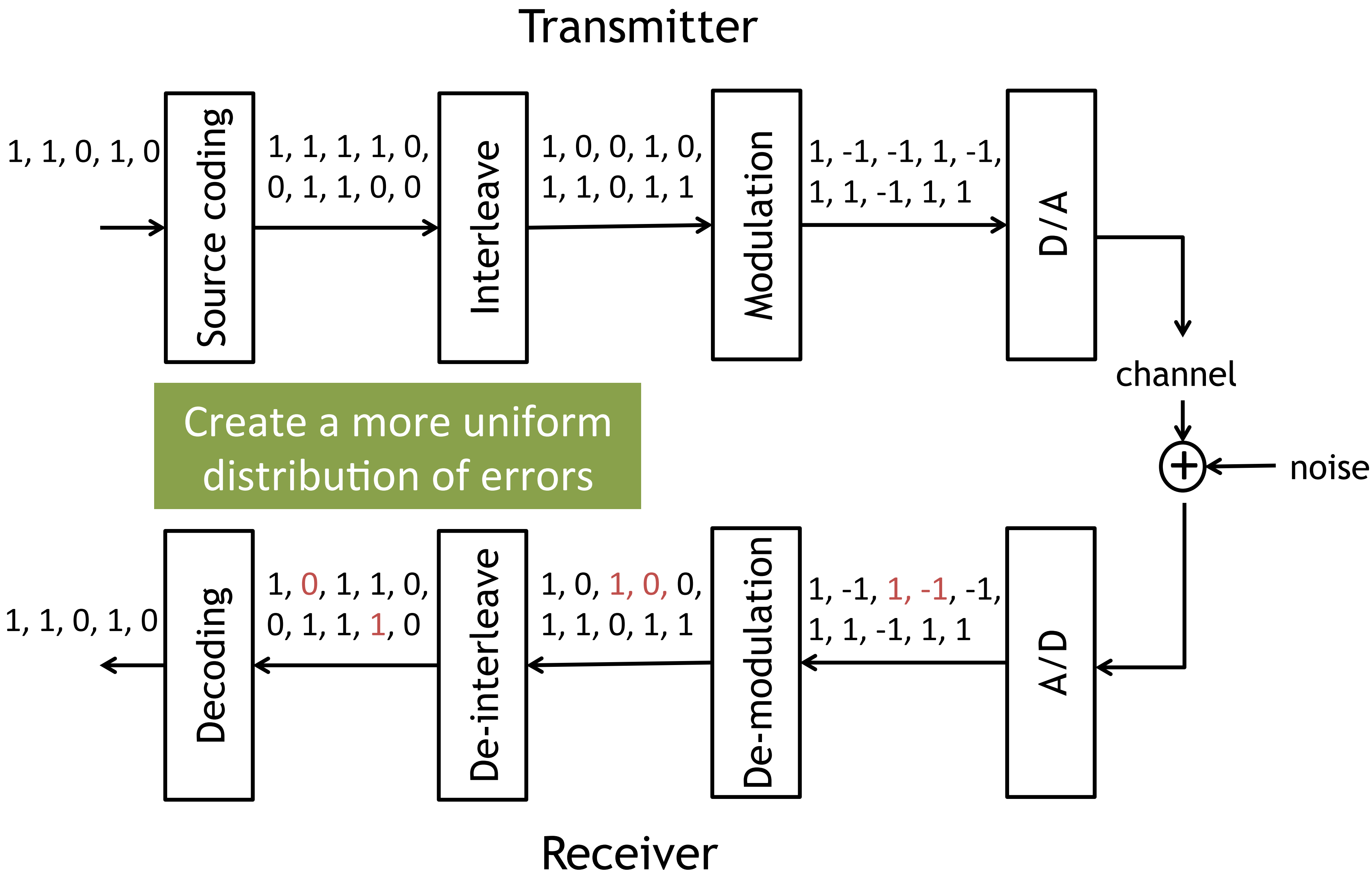
Bit-Rates in 802.11

Bit-rate	802.11 Standards	DSSS or OFDM	Modulation	Bits per Symbol	Coding Rate	Mega-Symbols per second
1	b	DSSS	BPSK	1	1/11	11
2	b	DSSS	QPSK	2	1/11	11
5.5	b	DSSS	CCK	1	4/8	11
11	b	DSSS	CCK	2	4/8	11
6	a/g	OFDM	BPSK	1	1/2	12
9	a/g	OFDM	BPSK	1	3/4	12
12	a/g	OFDM	QPSK	2	1/2	12
18	a/g	OFDM	QPSK	2	3/4	12
24	a/g	OFDM	QAM-16	4	1/2	12
36	a/g	OFDM	QAM-16	4	3/4	12
48	a/g	OFDM	QAM-64	6	2/3	12
54	a/g	OFDM	QAM-64	6	3/4	12

Coding Rate

- Avoid random errors
  - 1/2: Add 1x redundant bits
  - 3/4: Add 1/3x redundant bits
- Haven't solved the problem yet
  - Data input: 1, 1, 0, 1, 0, 1, 1, 0, …
  - After encoding:
    1, 1, 1, 1, 0, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, ….
  - Still one bit error → Suffer from bursty errors

Interleave and De-interleave



Channel Quality vs. Bit-Rate

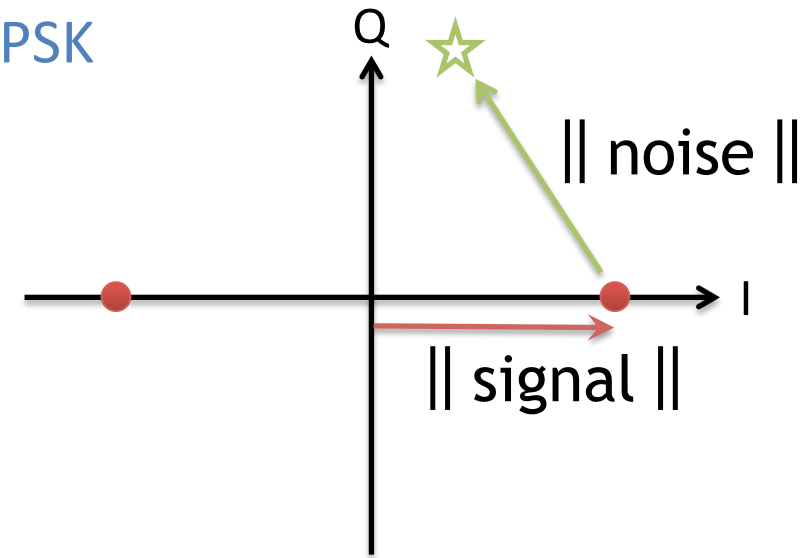
- When channels are very good
  - Encode more bits as a sample
- When channels are noisy
  - Encode fewer bits as a sample

Why is it affected by the channel quality?

Error Probability vs. Modulations

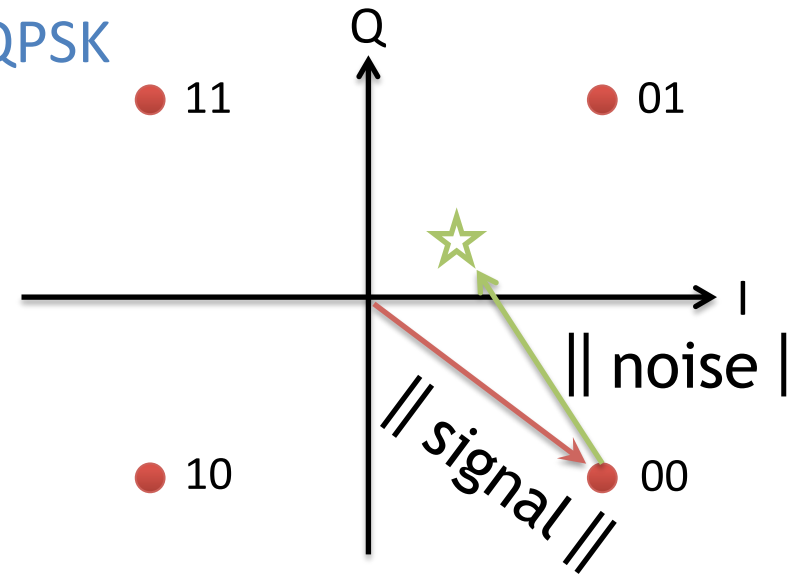
Given the same SNR

BPSK



Decode correctly

QPSK

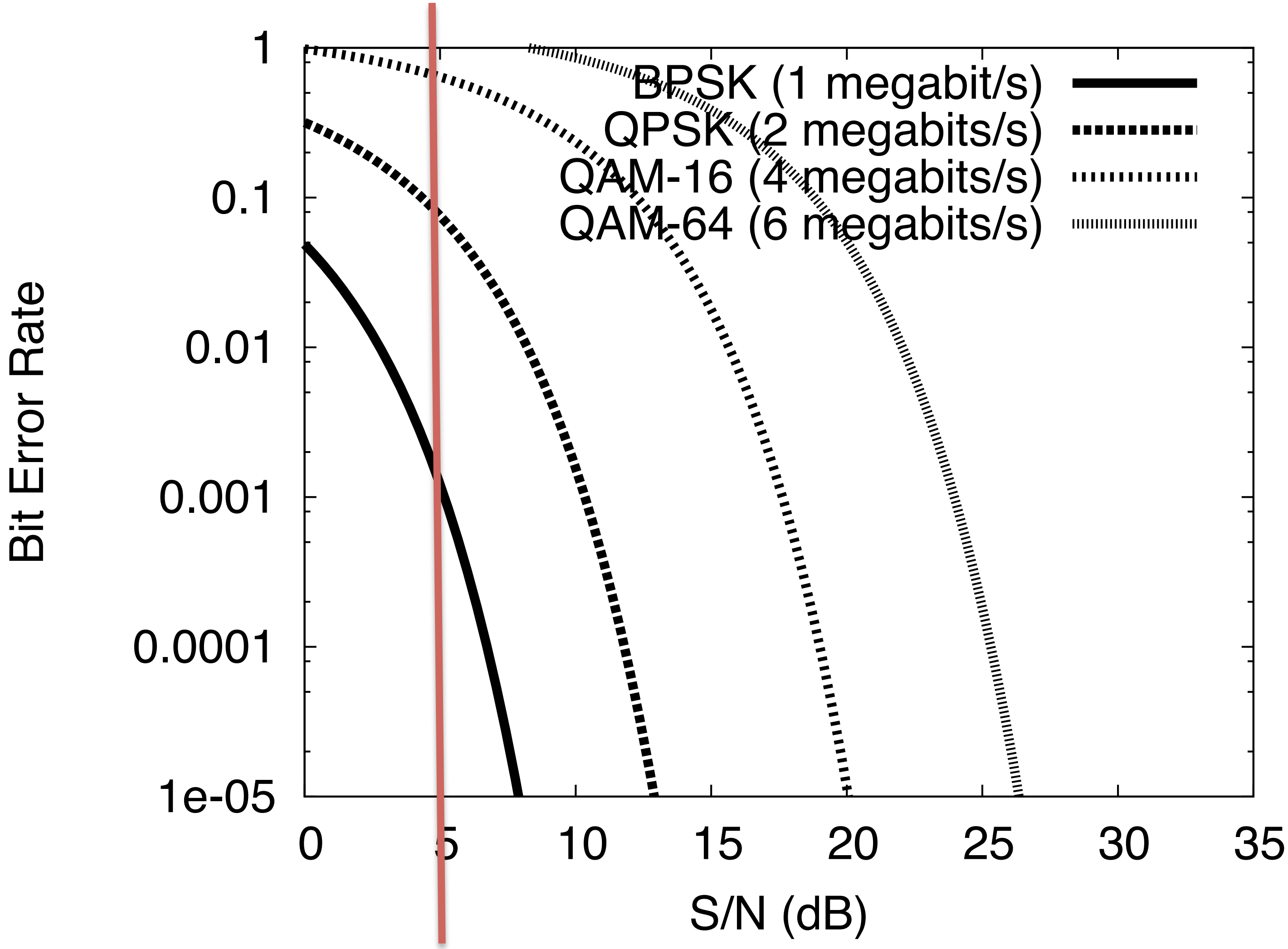


Decode incorrectly

SNR = 10log10 (|| signal || / || noise ||)

Given the same SNR, decodable for BPSK, but un-decodable for QPSK

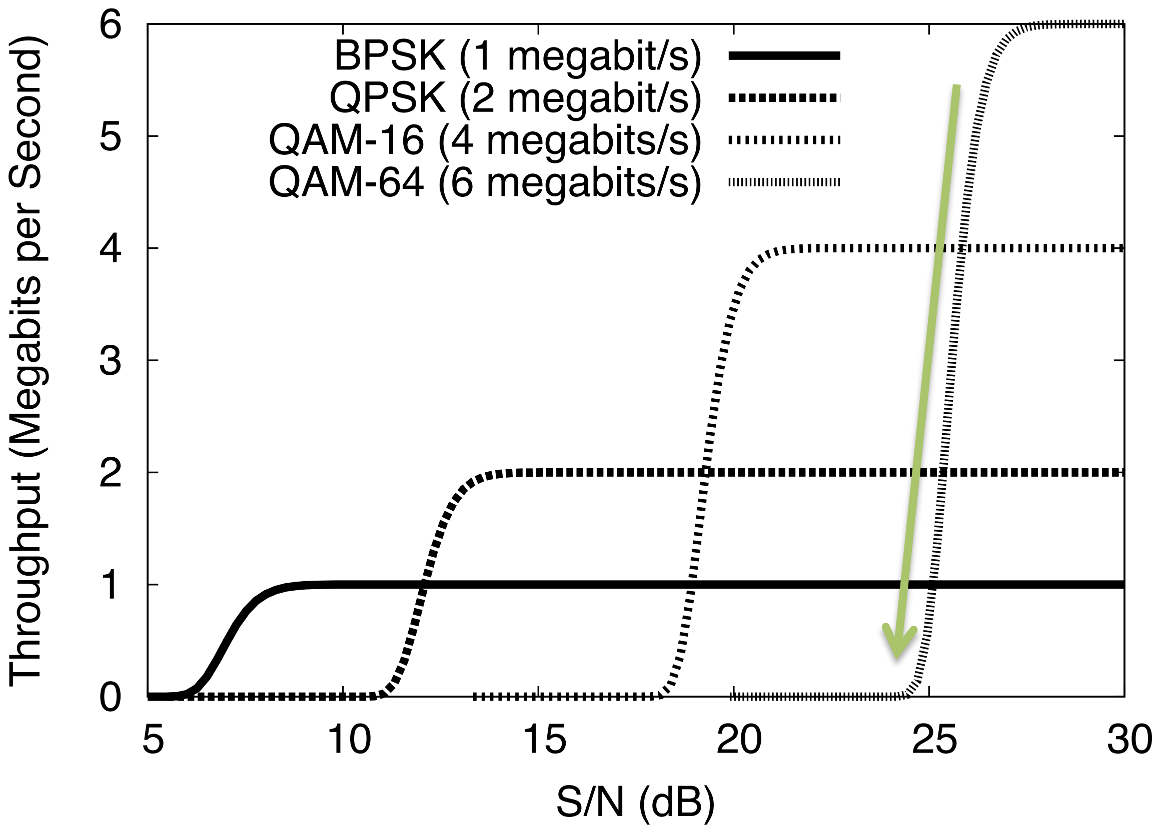
SNR vs. BER (Bit Error Rate)



802.11 operating region 5dB

SNR vs. PER (Packet Error Rate)

- In 802.11, a packet is received correctly if it passes the CRC check (all bits are correct)
  - Receive all or none



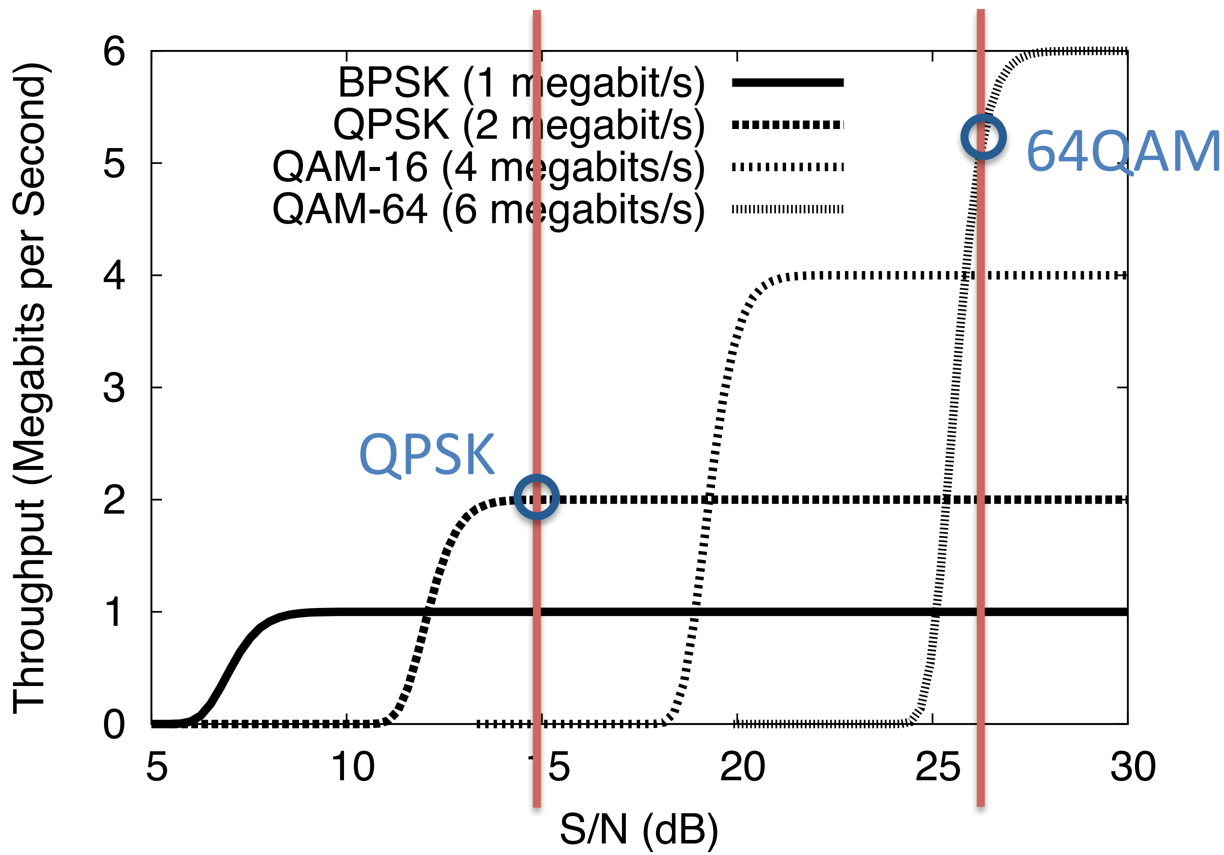
$\text{PER} = 1-(1-\text{BER})^n$

Throughput
$= (1-\text{BER})^n * \text{bit-rate}$

Throughput degrades quickly even with a little BER

Bit-Rate Selection

- Given the SNR, select the bit-rate that can achieve the highest throughput



Difficulties with Rate Adaptation

- Channel quality changes very quickly
  - Especially when the device is moving

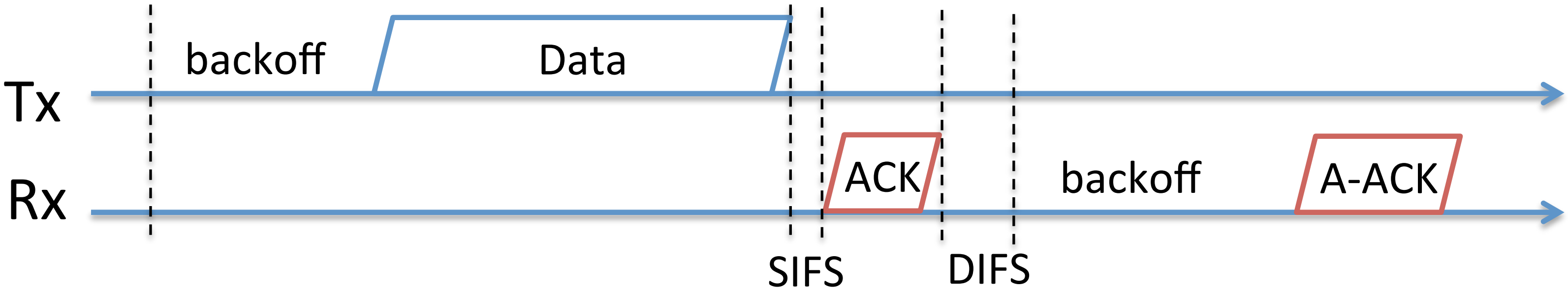
- Can't tell the difference between
  - poor channel quality due to noise/interference/collision (high || noise ||)
  - poor channel quality due to distance (low || signal ||)

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

Types of Auto-Rate Adaptation

	Transmitter-based	Receiver-Based
SNR-based		RBAR, OAR
ACK-based	ARF, AARF	
Throughput-based	SampleRate (default in Linux)	RRAA
	Selected by Tx (Less accurate)	Selected by Rx (Higher overhead)

Sync. ACK vs. Async ACK



- Sync. ACK
  - Cost the minimum overhead
  - Only know whether the packet is transmitted correctly
  - Don’t know whether the packet error is due to incorrect rate selection or collision
- Async. ACK
  - Cost extra overhead
  - Can include more detailed information

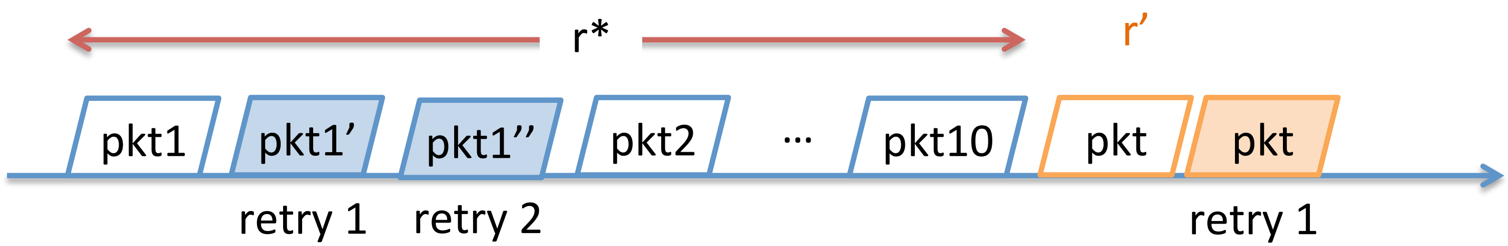
Robust Rate Adaption Algorithm (RRAA)

- Dynamically enable RTS/CTS before data transmission
- Detect that the low throughput is due to the incorrect bit-rate selection or collision (hidden terminals)
- Estimate the correct number of transmissions to keep RTS/CTS
- Disable RTS/CTS if it does not help

S. Wong, H. Yang, S. Lu, V. Bharghavan, “Robust Rate Adaptation for 802.11 Wireless Networks,” ACM MOBICOM, 2006

SampleRate

- Periodically send packets at bit-rates other than the current bit-rate



- Calculate the transmission time of each packet
  - packet length, bit-rate, number of retries, backoff time

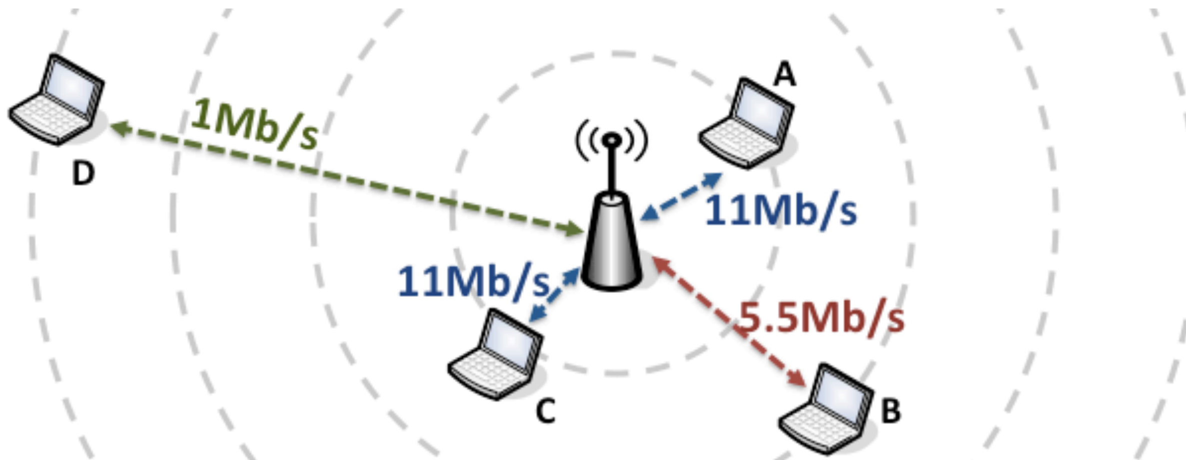
$$tx\_time(b, r, n) = difs + backoff(r) + (r+1) * (sifs + ack + header + (n * 8/b)$$

Sample Rates

- Select the rate that has the smallest predicted average packet transmission time
- 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

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

Rate Adaptation for Multicast?



- Can only assign a single rate to each packet
- Possible Solutions
  - For reliable transmission: select the rate based on the worst node
  - For non-reliable transmission: provide clients heterogeneous throughput

Recent Proposals

- ZipTx

  K. Lin, N. Kushman and D. Katabi, “Harnessing Partial Packets in 802.11 Networks,” ACM MOBICOM, 2008

  Exploit partial packets with consideration of bit-rate adaptation

- SoftRate

  M. Vutukuru, H. Balakrishnan and K. Jamieson, “Cross-Layer Wireless Bit Rate Adaptation,” ACM SIGCOMM, 2009

  Exploit soft information to improve selection accuracy

- FARA

  H. Rahul, F. Edalat, D. Katabi and C. Sodini, “Frequency-Aware Rate Adaptation and MAC Protocols,” ACM MOBICOM, 2009

  Adapt the bit-rate for every OFDM subcarrier

- ESNR

  D. Halperin, W. Hu, A. Sheth and D. Wetherall, “Predictable 802.11 Packet Delivery from Wireless Channel Measurements”, ACM SIGCOMM, 2010

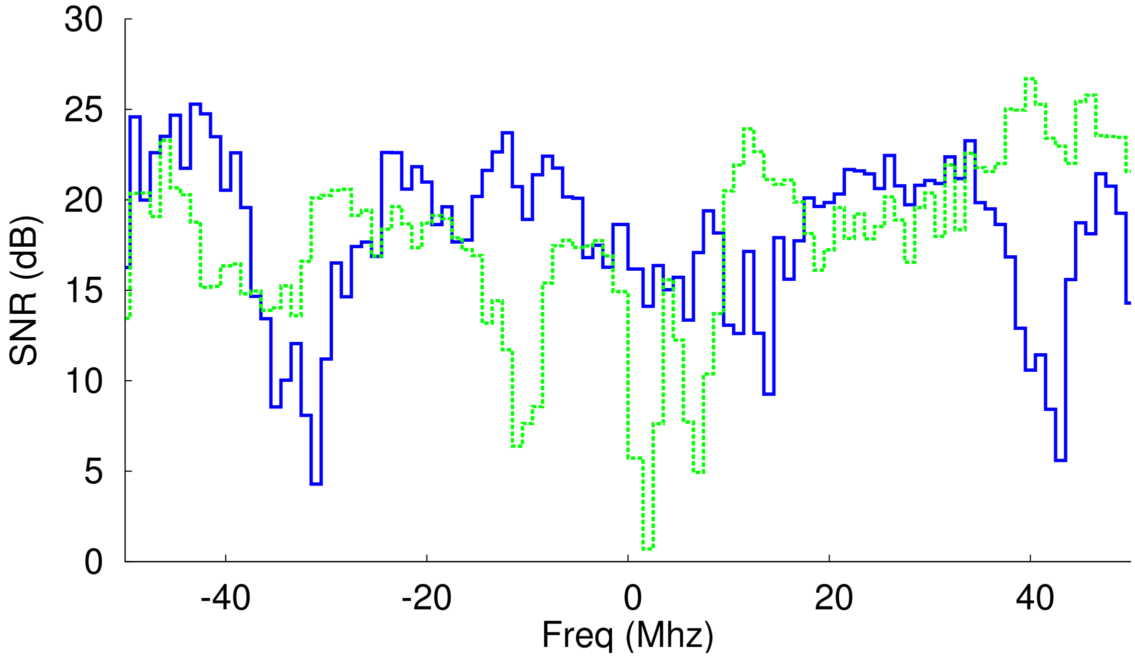
  Consider frequency selective fading

Frequency-Aware Rate Adaptation (FARA)

H. Rahul, F. Edalat, D. Katabi, C. Sodini

MOBICOM 2009

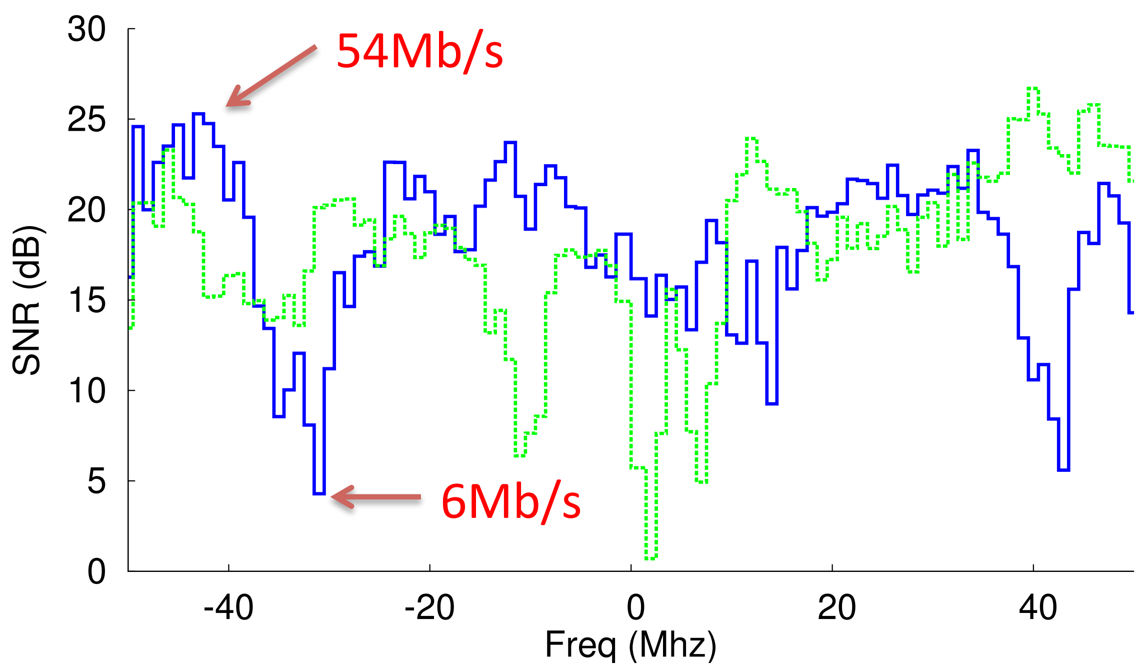
Frequency Diversity



- Frequency diverse across 100MHz of 802.11a spectrum
- The SNRs of different frequencies can be as much as 20dB on a single link
- Different receivers could prefer different frequencies

FARA

- Instead of assigning the same rate to the entire frequency band, it allows each OFDM sub-carrier to pick a modulation and a code rate that match its SNR



FARA

- Receiver driver protocol
  - Initially, the sender transmit few symbols using the lowest bit-rate for all sub-carriers
  - The receiver selects the bit-rate based on an SNR-Rate mapping table

Minimum Required SNR	Modulation	Coding
$<$3.5 dB	Suppress subband	
3.5 dB	BPSK	1/2
5.0 dB	BPSK	3/4
5.5 dB	4-QAM	1/2
8.5 dB	4-QAM	3/4
12.0 dB	16-QAM	1/2
15.5 dB	16-QAM	3/4
20.0 dB	64-QAM	2/3
21.0 dB	64-QAM	3/4

Predictable 802.11 Packet Delivery from Wireless Channel Measurements

D. Halperin, W. Hu, A. Sheth and D. Wetherall

ACM SIGCOMM, 2010

SNR-based Rate Adaptation

- SNR-based rate adaptation is usually inaccurate because we
  - Assume frequency-flat fading
  - Select the bit-rate based on “average SNR” across bins
- However, this will over-estimate the channel quality because
  - A packet will fail to pass the CRC check even if only few bits are erroneous due to frequency-selective fading

Effective SNR

- Bias toward the weaker sub-carrier SNRs

$$BER_{eff,k} = \frac{1}{52} BER_k(SNR_s)$$

$$SNR_{eff,k} = BER_k^{-1}(BER_{eff,k})$$

Modulation	Bits/Symbol (k)	$\mathrm{BER}_k(\rho)$
BPSK	1	$Q\left(\sqrt{2\rho}\right)$
QPSK	2	$Q\left(\sqrt{\rho}\right)$
QAM-16	4	$\frac{3}{4}Q\left(\sqrt{\rho/5}\right)$
QAM-64	6	$\frac{7}{12}Q\left(\sqrt{\rho/21}\right)$

Effective SNR

- Look up the SNR-MAP table using ESNR