AccuRate: Constellation Aware Rate Estimation in Wireless Networks

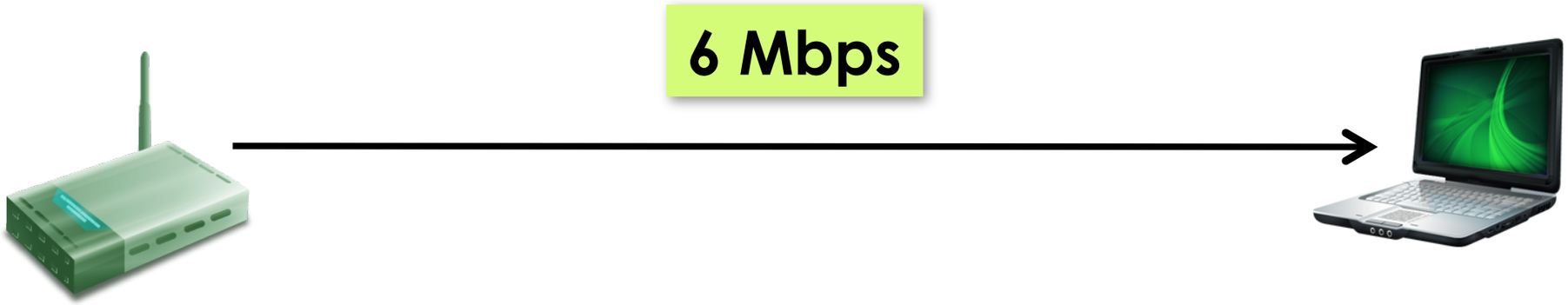
Souvik Sen,
Naveen Santhapuri, Romit Roy Choudhury, Srihari Nelakuditi

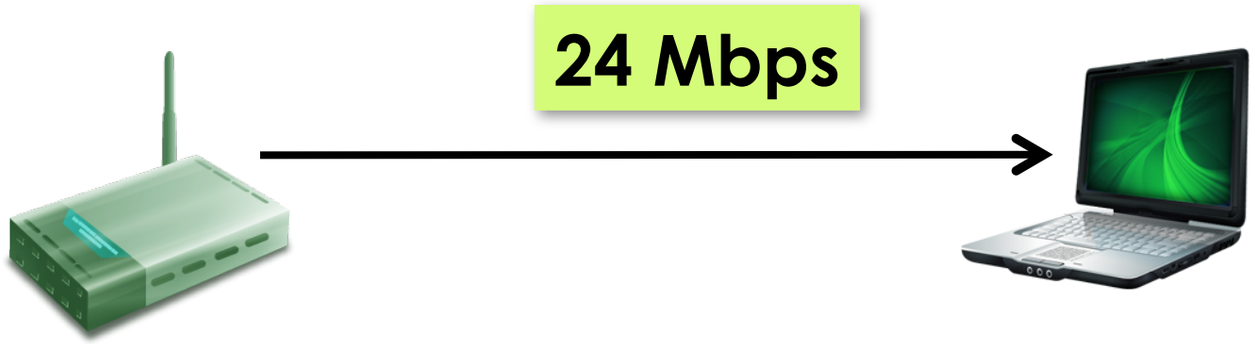
Duke UNIVERSITY

UNIVERSITY OF SOUTH CAROLINA

Bit-rate in Wireless Networks

Wireless link throughput depends on transmission bit-rate





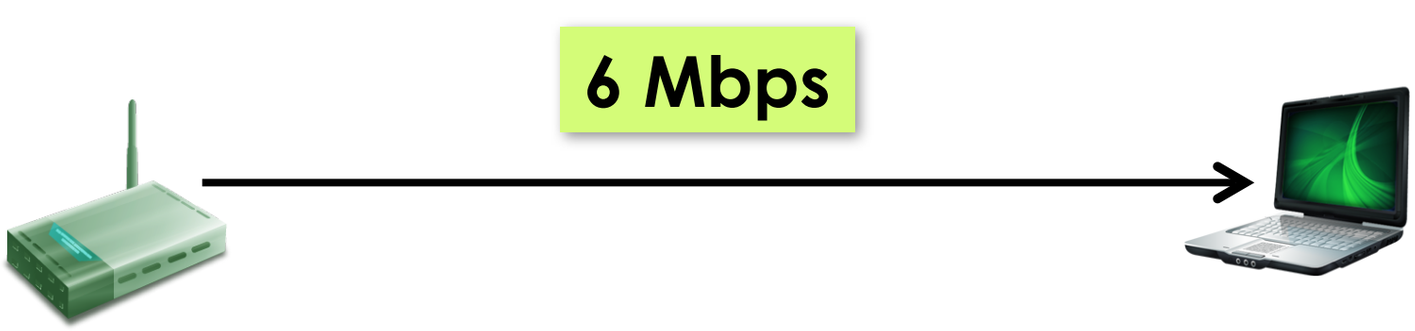
Choosing the optimal bit-rate is an important problem

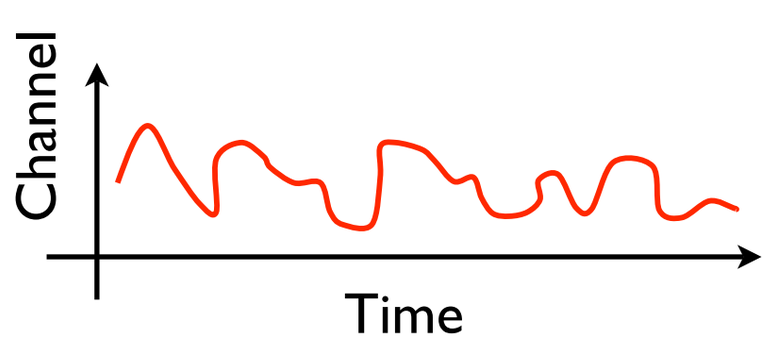
Bit-rate in Wireless Networks

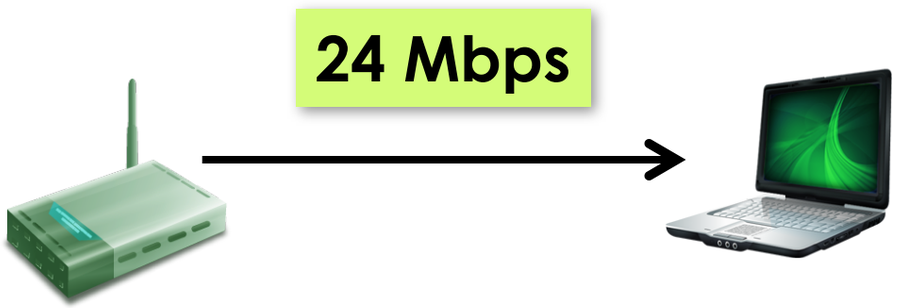
Optimal bit-rate selection is challenging because the wireless channel varies over:

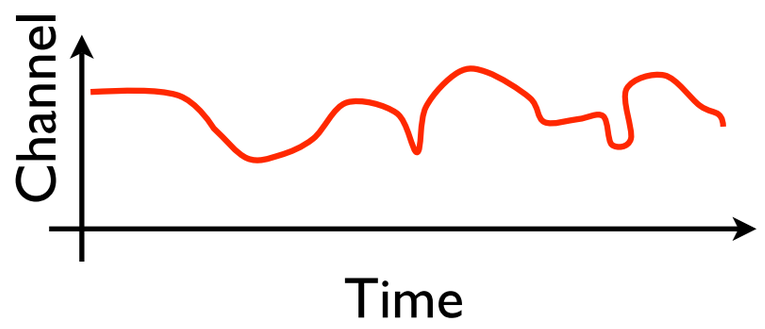
Space

Time



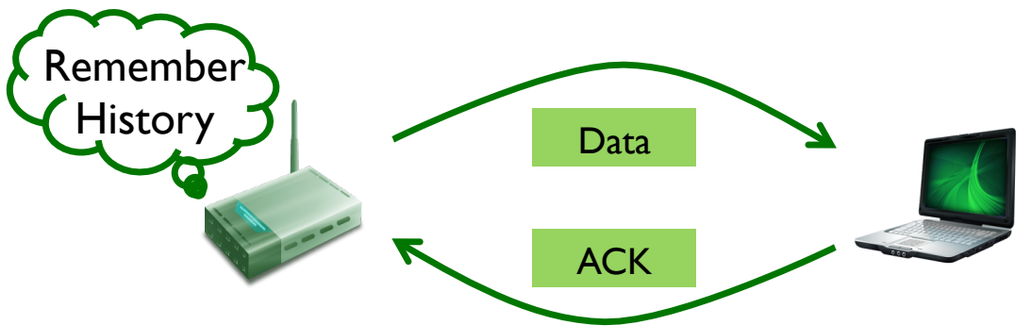






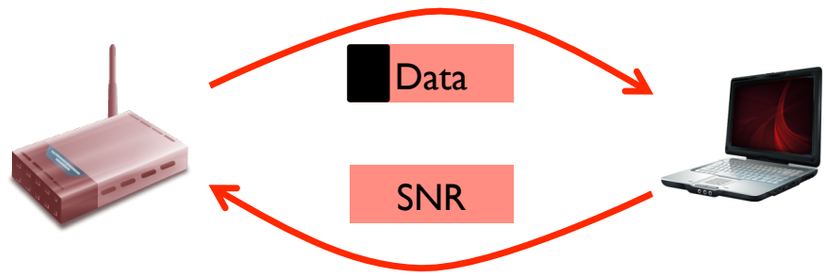
Current Wireless Rate Selection

Frame Based



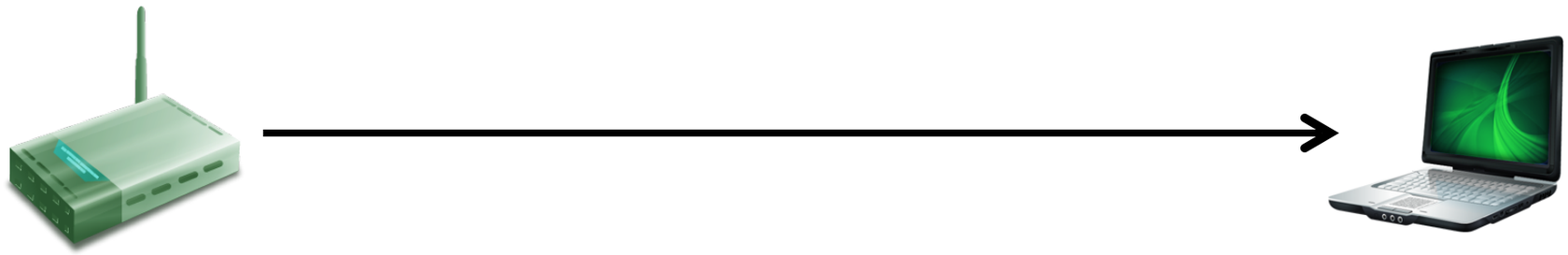
SampleRate, RRAA

SNR Based

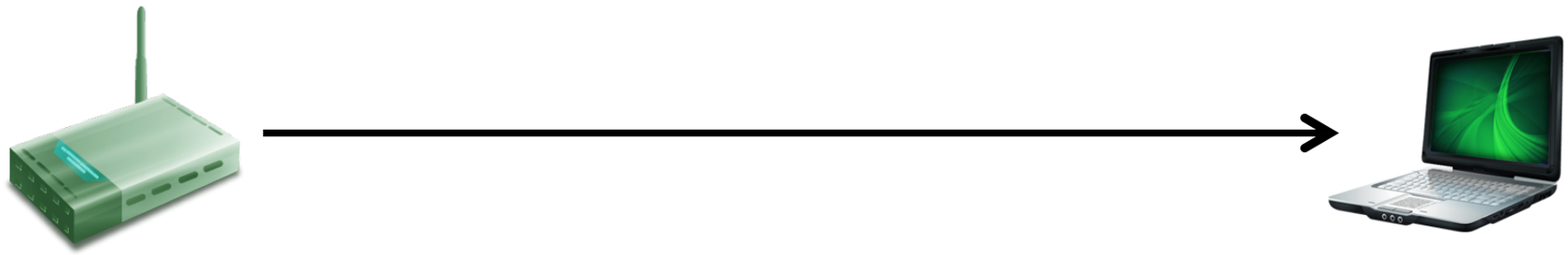


RBAR, CHARM

- Recently PHY-based:
  - SoftRate [SIGCOMM ’09]
    - Uses a BER heuristic to estimate bit rate
    - BER accurately identifies when to increase/decrease rate
    - However, may not be able to jump to optimal rate



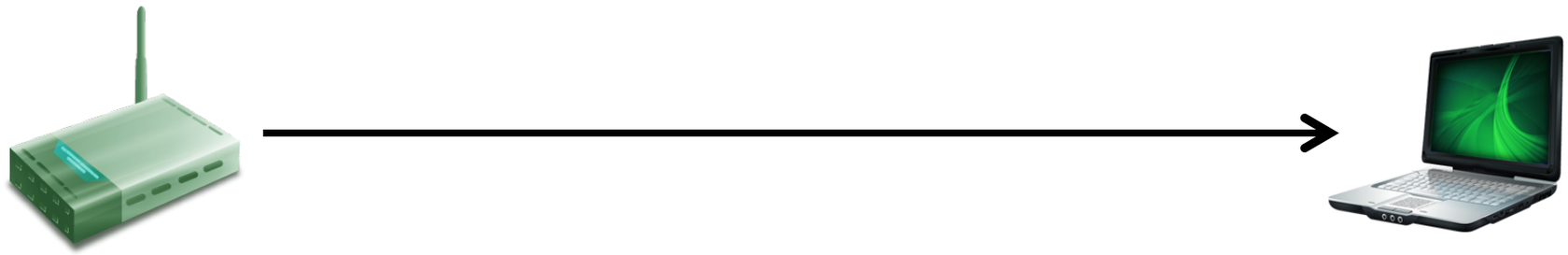
Ideally Tx wants optimal rate for next packet



Ideally Tx wants optimal rate for next packet

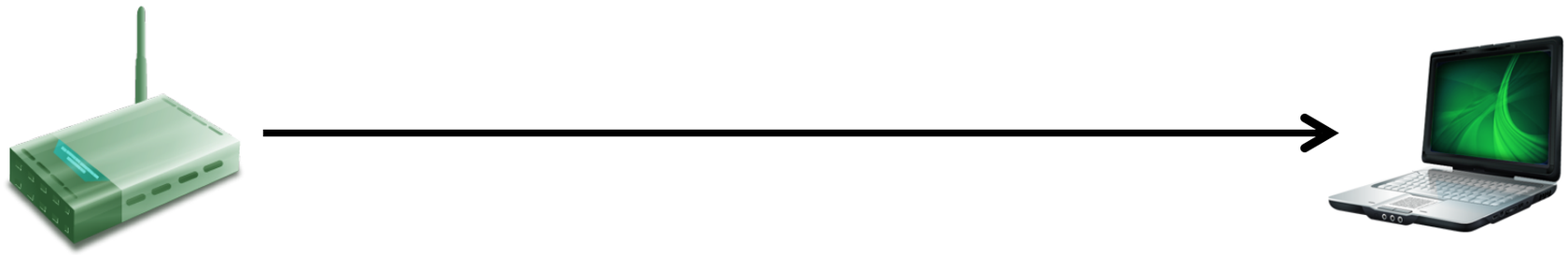
⇩

Function of optimal rate of the previous packet



Ideally Tx wants optimal rate for next packet

Function of optimal rate of the previous packet

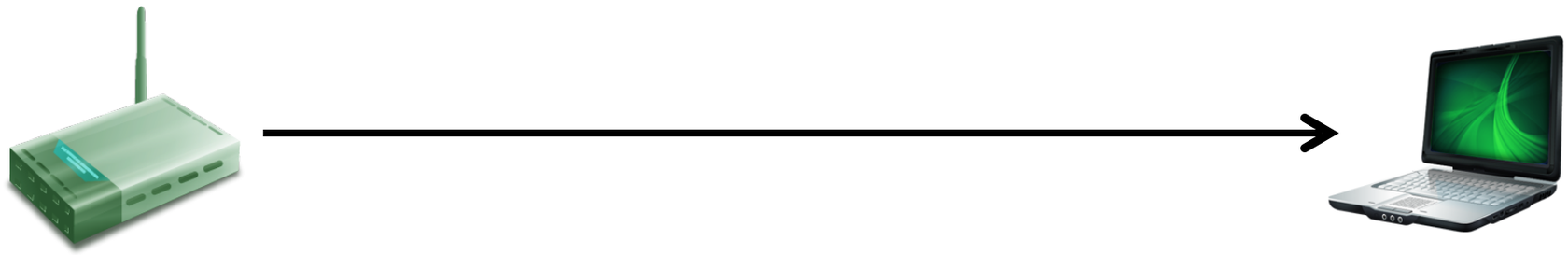


Ideally Tx wants optimal rate for next packet

Function of optimal rate of the previous packet

In other words,

Given a transmission at rate R,
what would have been the max rate R*,
at which that transmission **would have been** successful



Ideally Tx wants optimal rate for next packet

Function of optimal rate of the previous packet

In other words,

Given a transmission at rate R,
what would have been the max rate R*,
at which that transmission **would have been** successful

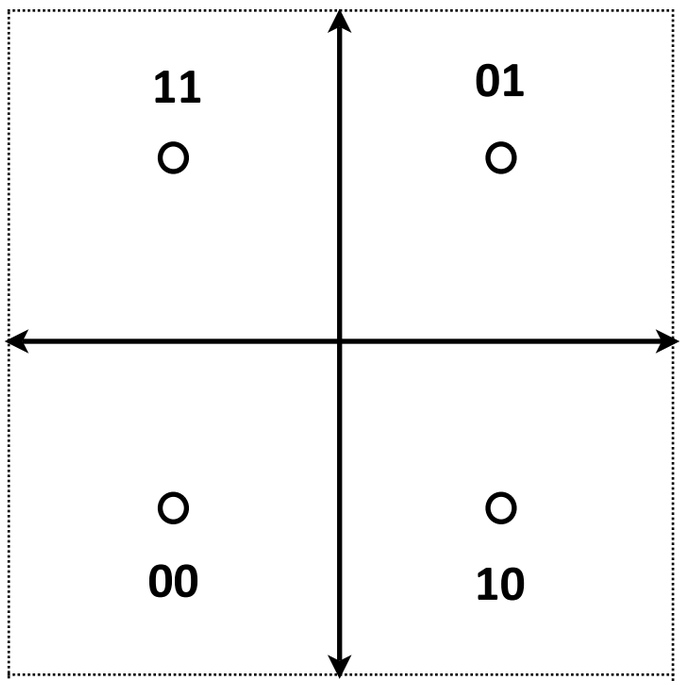
We propose **AccuRate**

Background:

Symbols, Modulation, Bit-rate

Physical Layer Symbols

Data = 01111001 ....

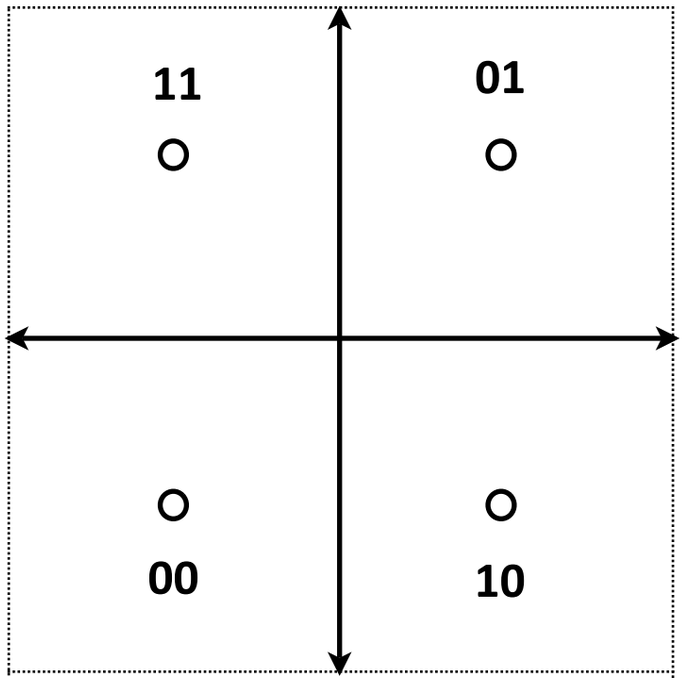


Tx 4QAM Symbol

Physical Layer Symbols

Data = 01111001 ....

2 bits
together

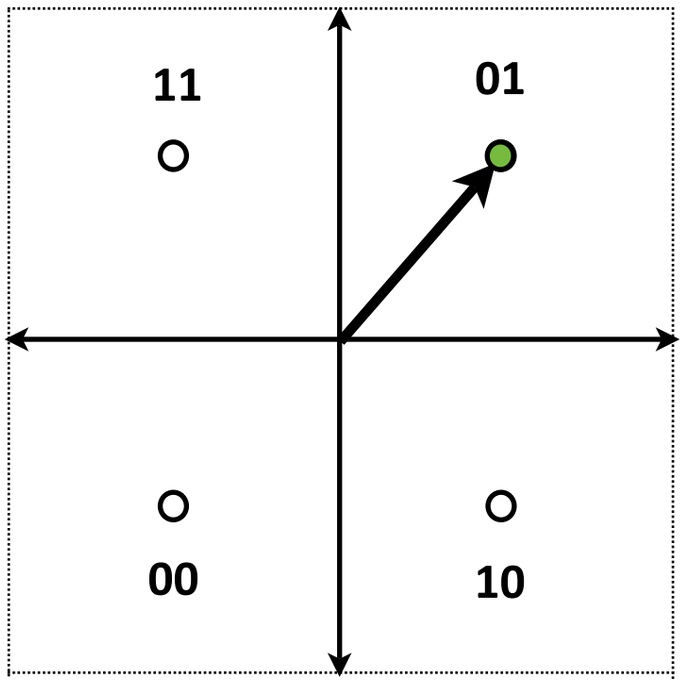


Tx 4QAM Symbol

Physical Layer Symbols

Data = 01111001 ....

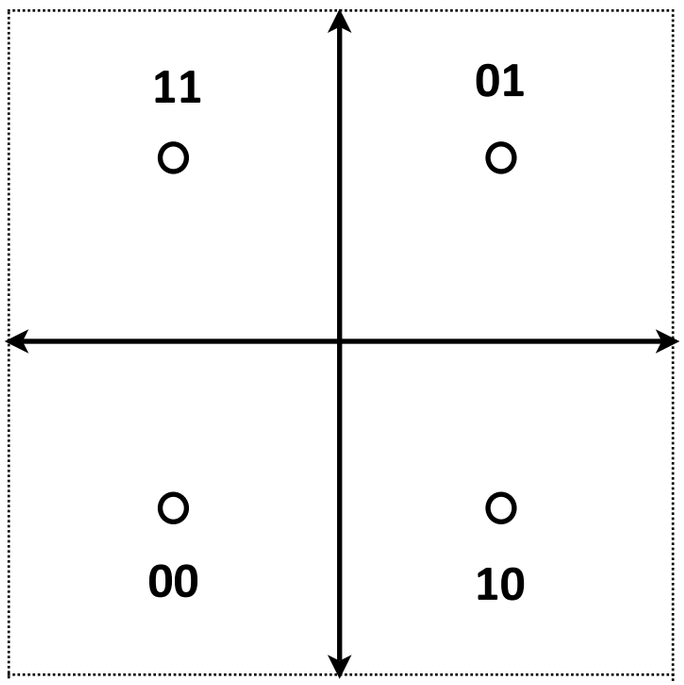
2 bits together



Tx 4QAM Symbol

Symbols to Modulation

Data = 01111001 ....

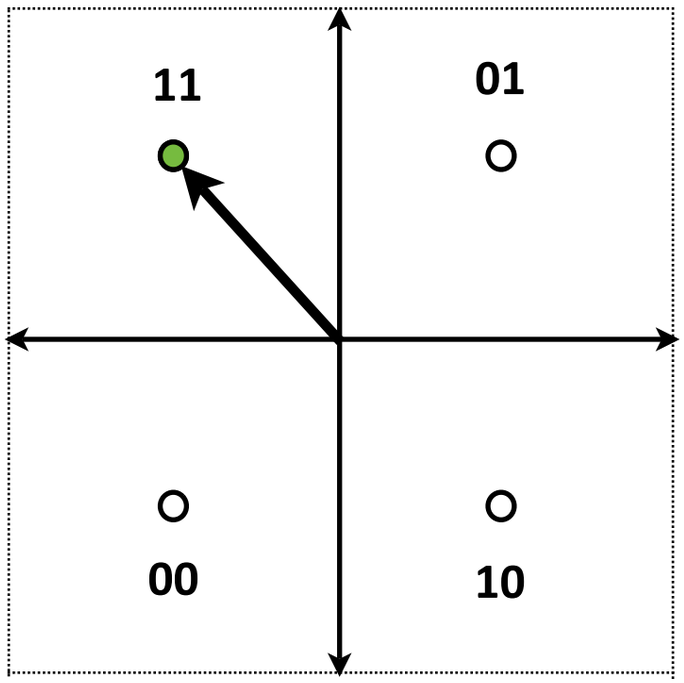


Tx 4QAM Symbol

Symbols to Modulation

Data = 01**11**1001 ....

2 bits together

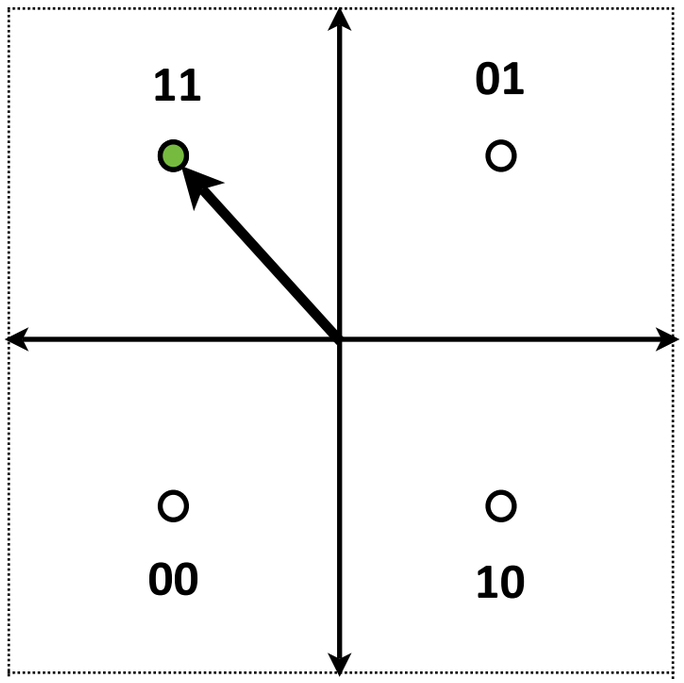


Tx 4QAM Symbol

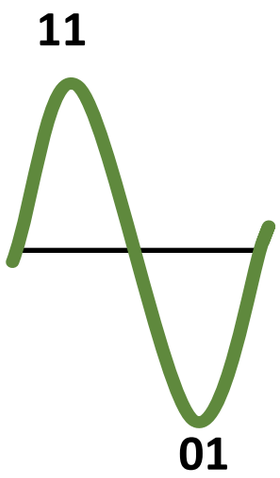
Symbols to Modulation

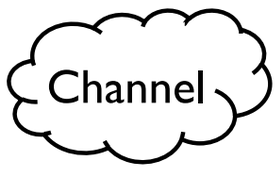
Data = 01|11|1001 ....

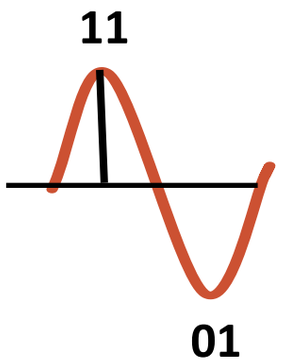
2 bits together

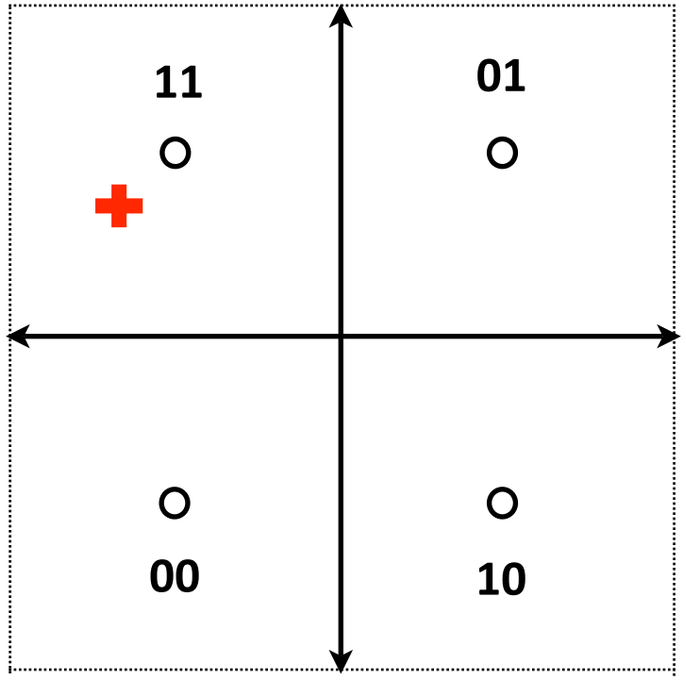


Tx 4QAM Symbol









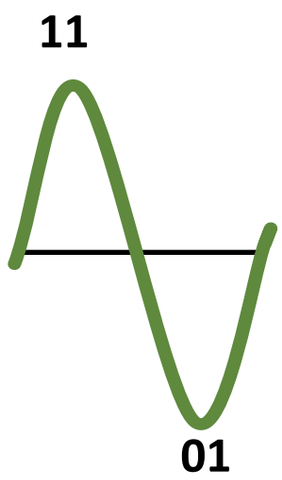
Rx 4QAM Symbol

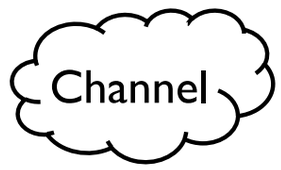
Symbols to Modulation

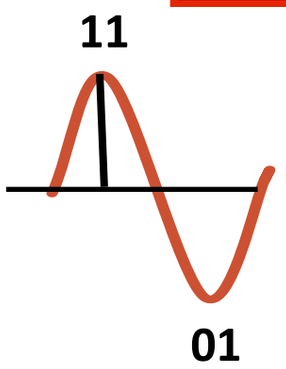
Data = 01**11**1001 ....

2 bits
together

Tx 4QAM Symbol







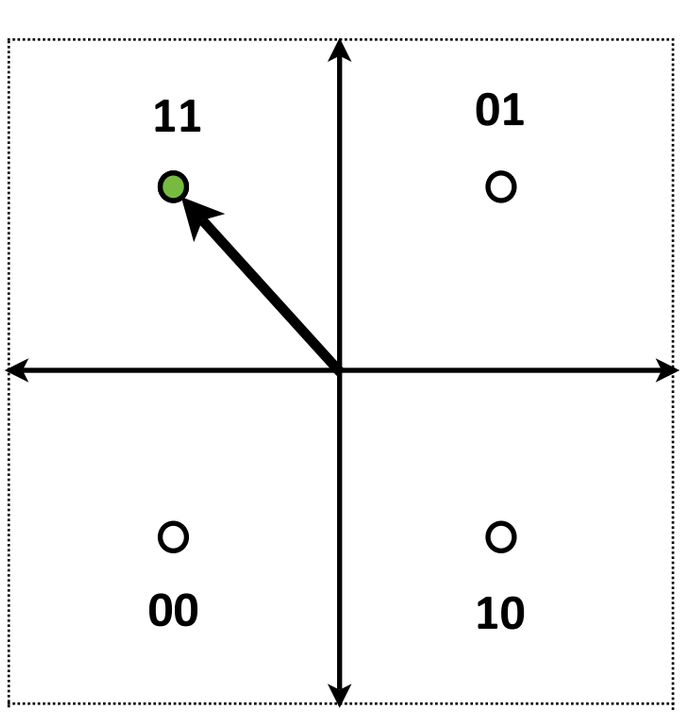
Dispersion

Rx 4QAM Symbol

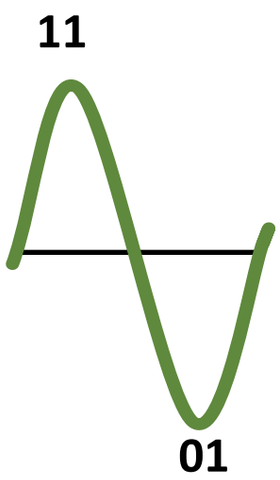
Symbols to Modulation

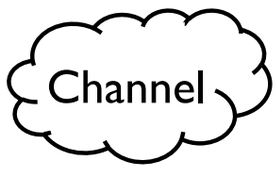
Data = 01**11**1001 ....

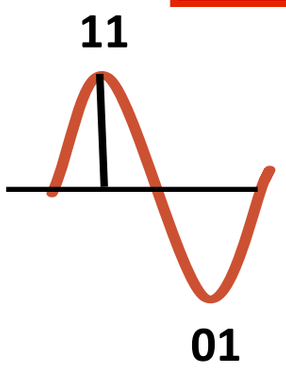
2 bits
together

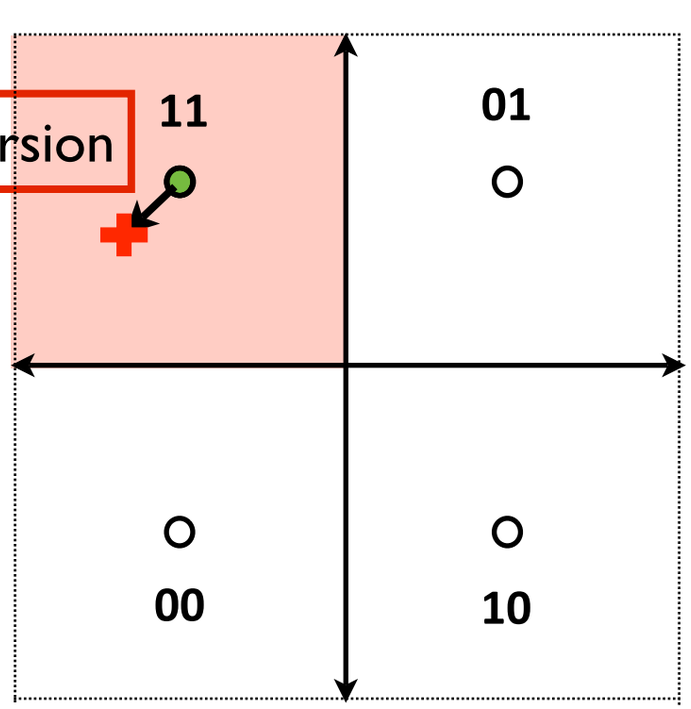


Tx 4QAM Symbol









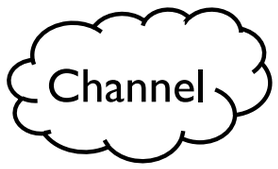
Rx 4QAM Symbol

Symbols to Modulation

Data = 01**11**1001 ....

2 bits
together

Tx 4QAM Symbol

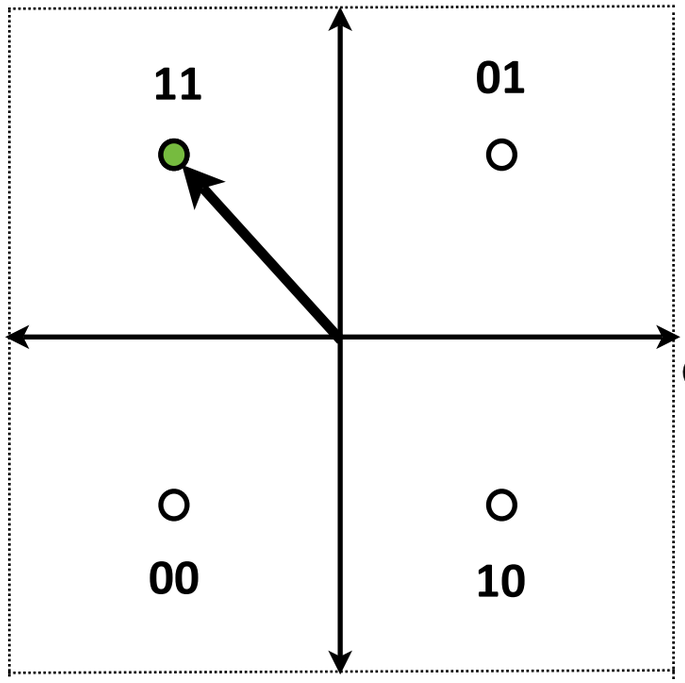


Rx 4QAM Symbol

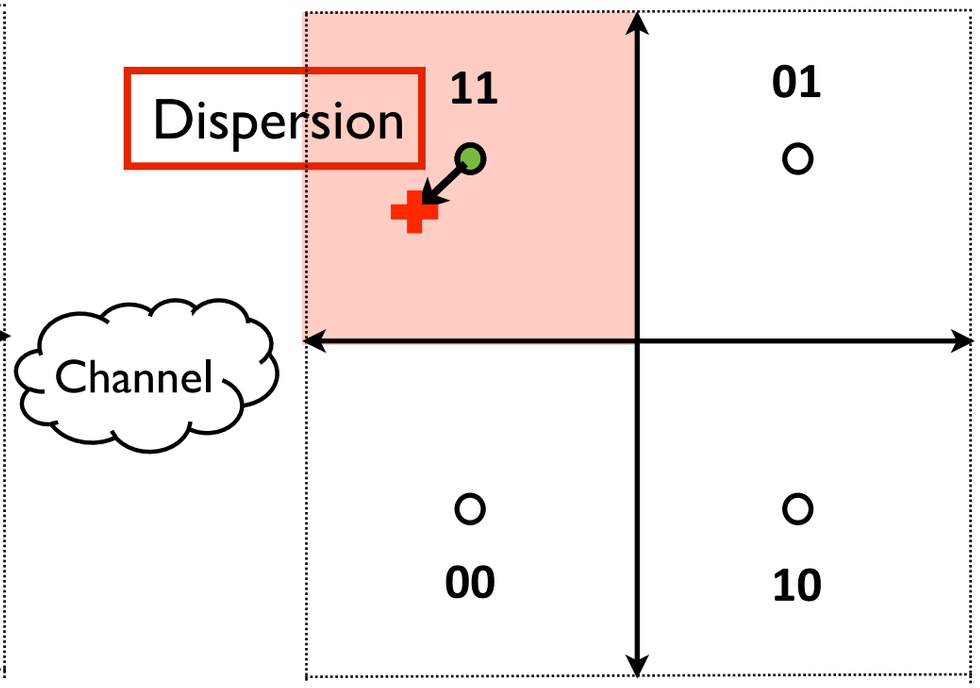
Symbols to Modulation

Data = 01|11|1001 ....

2 bits together



Tx 4QAM Symbol



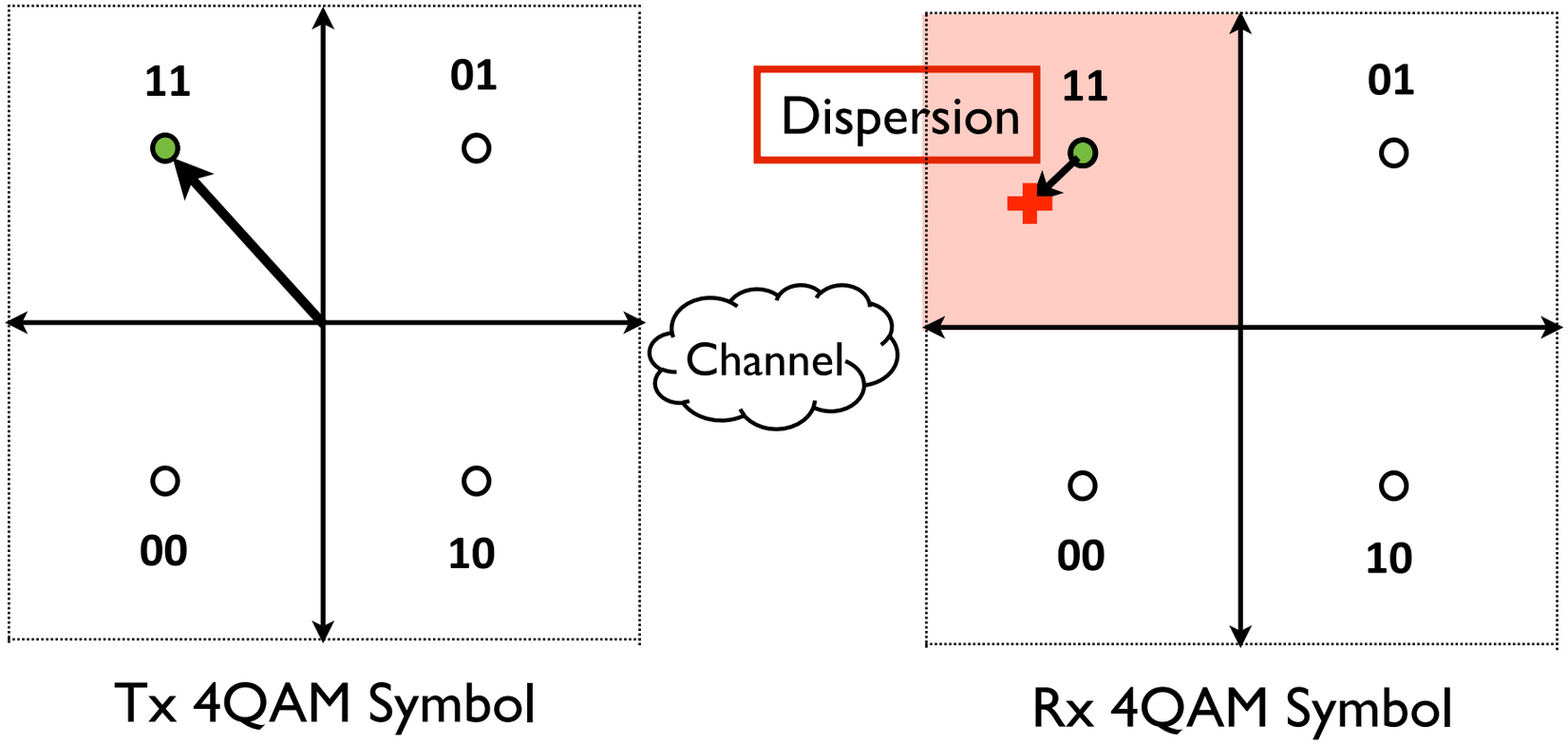
Rx 4QAM Symbol

Channel

Different Modulations in 802.11

Data = 01|11|1001 ....

2 bits together

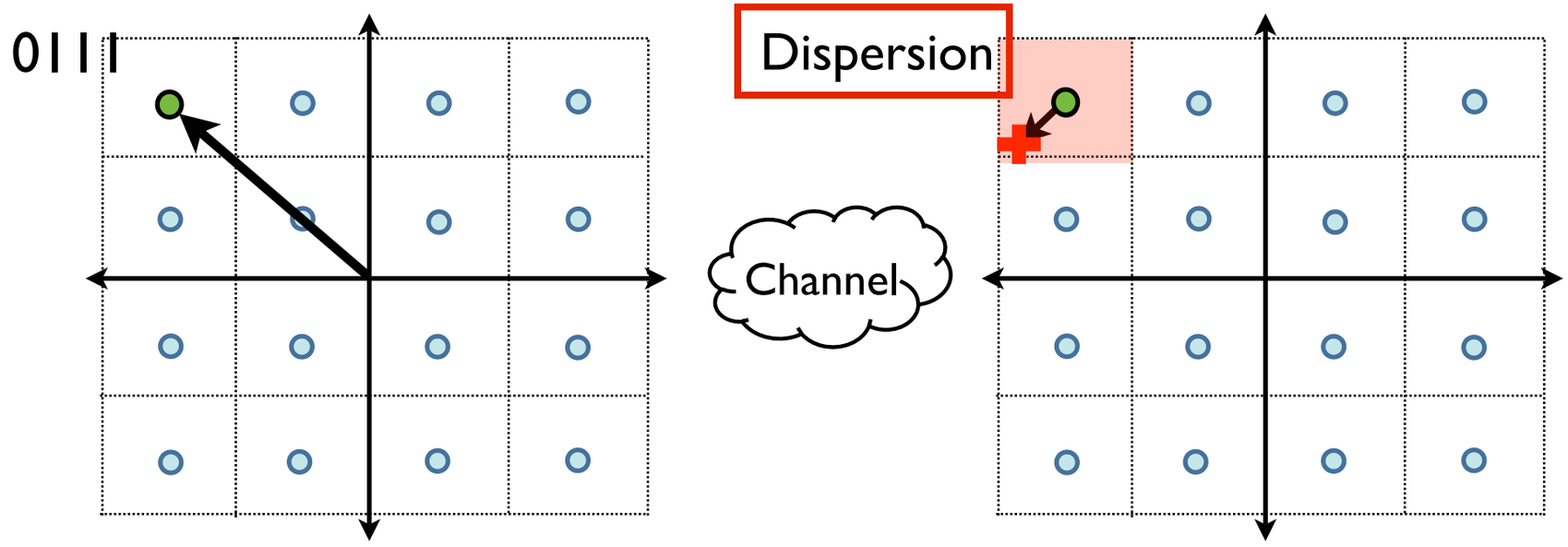


Tx 4QAM Symbol

Rx 4QAM Symbol

Data = 0111|1001 ....

4 bits together



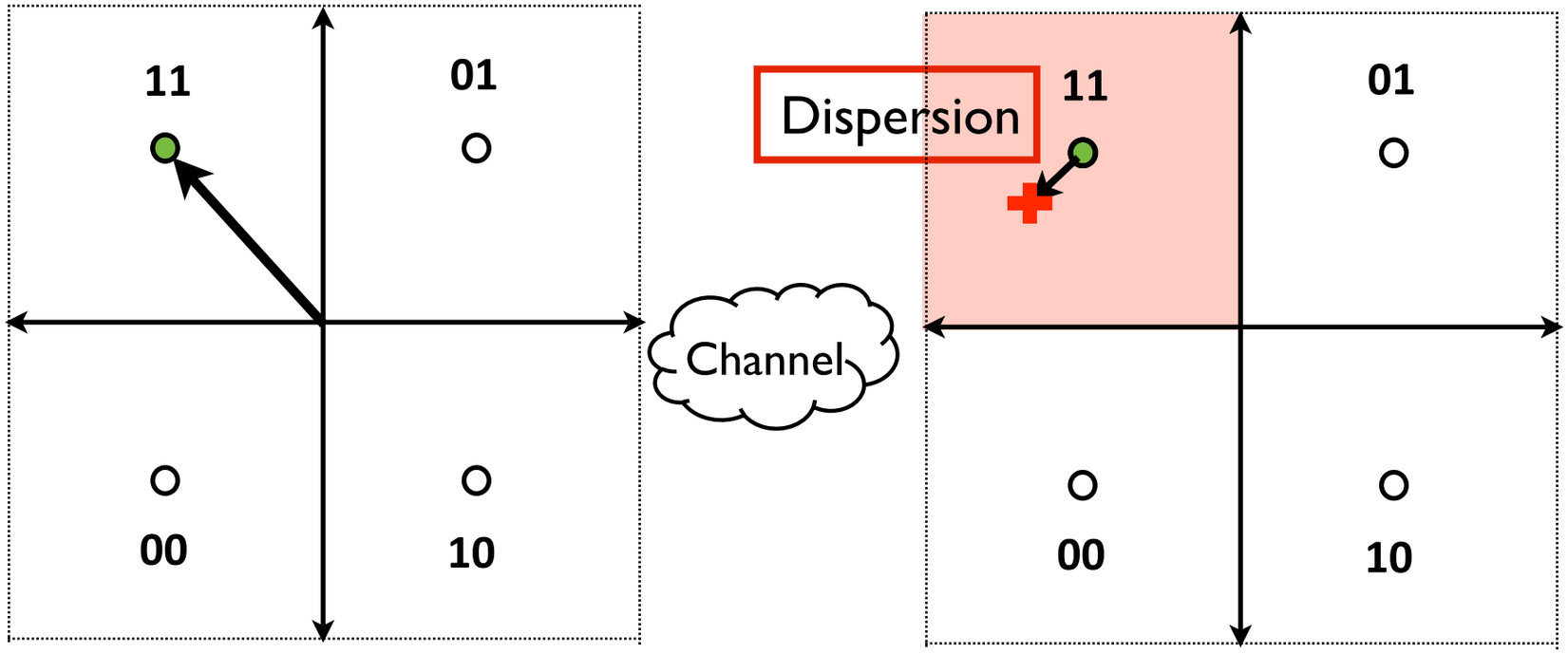
Tx 16QAM Symbol

Rx 16QAM Symbol

Different Modulations in 802.11

Data = 01|11|1001 ....

2 bits together

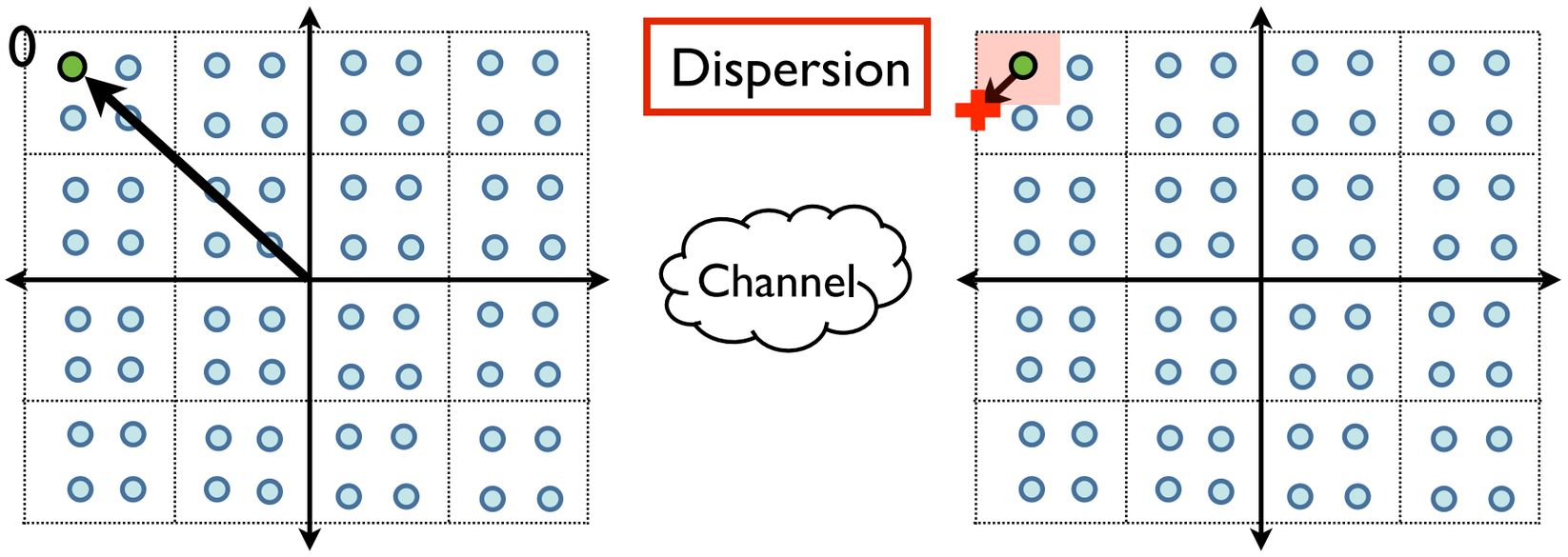


Tx 4QAM Symbol

Rx 4QAM Symbol

Data = 01111001 ....

6 bits together



Tx 64QAM Symbol

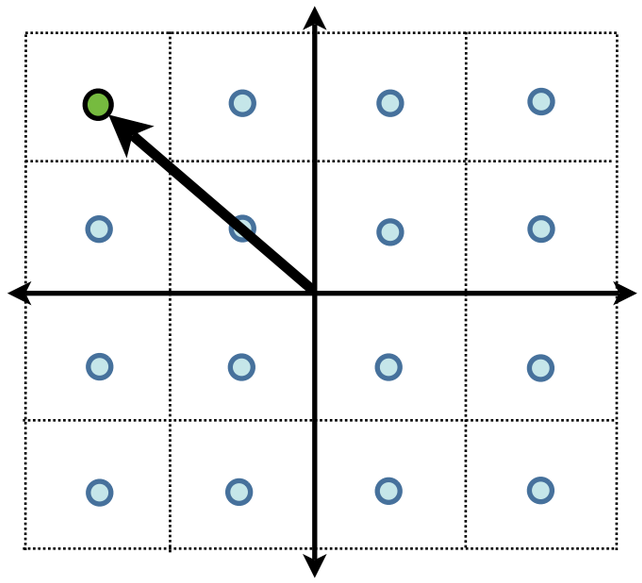
Rx 64QAM Symbol

Why not always transmit many bits per symbol?

e.g., 64QAM or 54Mbps

Weak Channel Induces Errors

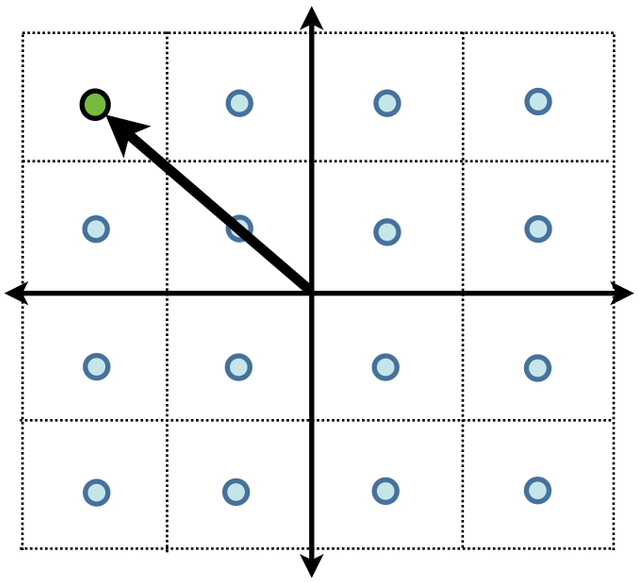
Data = 01111001 ....



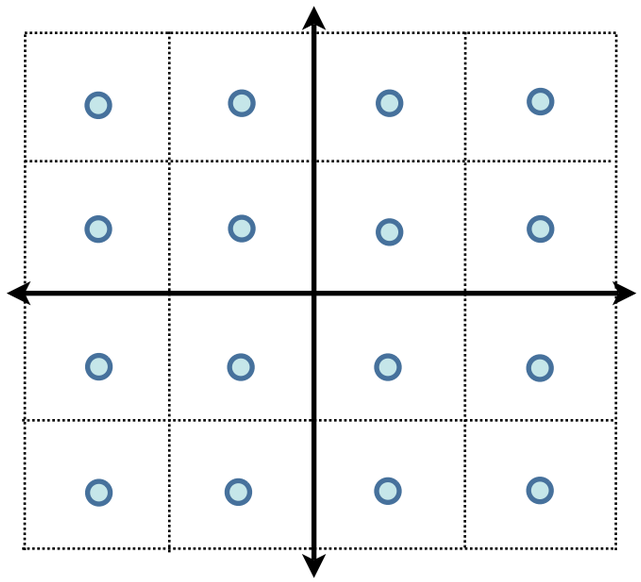
Tx 16QAM Symbol

Weak Channel Induces Errors

Data = 01111001 ....

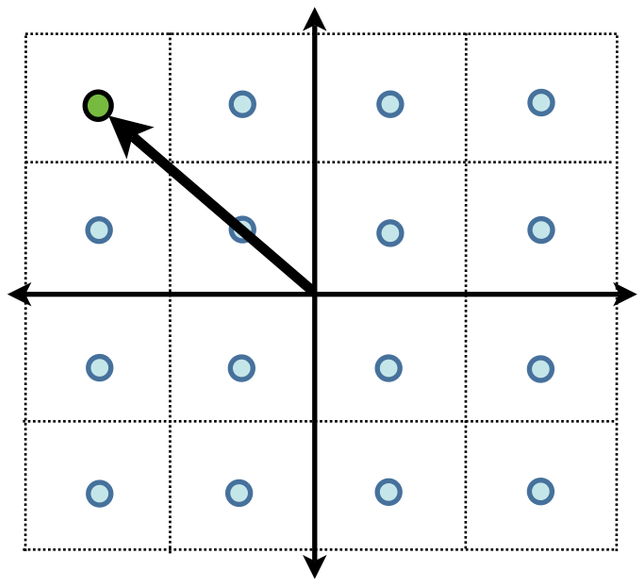


Tx 16QAM Symbol



Weak Channel Induces Errors

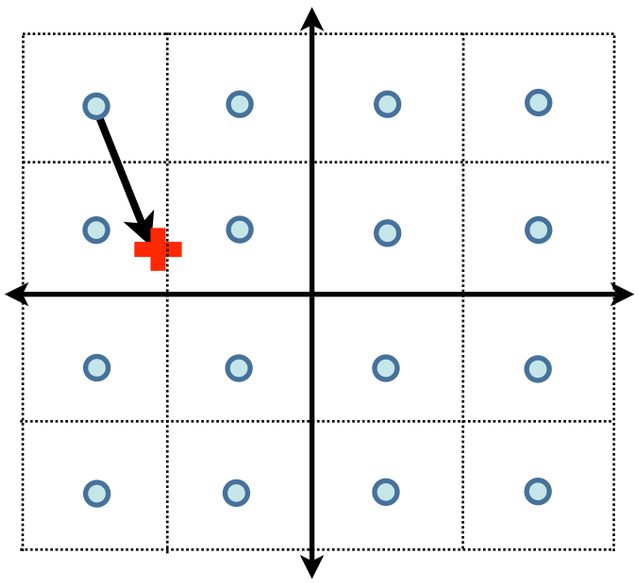
Data = 0111 1001 ....



Tx 16QAM Symbol

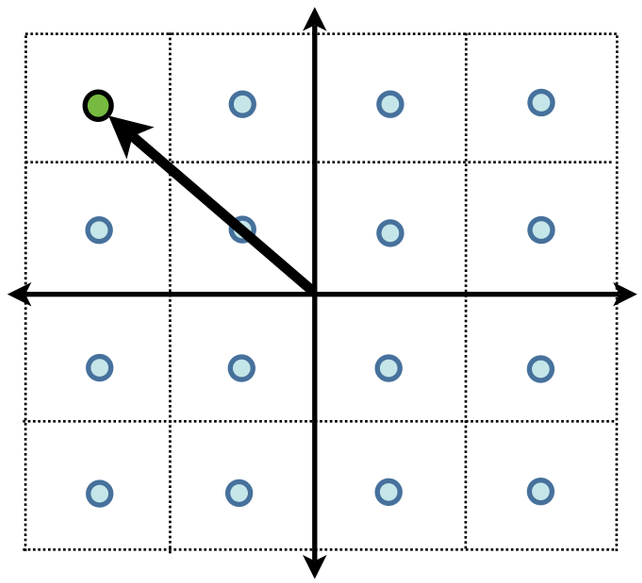
High Dispersion

Weak Channel



Weak Channel Induces Errors

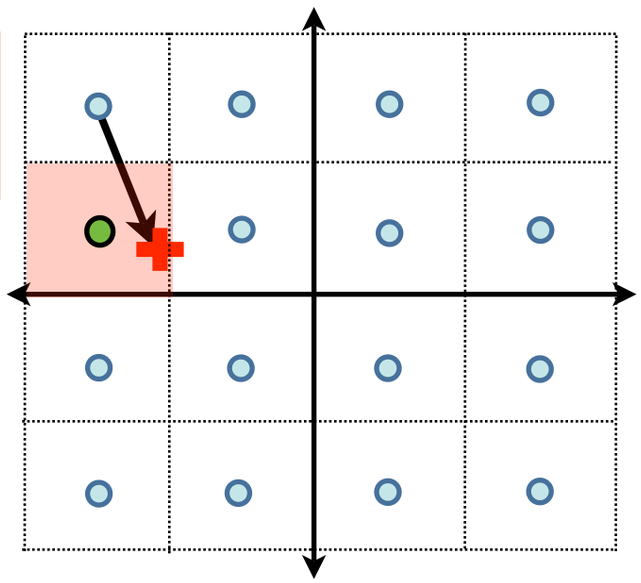
Data = 0111 1001 ....



Tx 16QAM Symbol

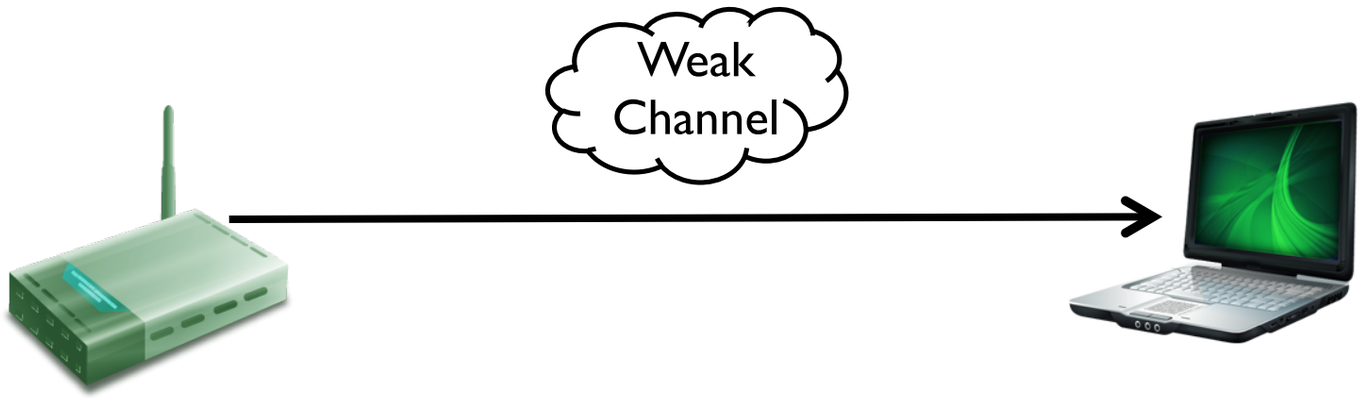
High Dispersion

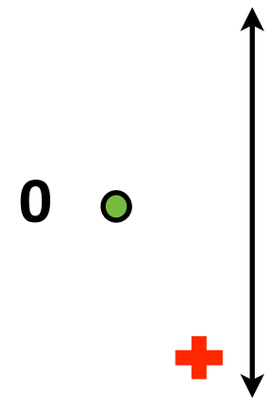
Weak Channel

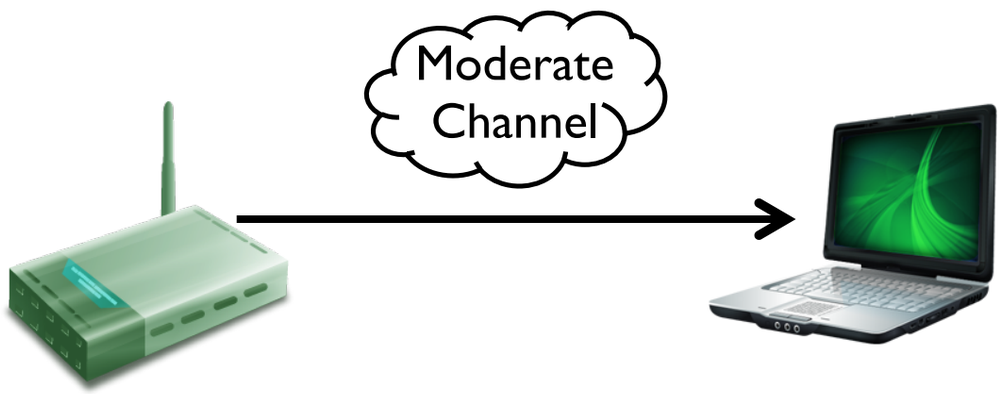


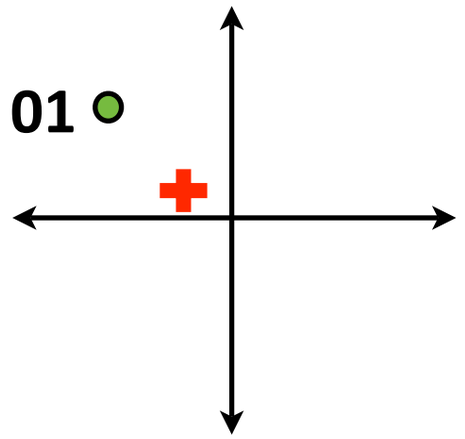
Wrongly demodulated symbol

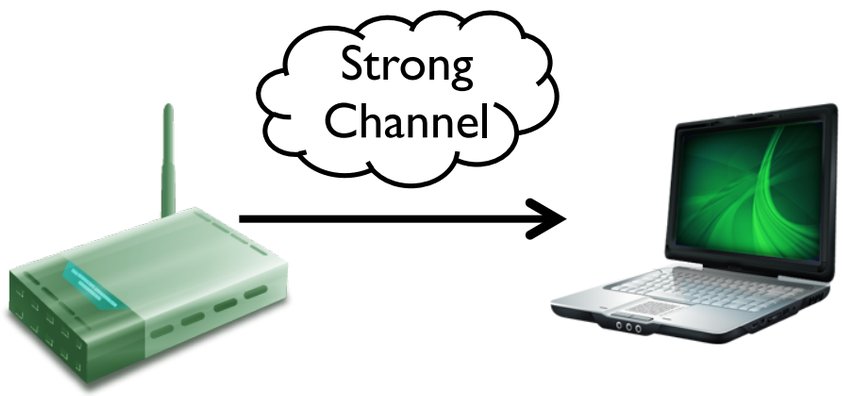
In General ...

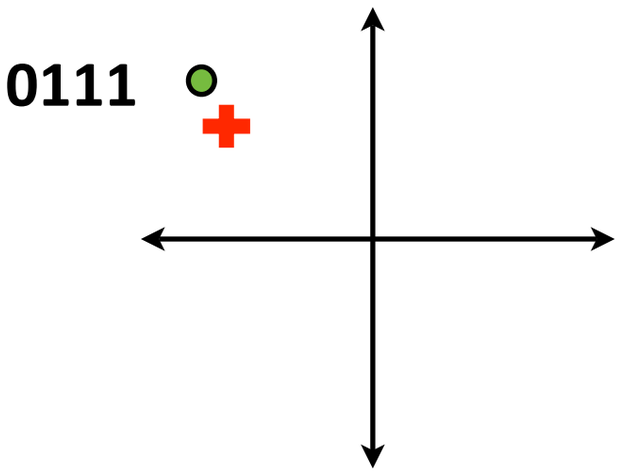




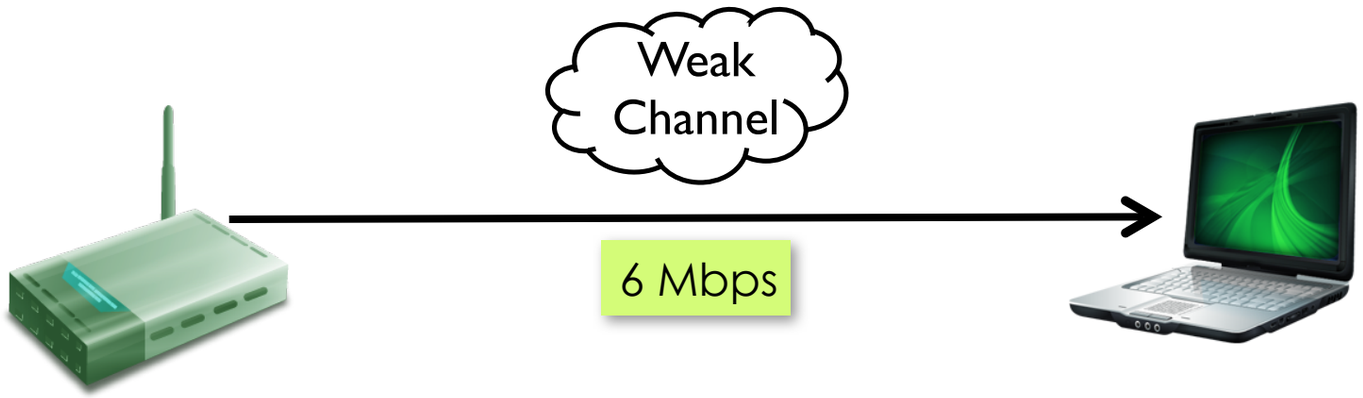


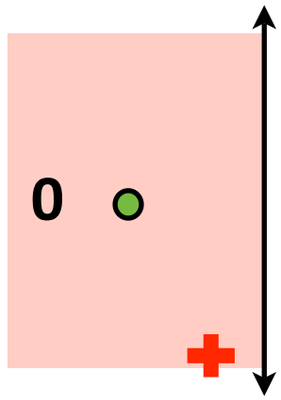


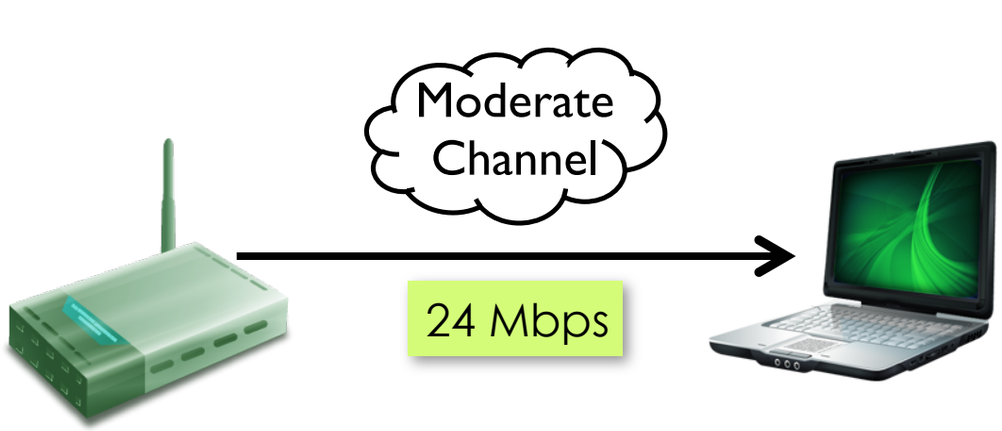


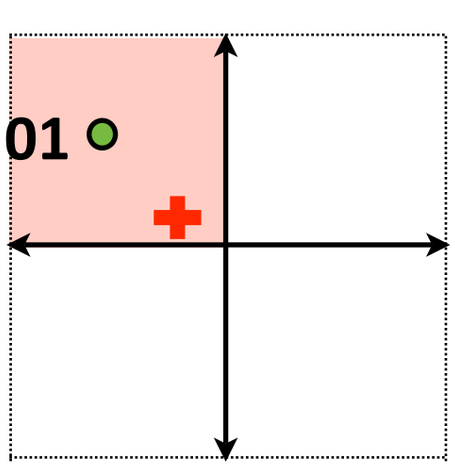


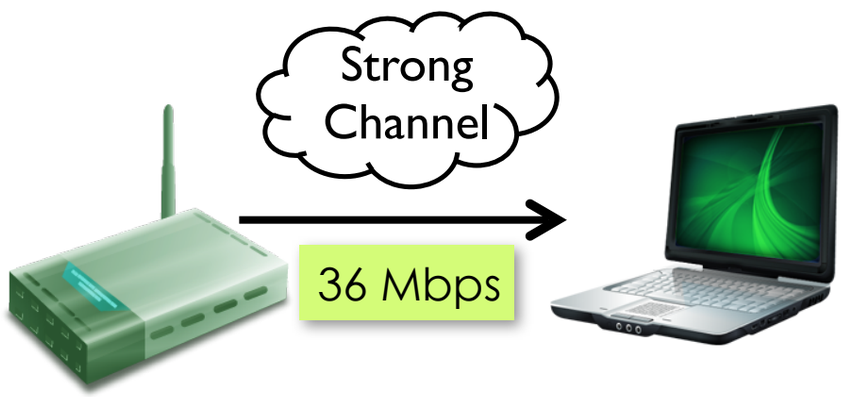
In General ...

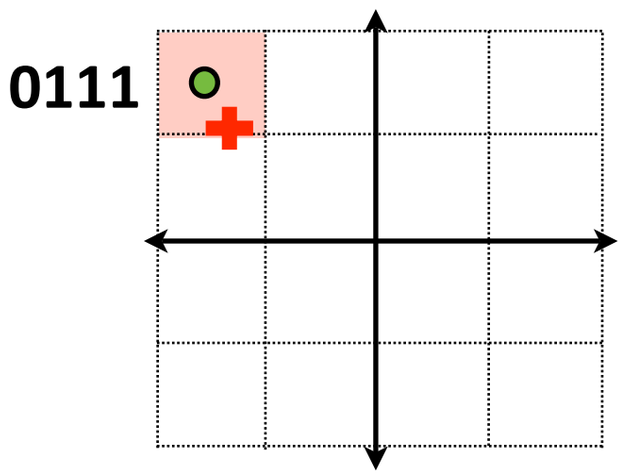

Weak
Channel
6 Mbps


0

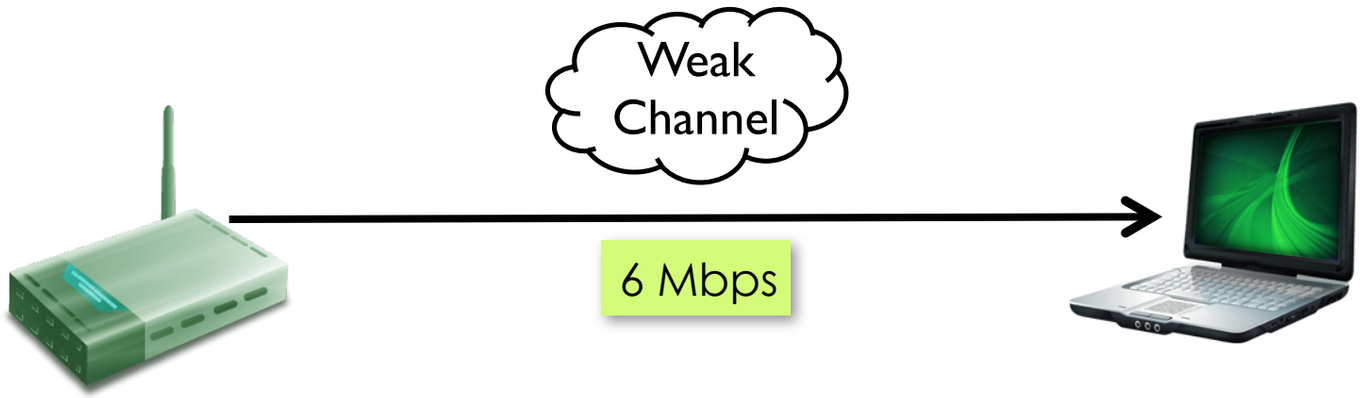

Moderate
Channel
24 Mbps

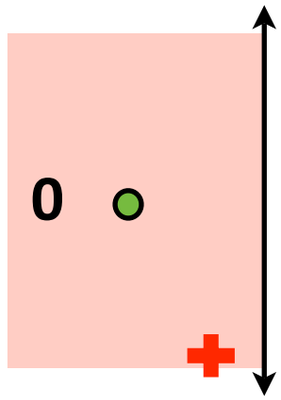

01

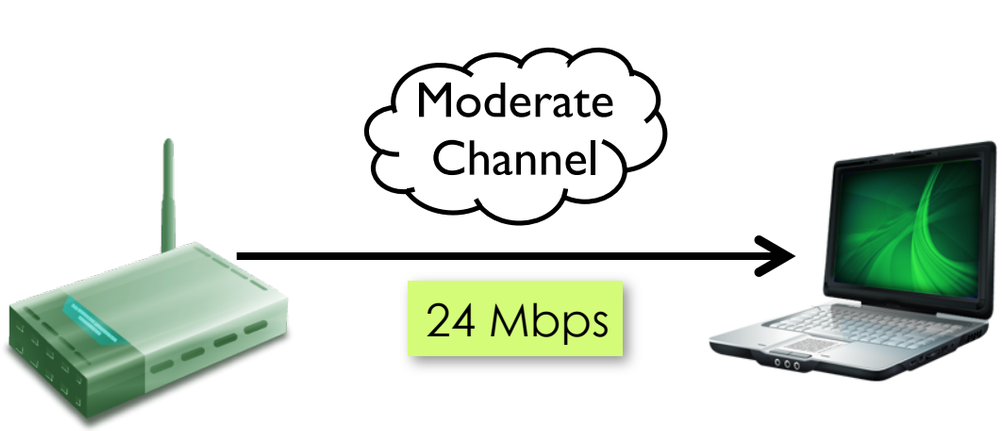

Strong
Channel
36 Mbps

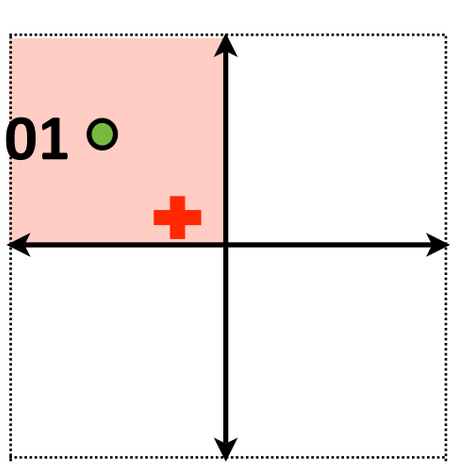

0111

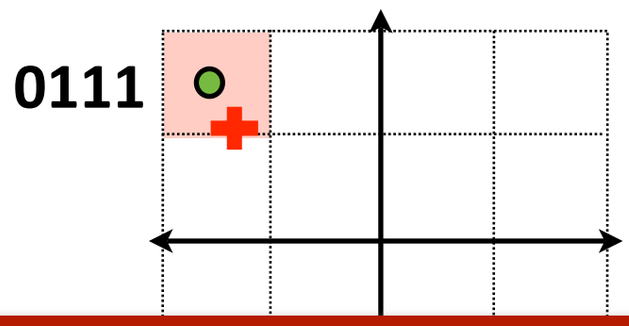
In General ...











Smaller dispersion permits higher rate

AccuRate

Design and Implementation

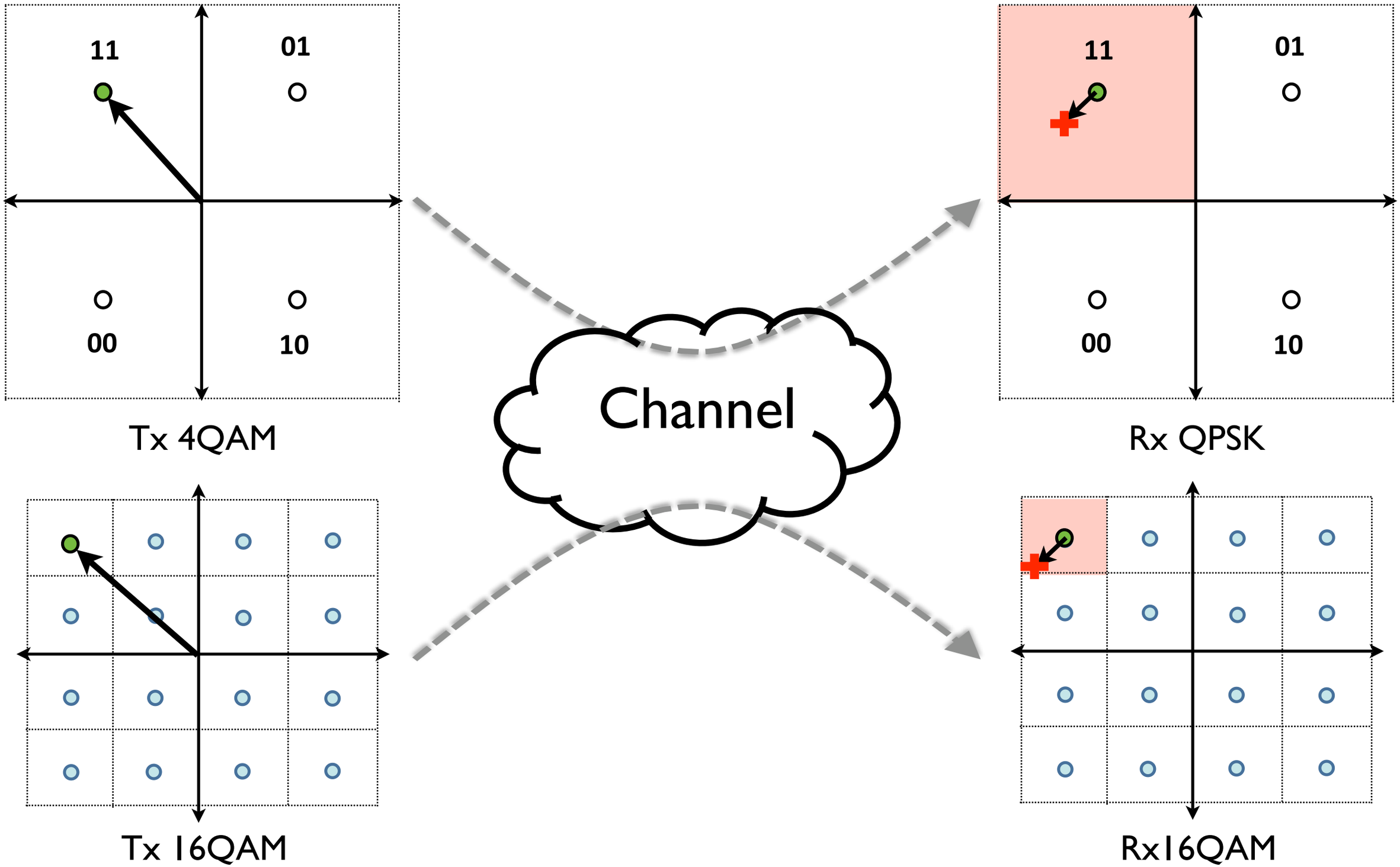
AccuRate

Design and Implementation

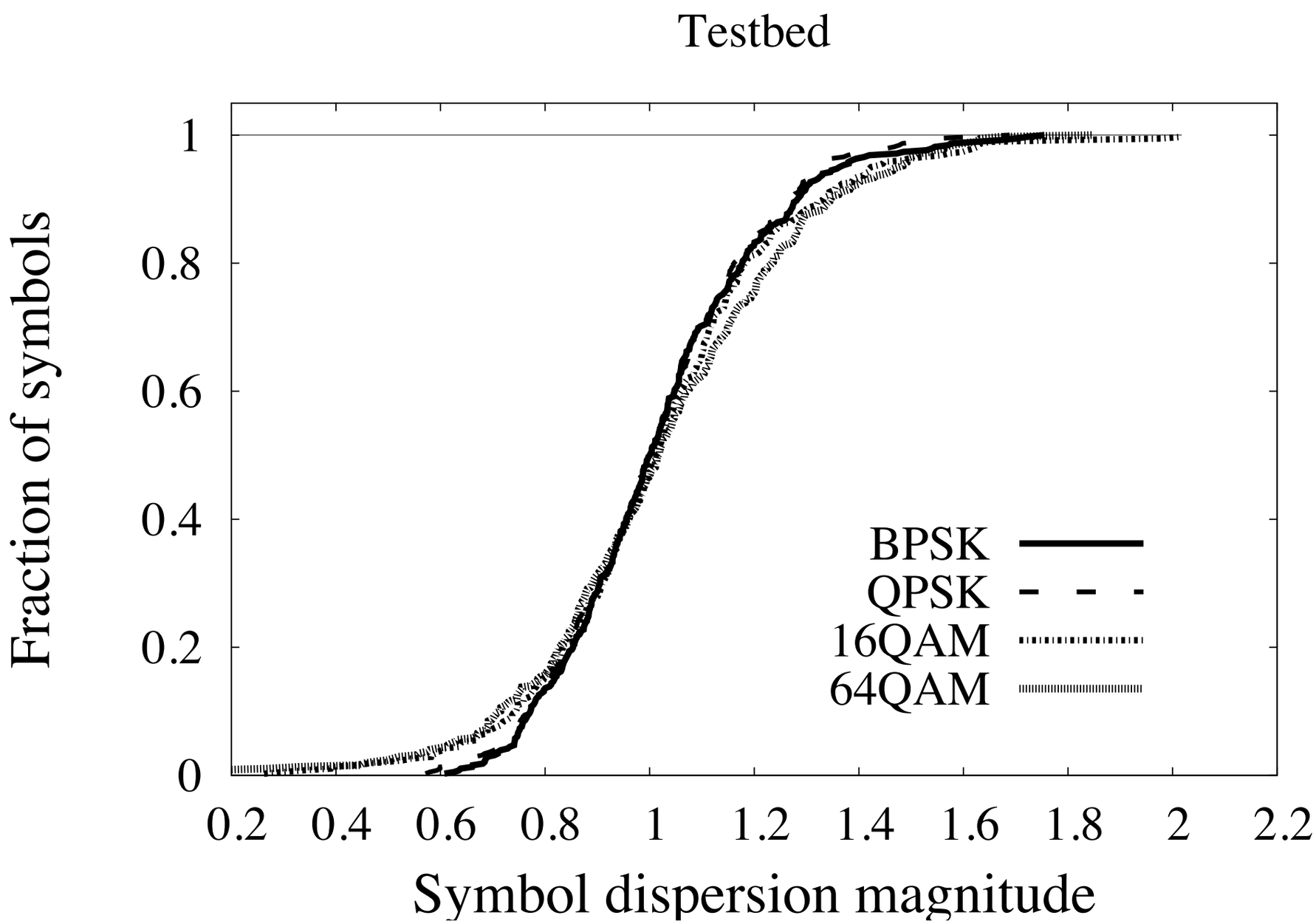
Hypothesis:

Symbol dispersion is independent of modulation

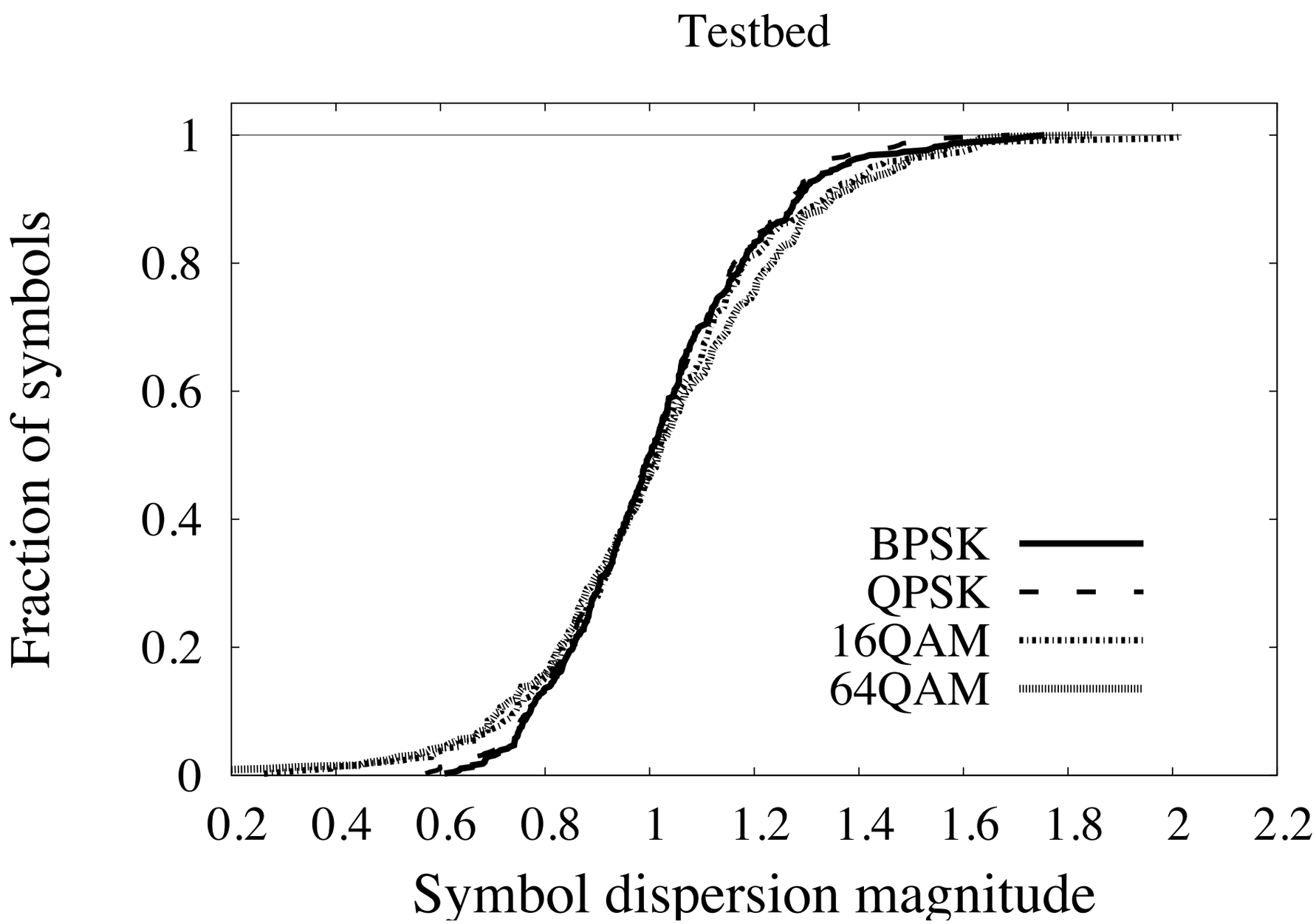
Dispersion Independent of Modulation?



Dispersion Independent of Modulation?



Dispersion Independent of Modulation?

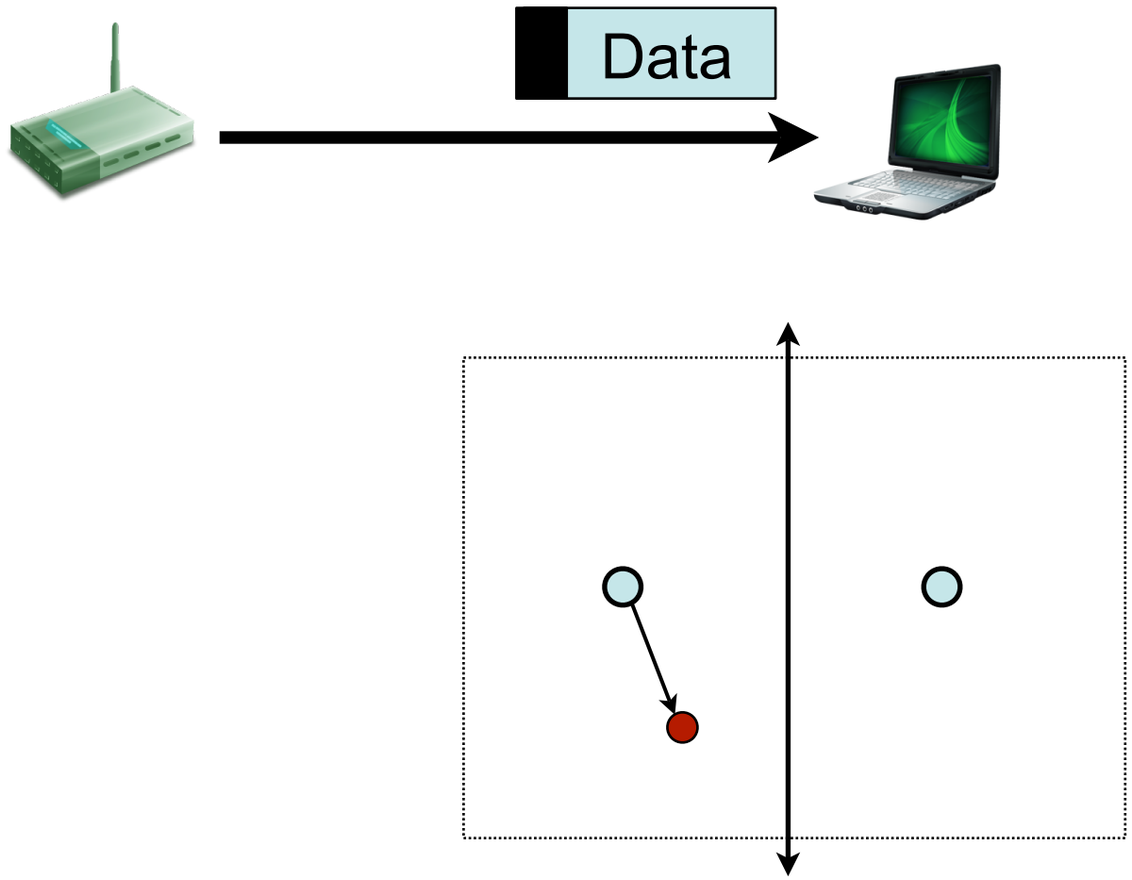


McKinley et. al., 2004, "EVM calculation for broadband modulated signals"

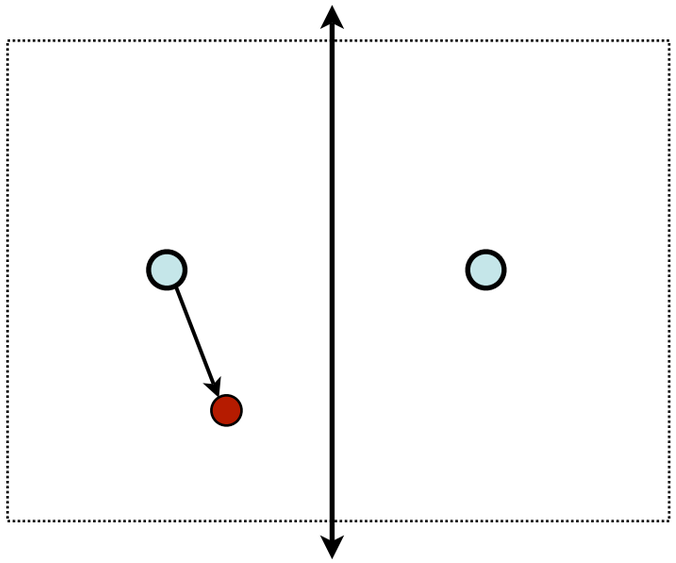
Hypothesis:

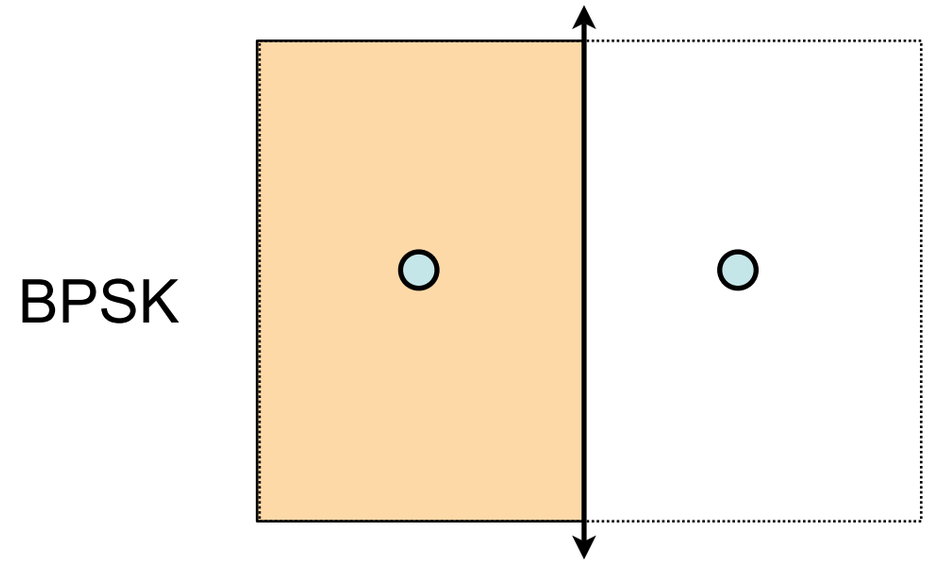
Symbol dispersion is independent of modulation

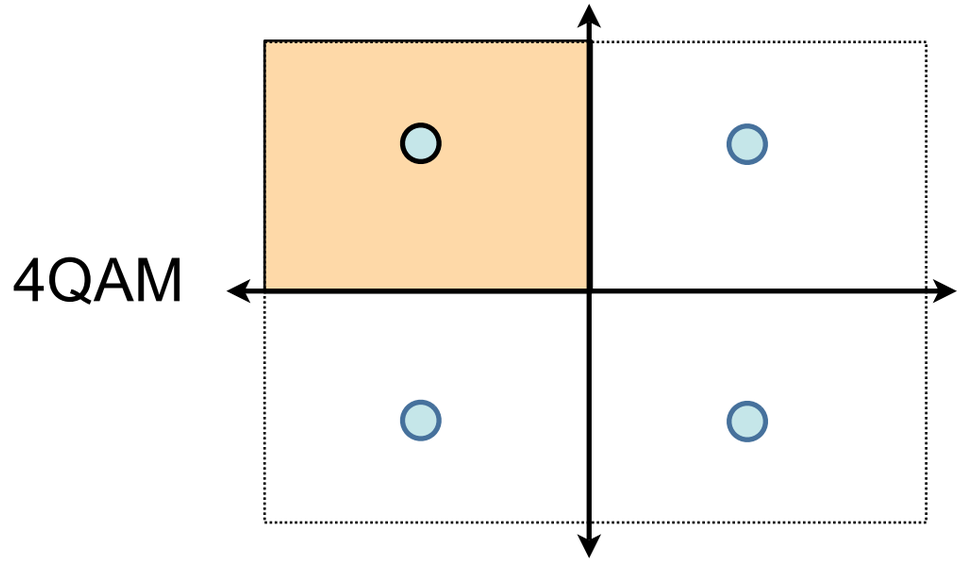
Selection of optimal modulation

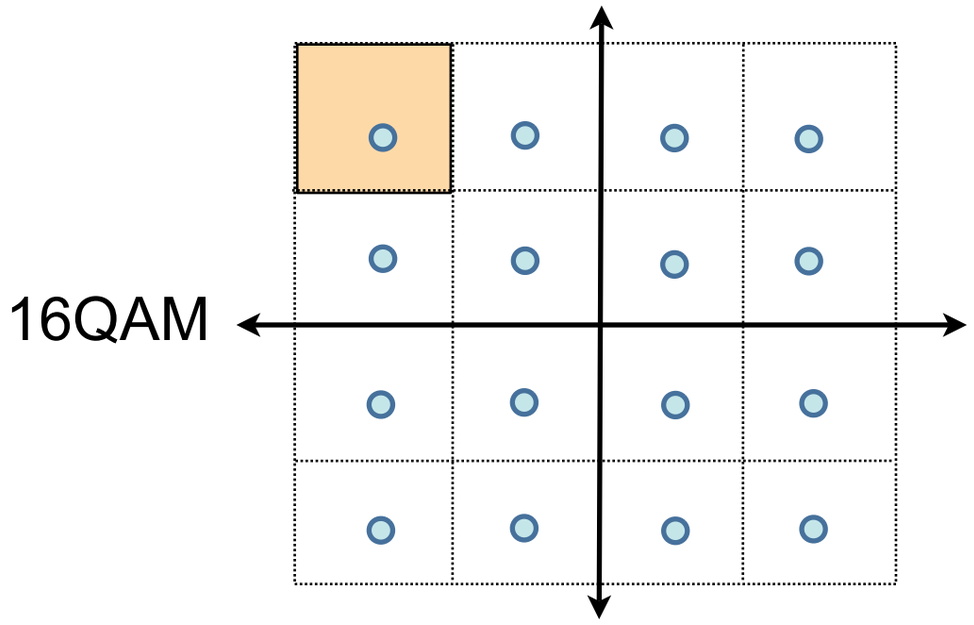

Data


Data

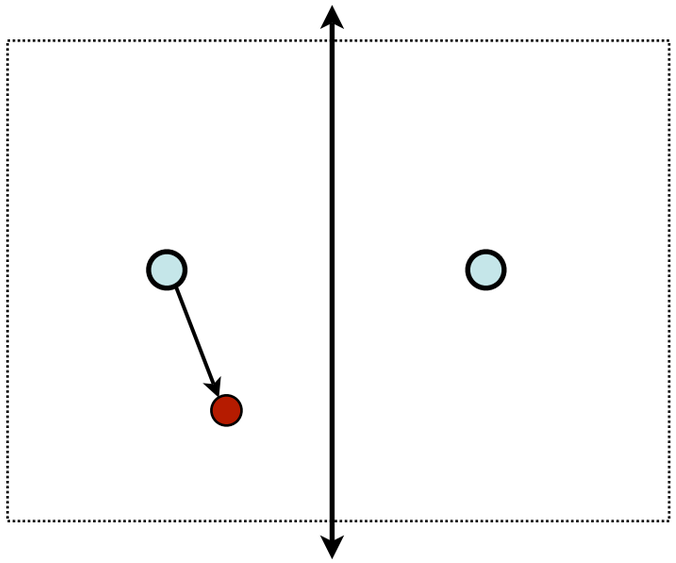


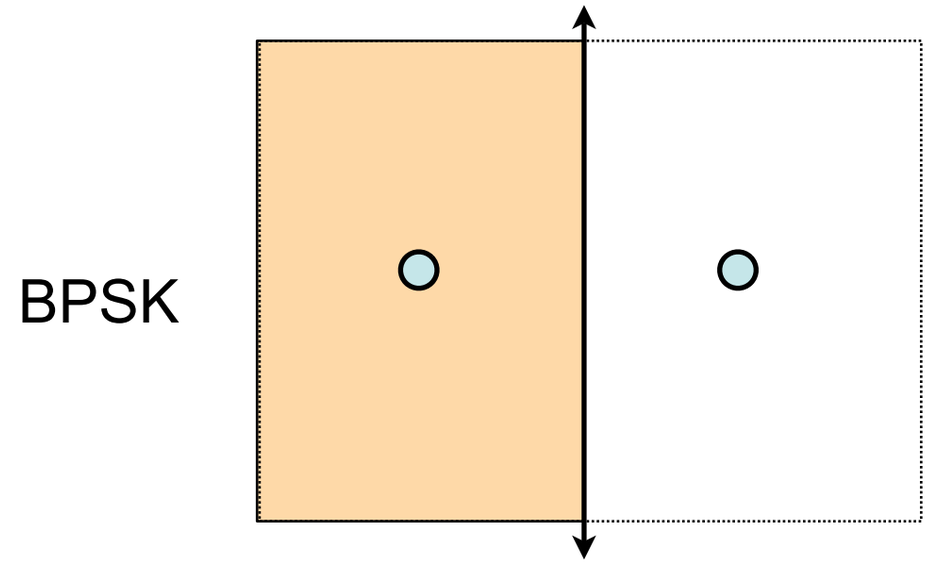

BPSK

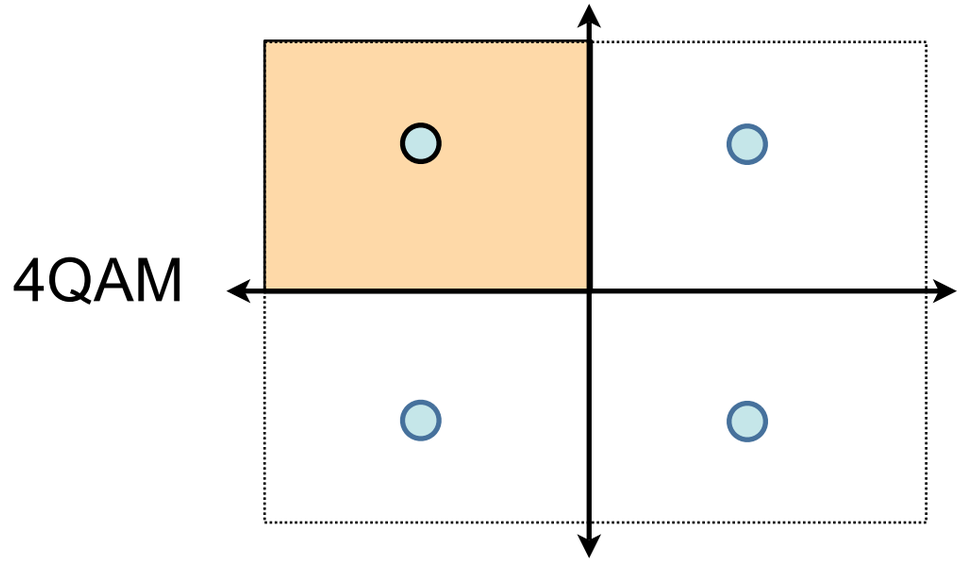

4QAM

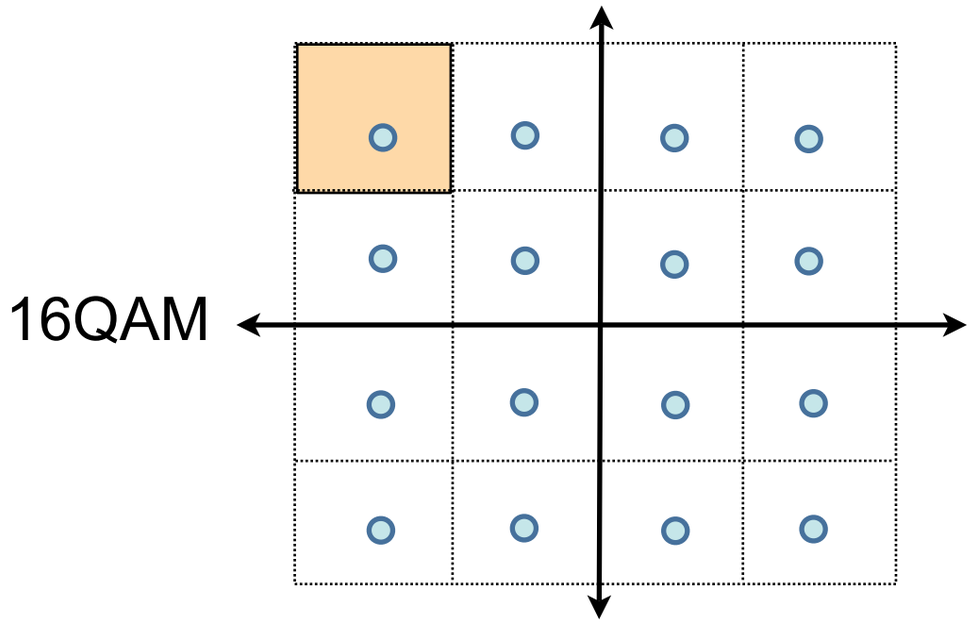

16QAM

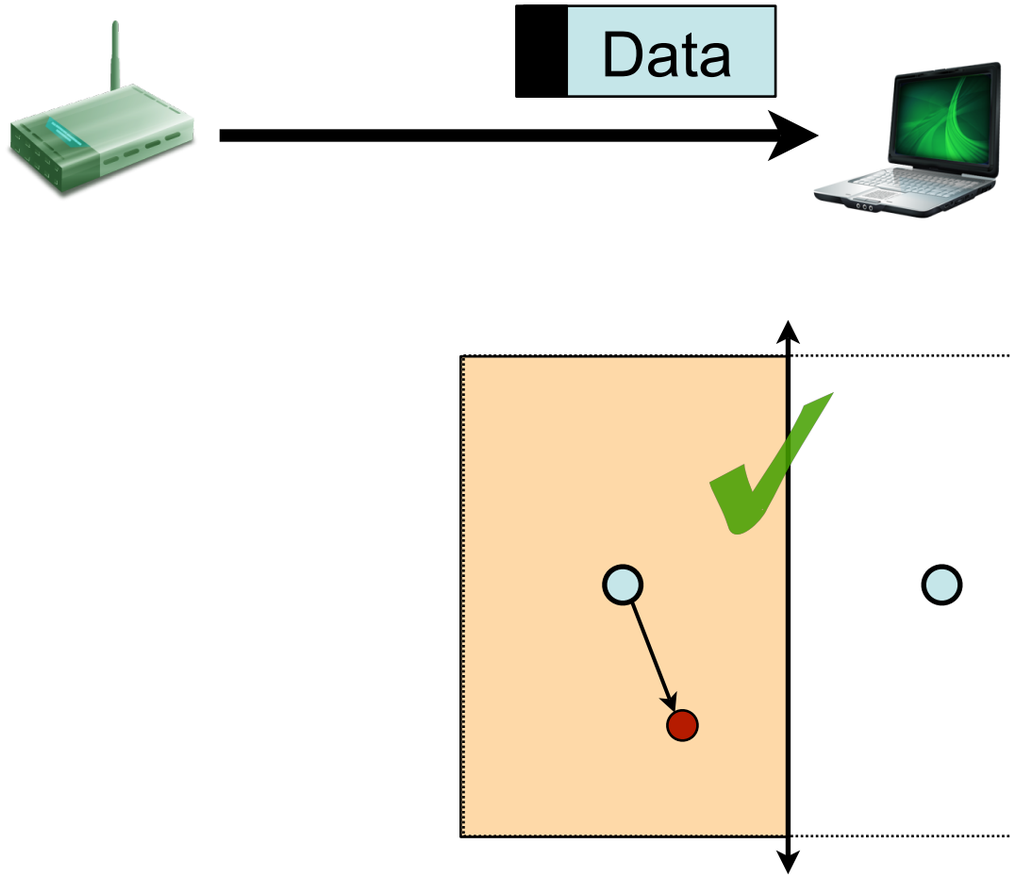

Data

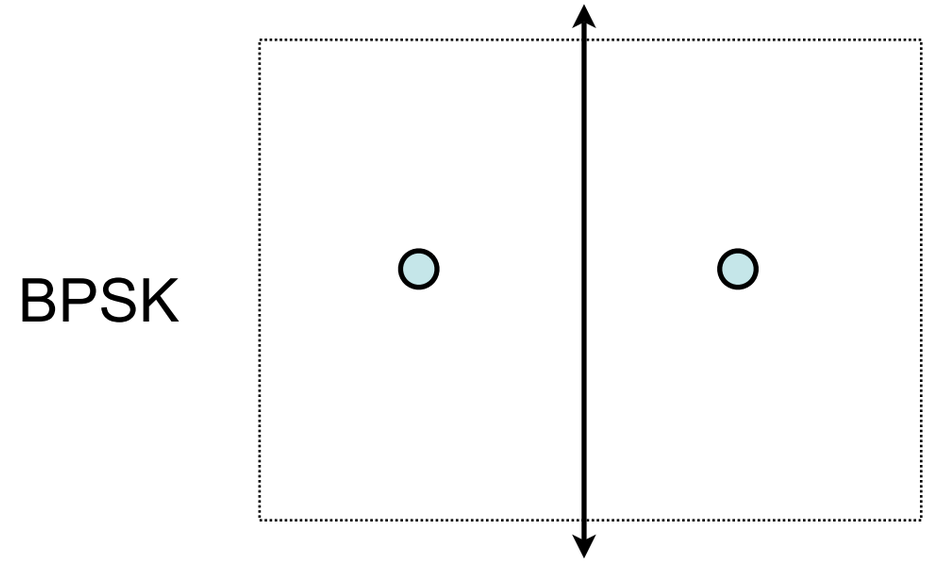


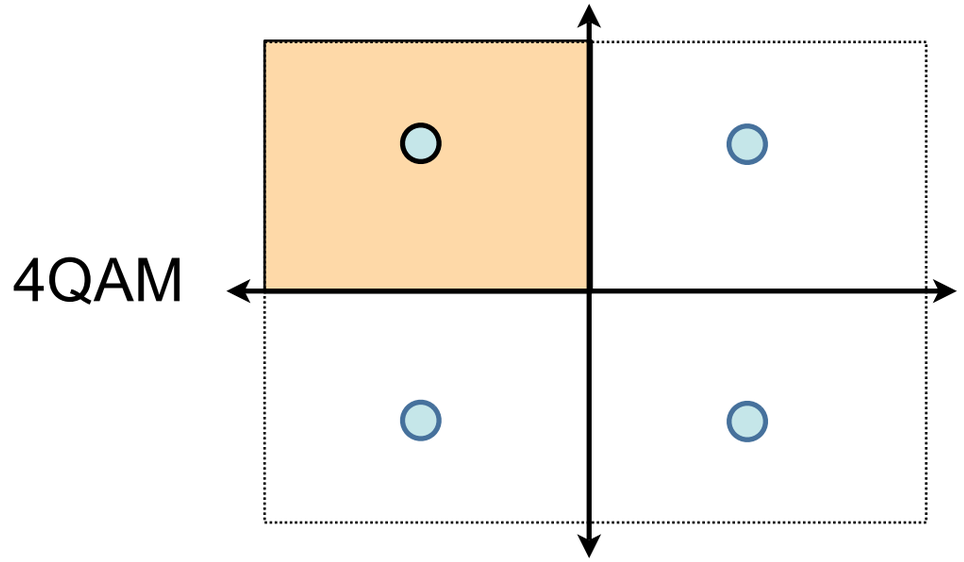

BPSK

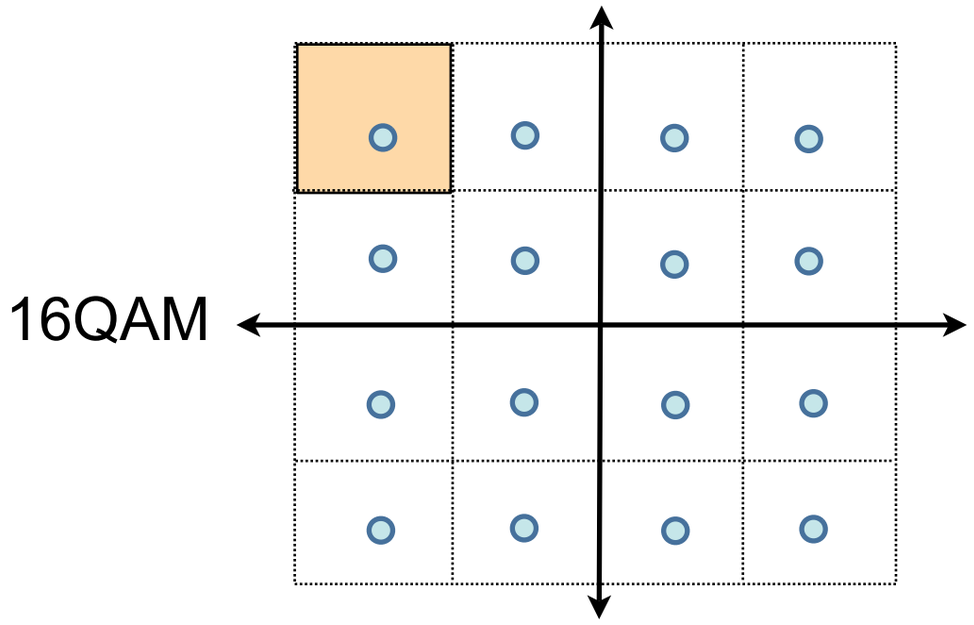

4QAM


16QAM

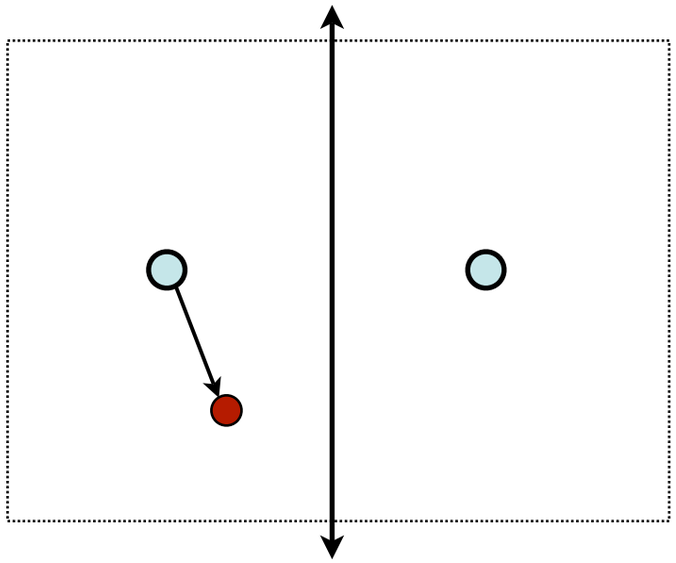

Data

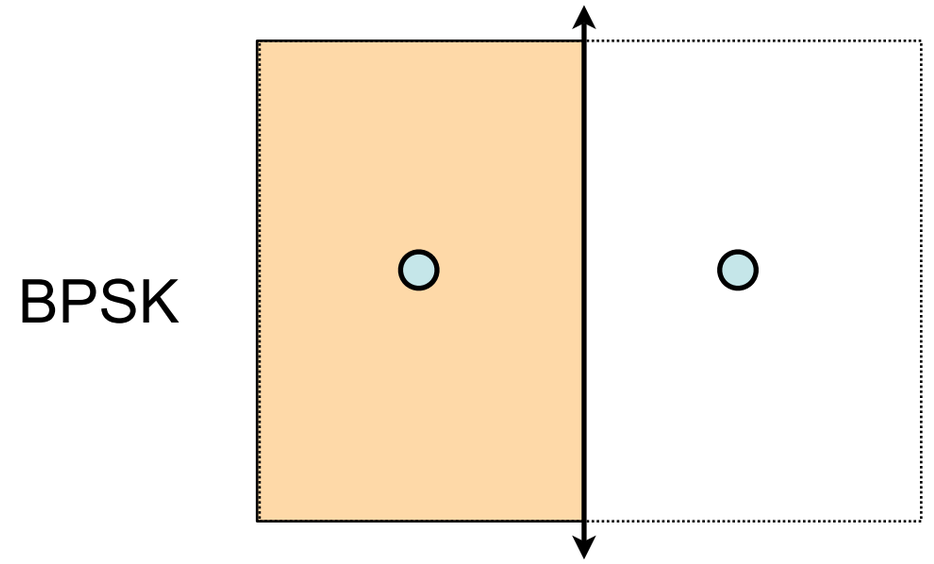

BPSK

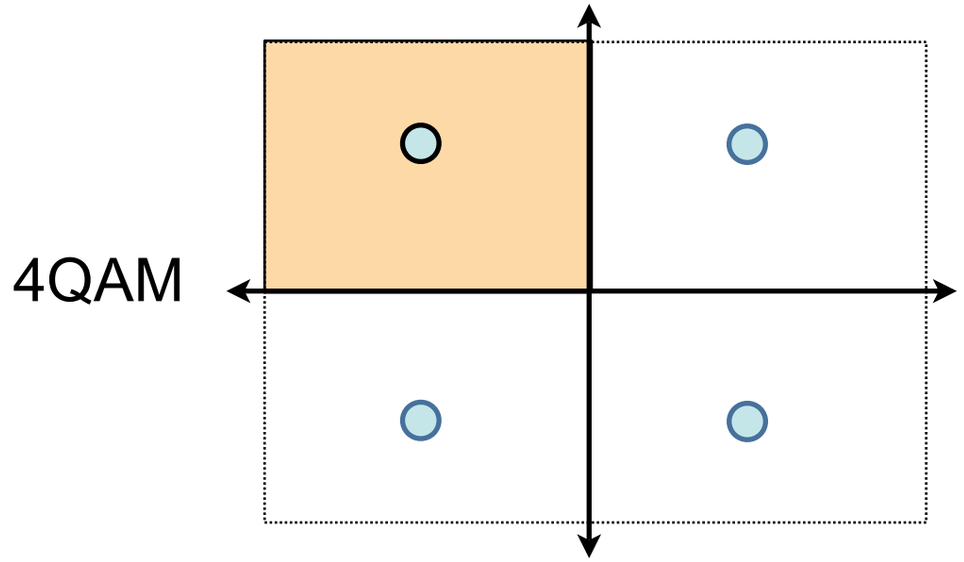

4QAM

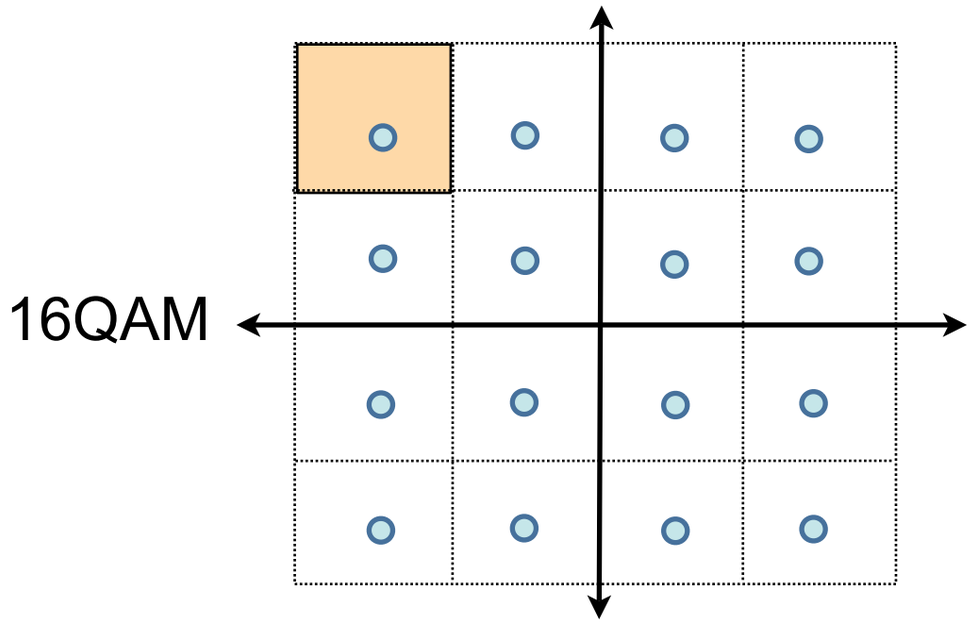

16QAM


Data

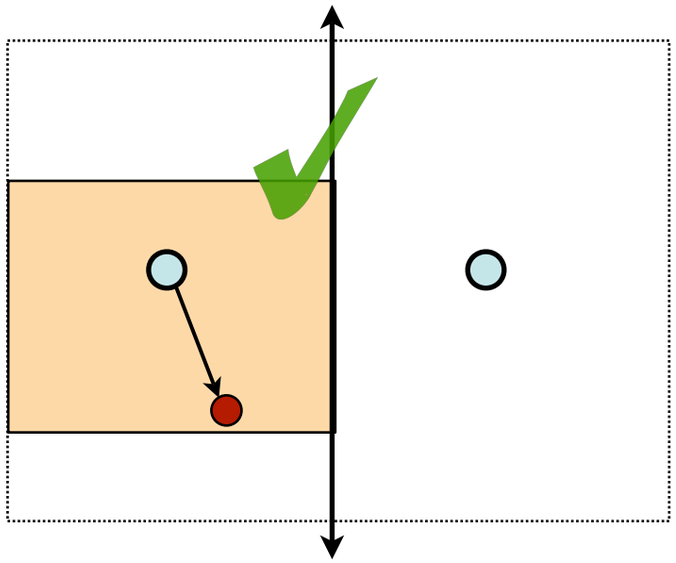


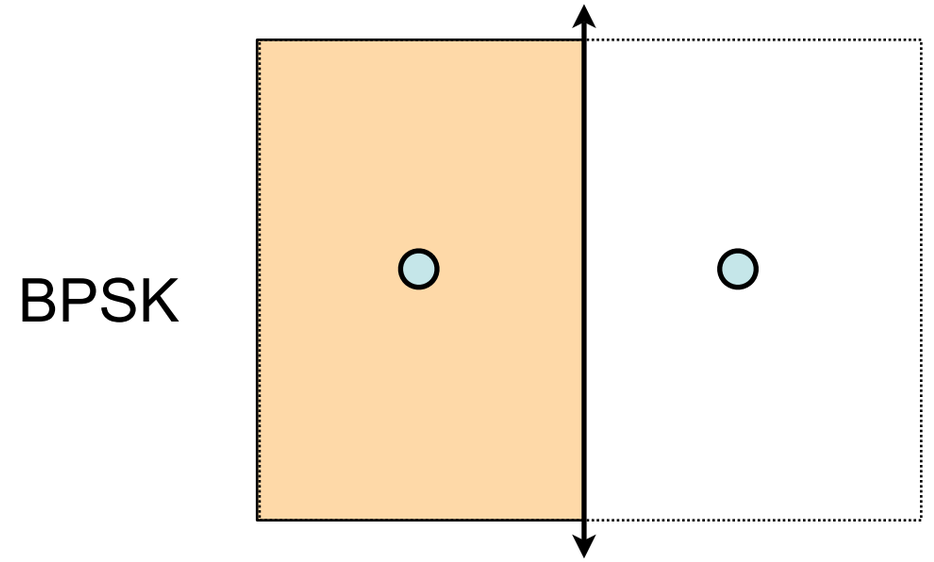

BPSK

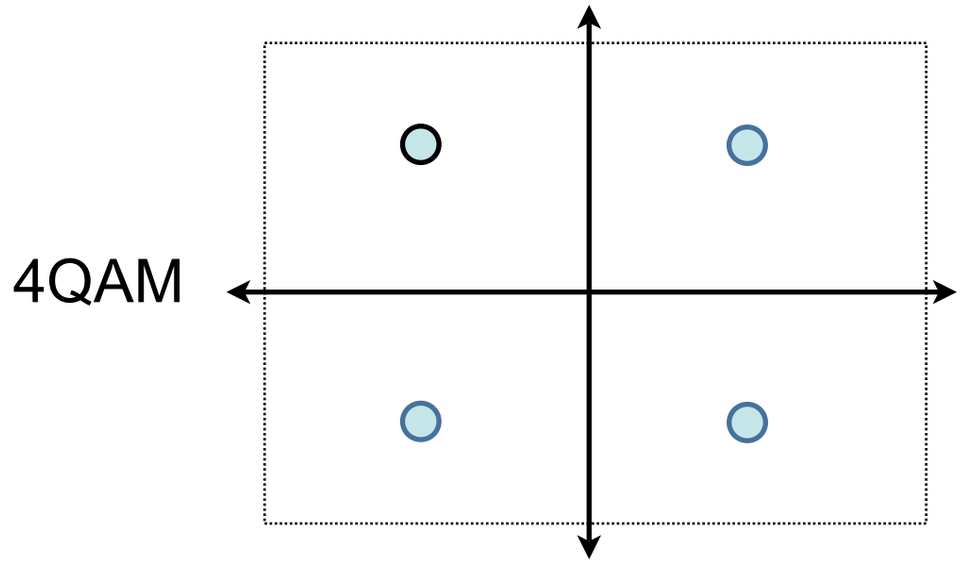

4QAM

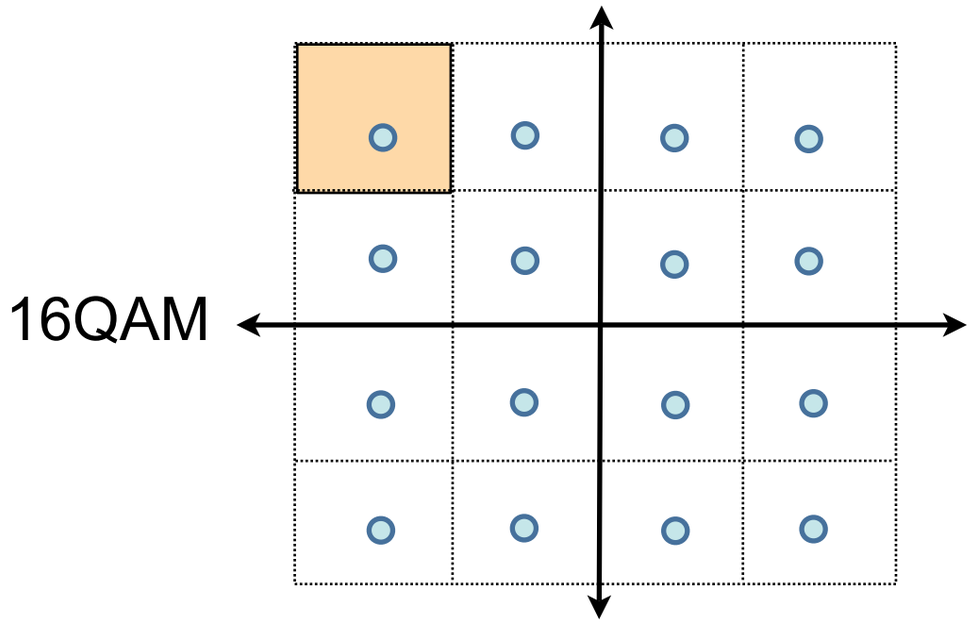

16QAM


Data

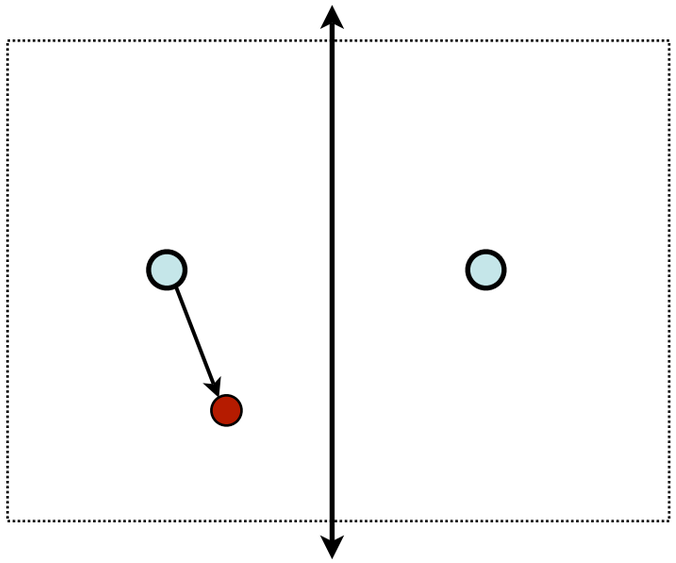


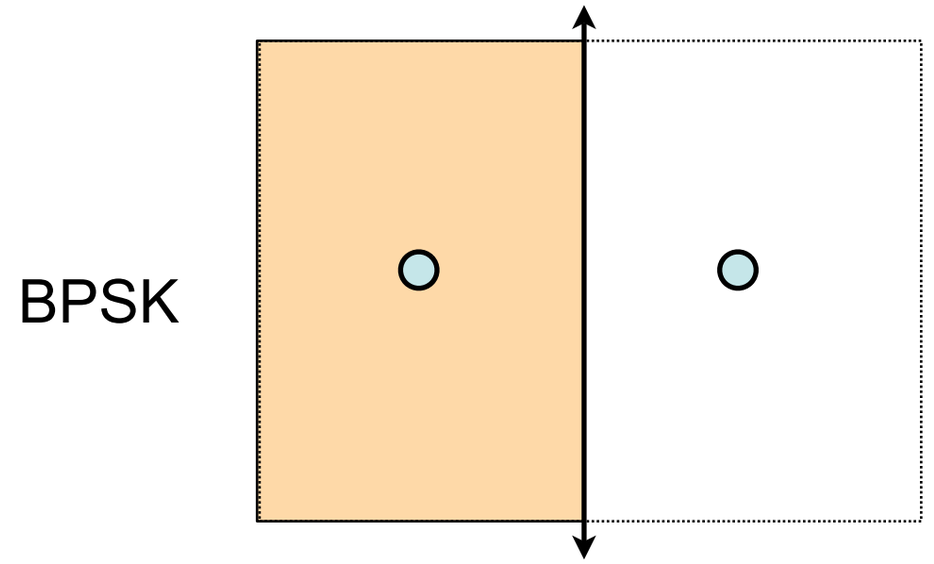

BPSK

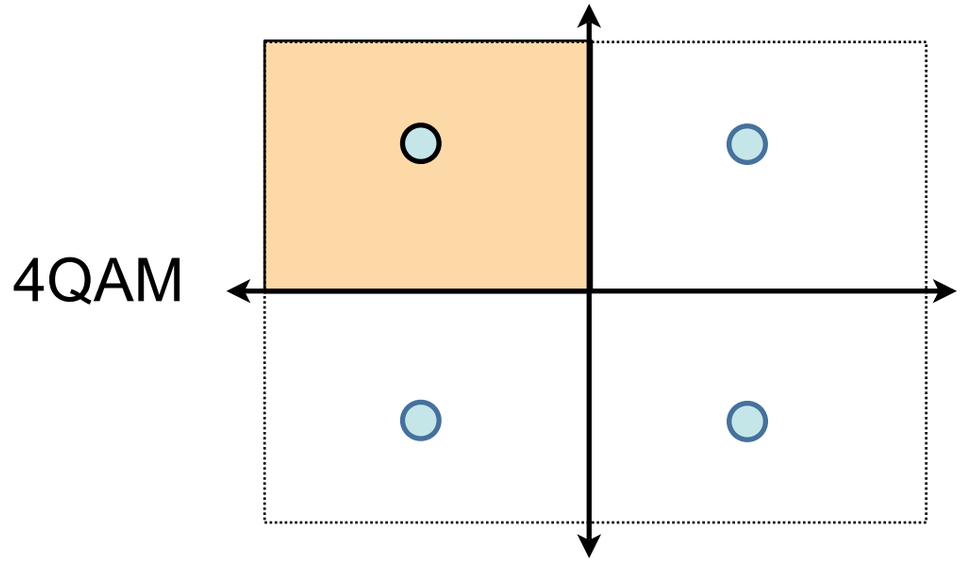

4QAM

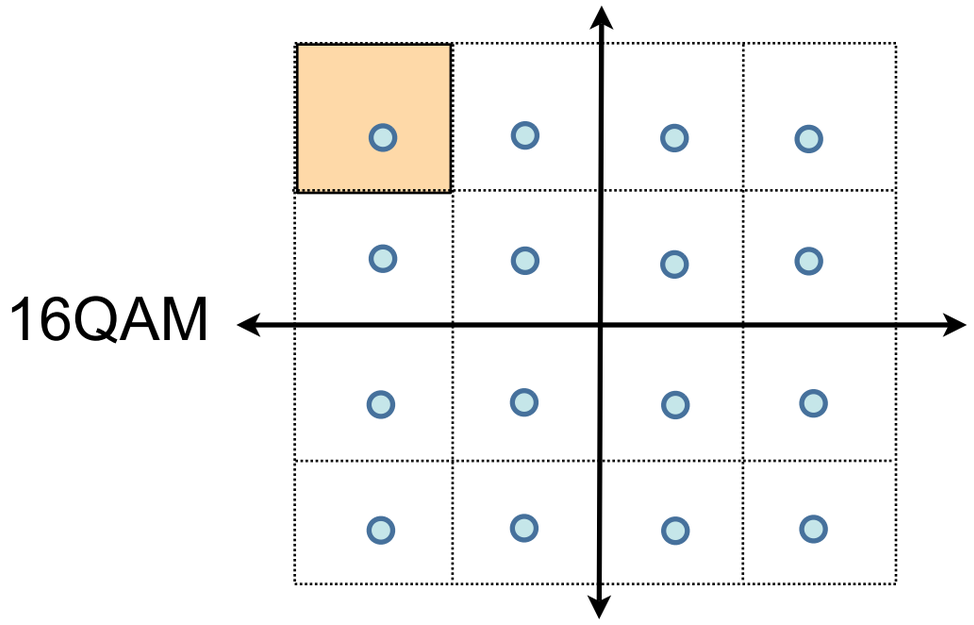

16QAM

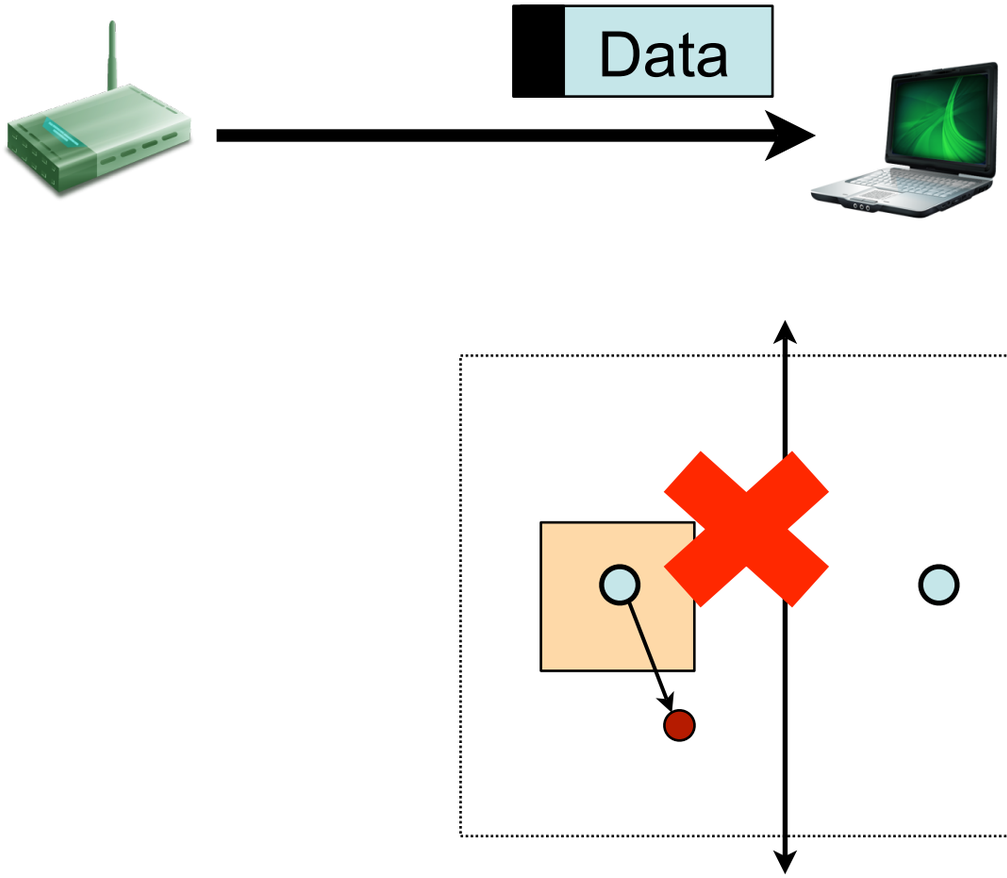

Data

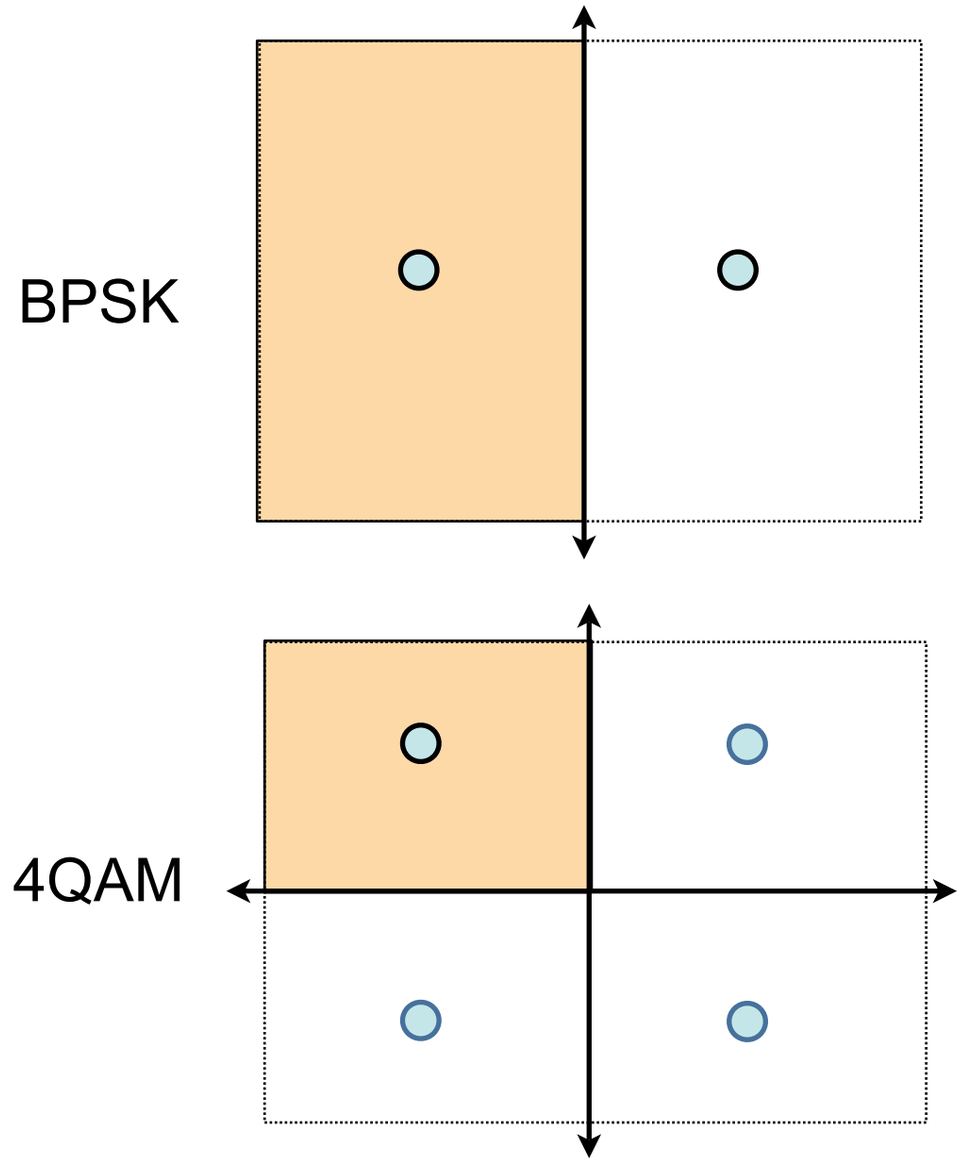



BPSK

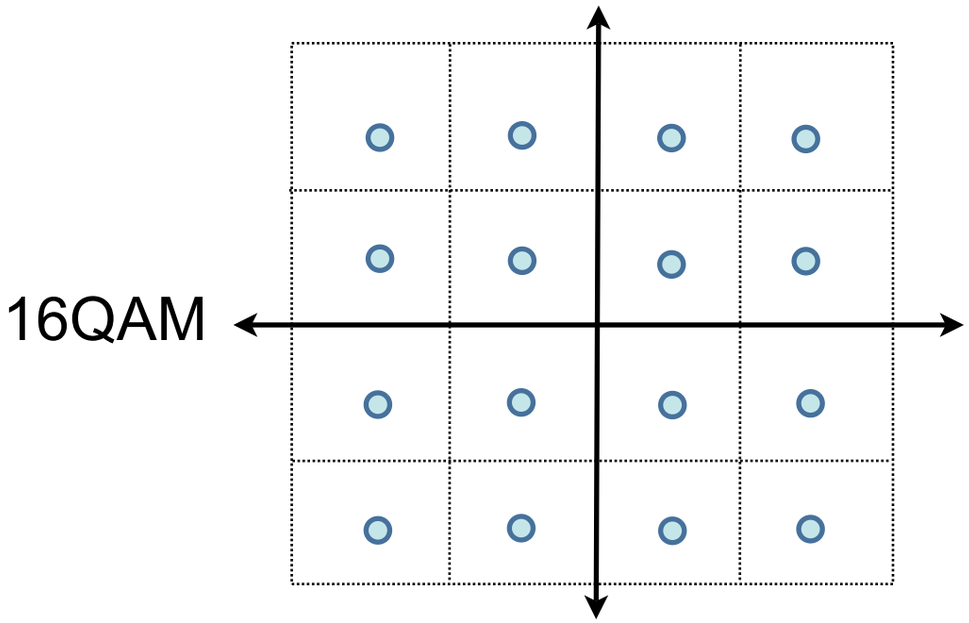

4QAM

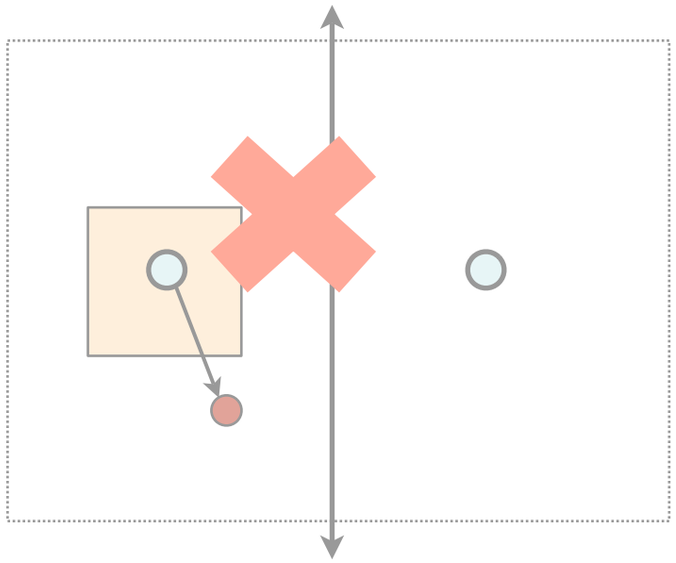

16QAM

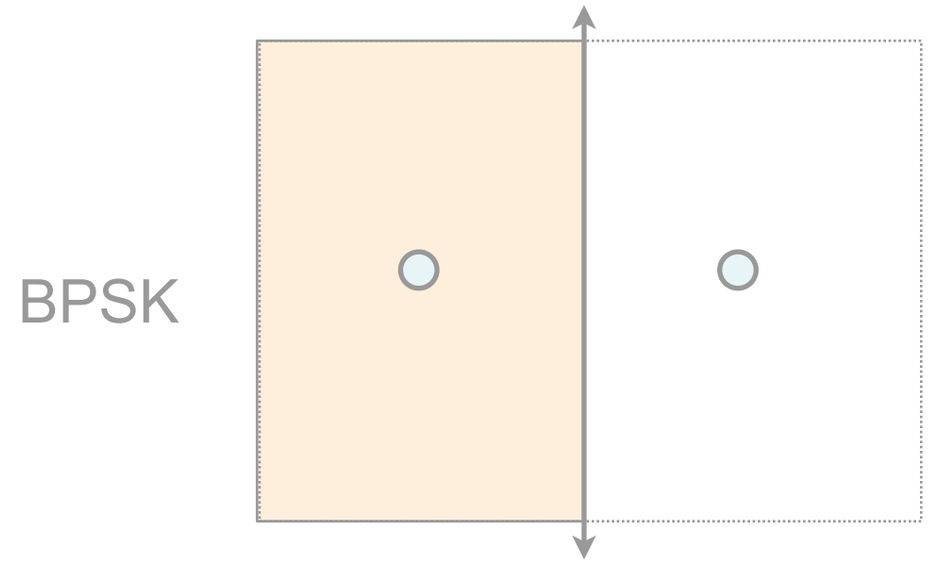

Data

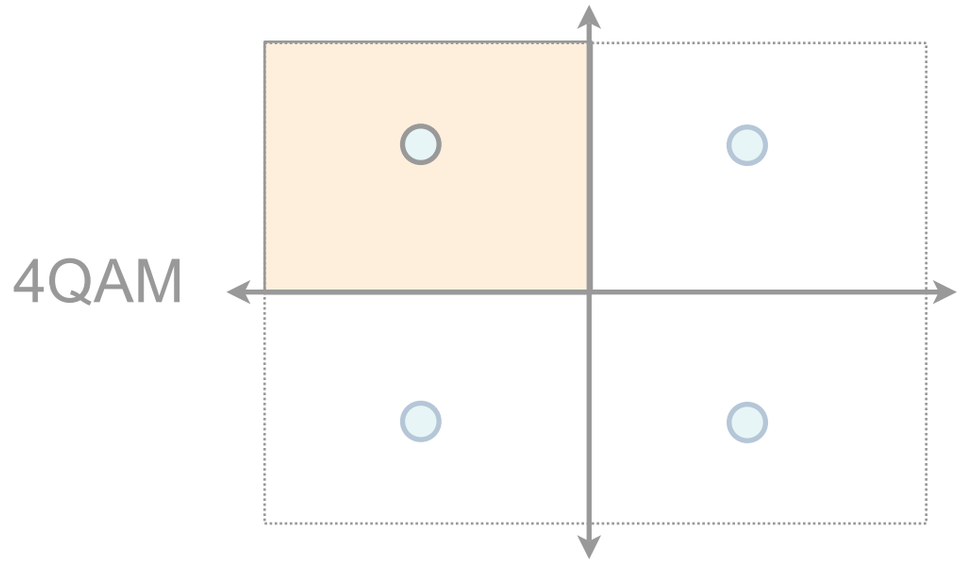

BPSK

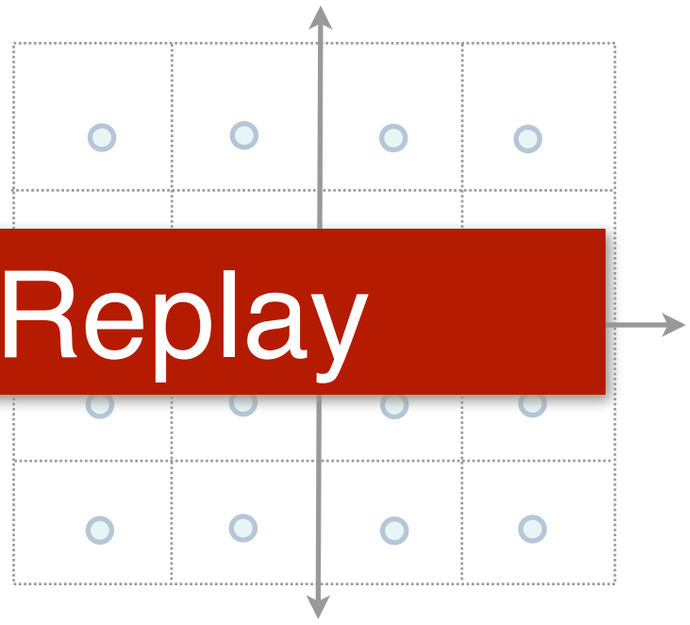
4QAM


16QAM





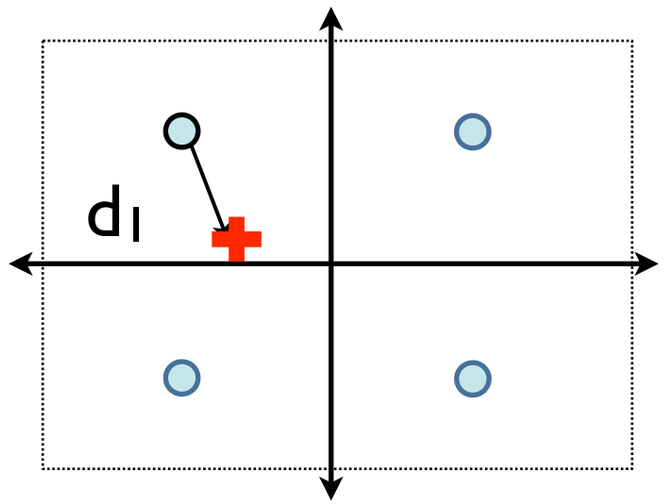




We call it Virtual Channel Replay

Channel Replay Vector

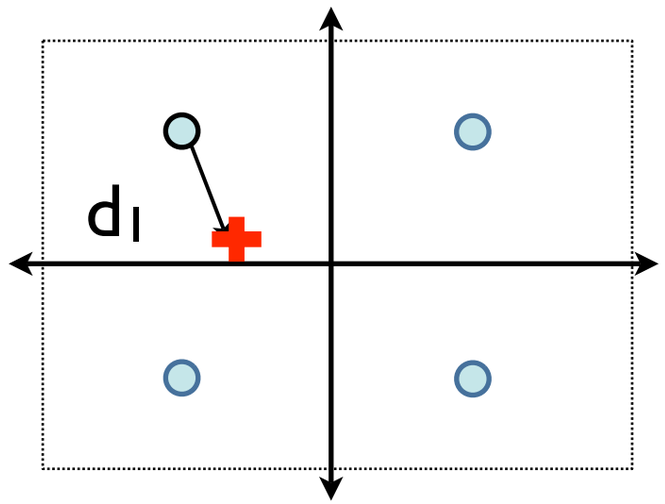
- AccuRate records dispersion for every symbol in a packet
  - Creates a vector: **Channel Replay Vector (V)**



$$V = \{d_1, d_2, ..., d_n\}$$

Channel Replay Vector

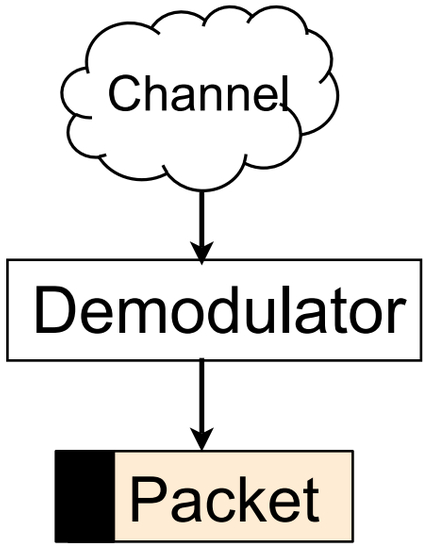
- AccuRate records dispersion for every symbol in a packet
  - Creates a vector: **Channel Replay Vector (V)**



$$V = \{d_1, d_2, ..., d_n\}$$

- When packet succeeds
  - All dispersions are known
- When packet fails
  - Approximates V from (known) preamble/postamble

Receiver



Receiver

Channel

Demodulator

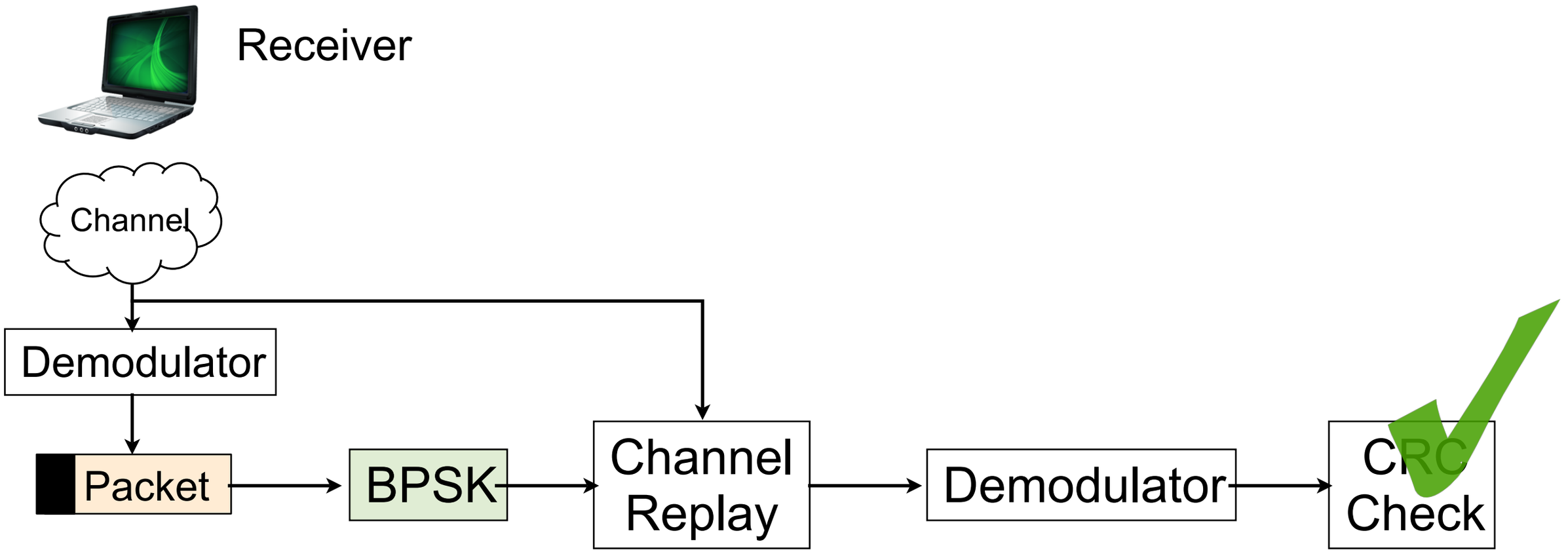
Packet

BPSK

Channel Replay

Demodulator

CRC Check


Receiver
Channel
Demodulator
Packet
BPSK
Channel Replay
Demodulator
CRC Check

Receiver

Channel

Demodulator

Packet

BPSK

Channel Replay

Demodulator

CRC Check

4QAM

Channel Replay

Demodulator

CRC Check

Receiver

Channel

Demodulator

Packet

BPSK

Channel Replay

Demodulator

CRC Check

4QAM

Channel Replay

Demodulator

CRC Check

Receiver

Channel

Demodulator

Packet

BPSK

Channel Replay

Demodulator

CRC Check

4QAM

Channel Replay

Demodulator

CRC Check

16QAM

Channel Replay

Demodulator

CRC Check

Receiver

Channel

Demodulator

Packet

BPSK

Channel Replay

Demodulator

CRC Check

4QAM

Channel Replay

Demodulator

CRC Check

16QAM

Channel Replay

Demodulator

CRC Check

Receiver

Channel

Demodulator

Packet

BPSK

Channel Replay

Demodulator

CRC Check

Best Rate

4QAM

Channel Replay

Demodulator

CRC Check

16QAM

Channel Replay

Demodulator

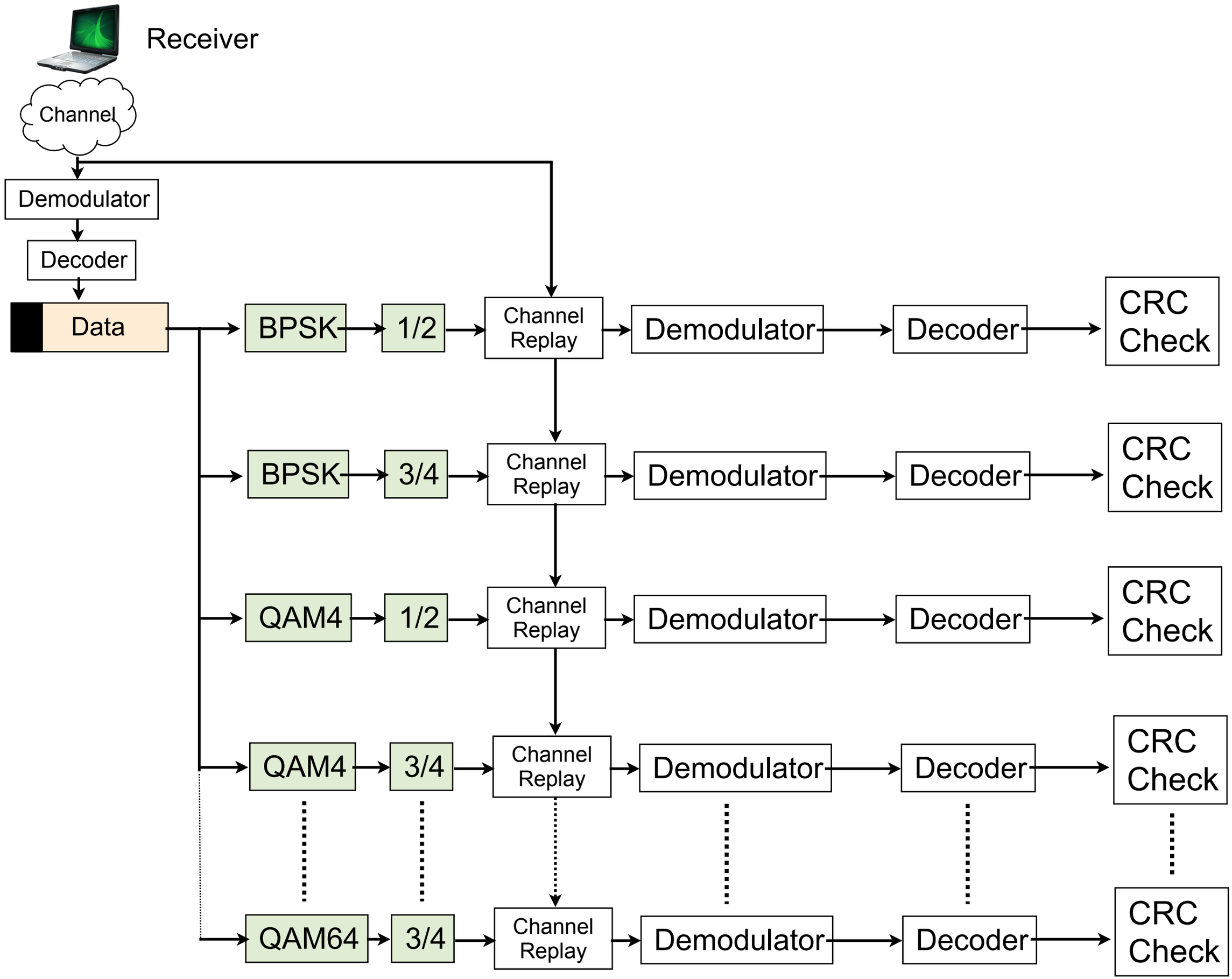
CRC Check

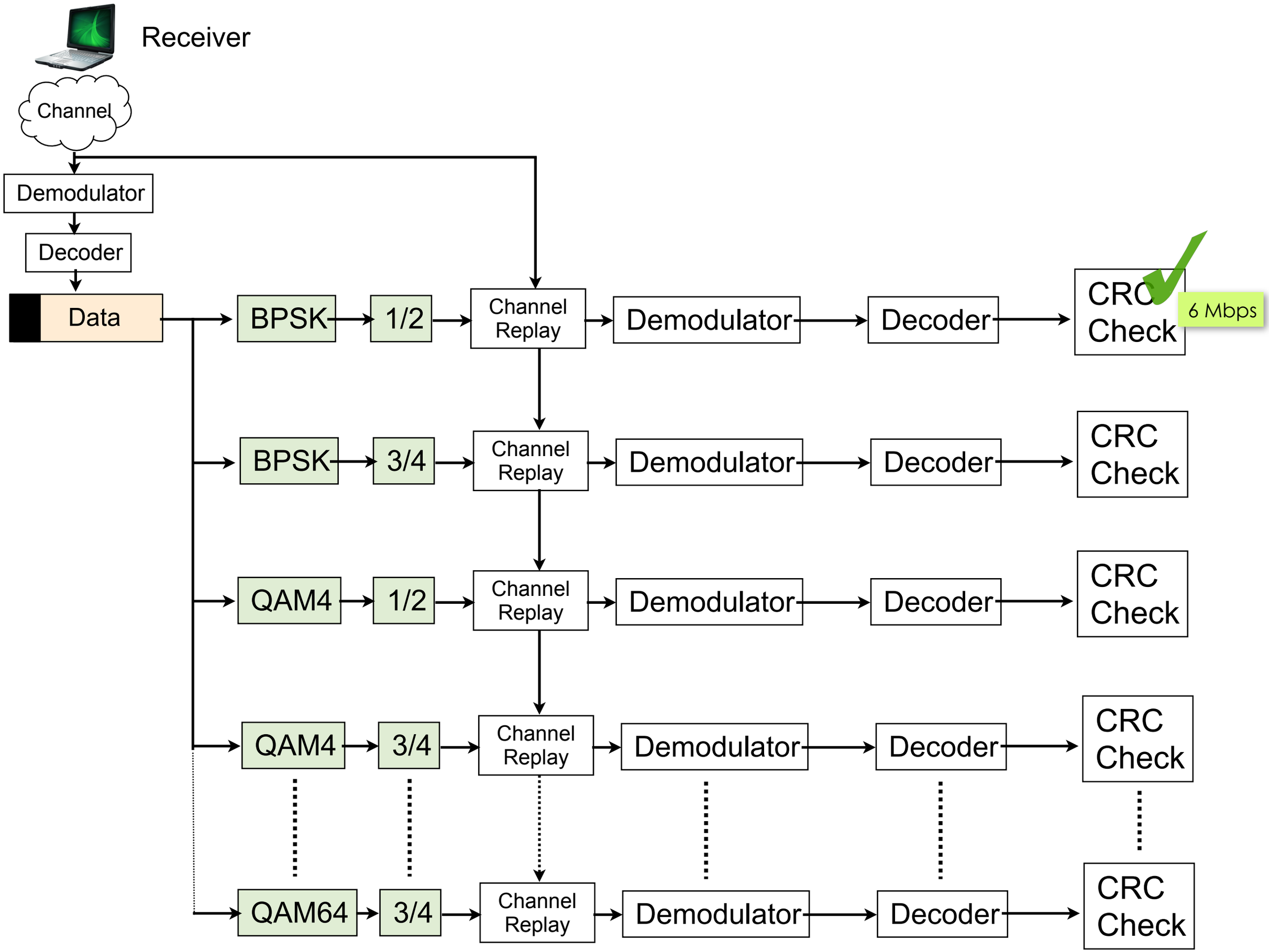
Optimal modulation ≠ Optimal rate

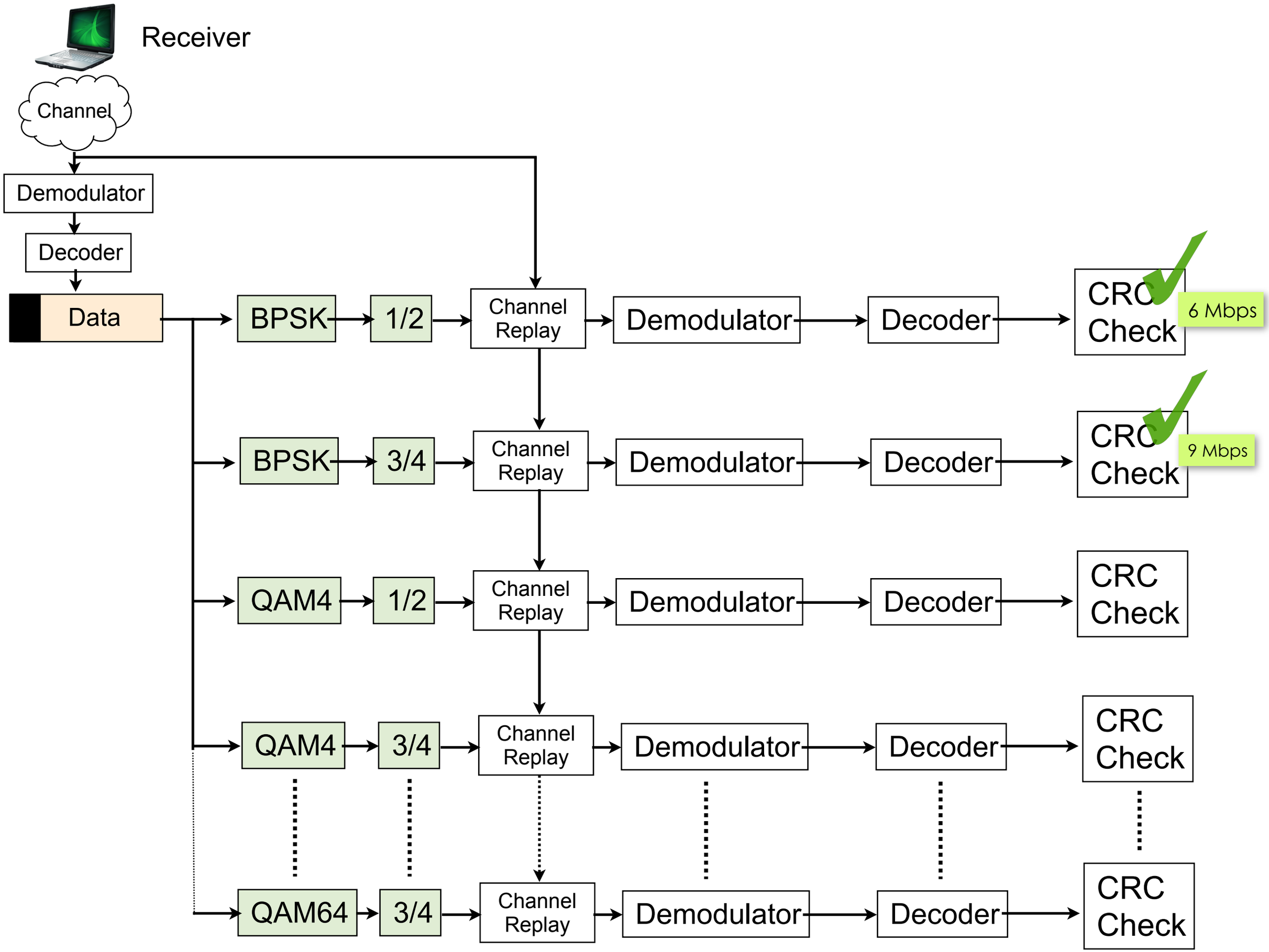
Optimal modulation ≠ Optimal rate

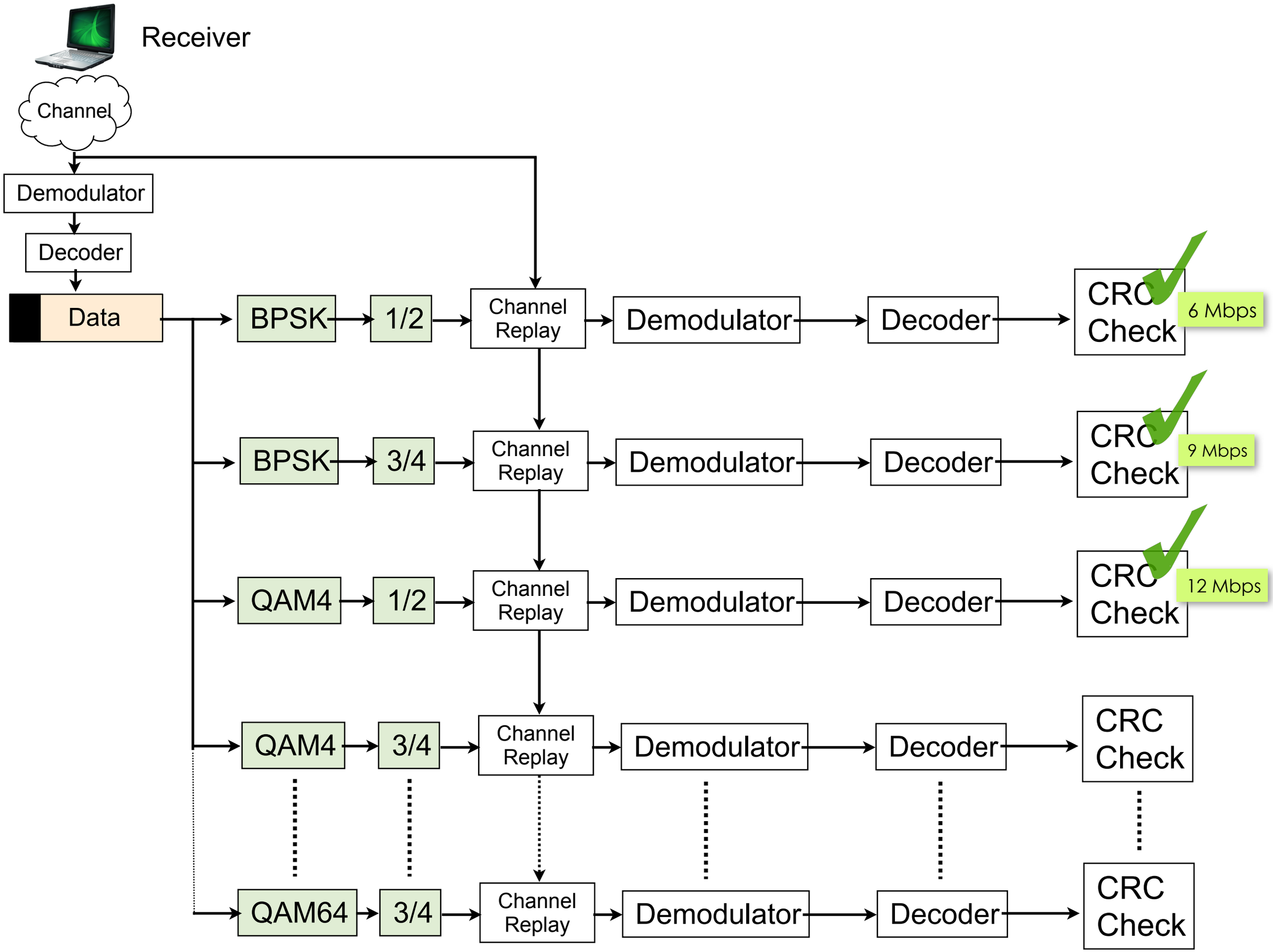
Bit-rate is a function of
both modulation and coding

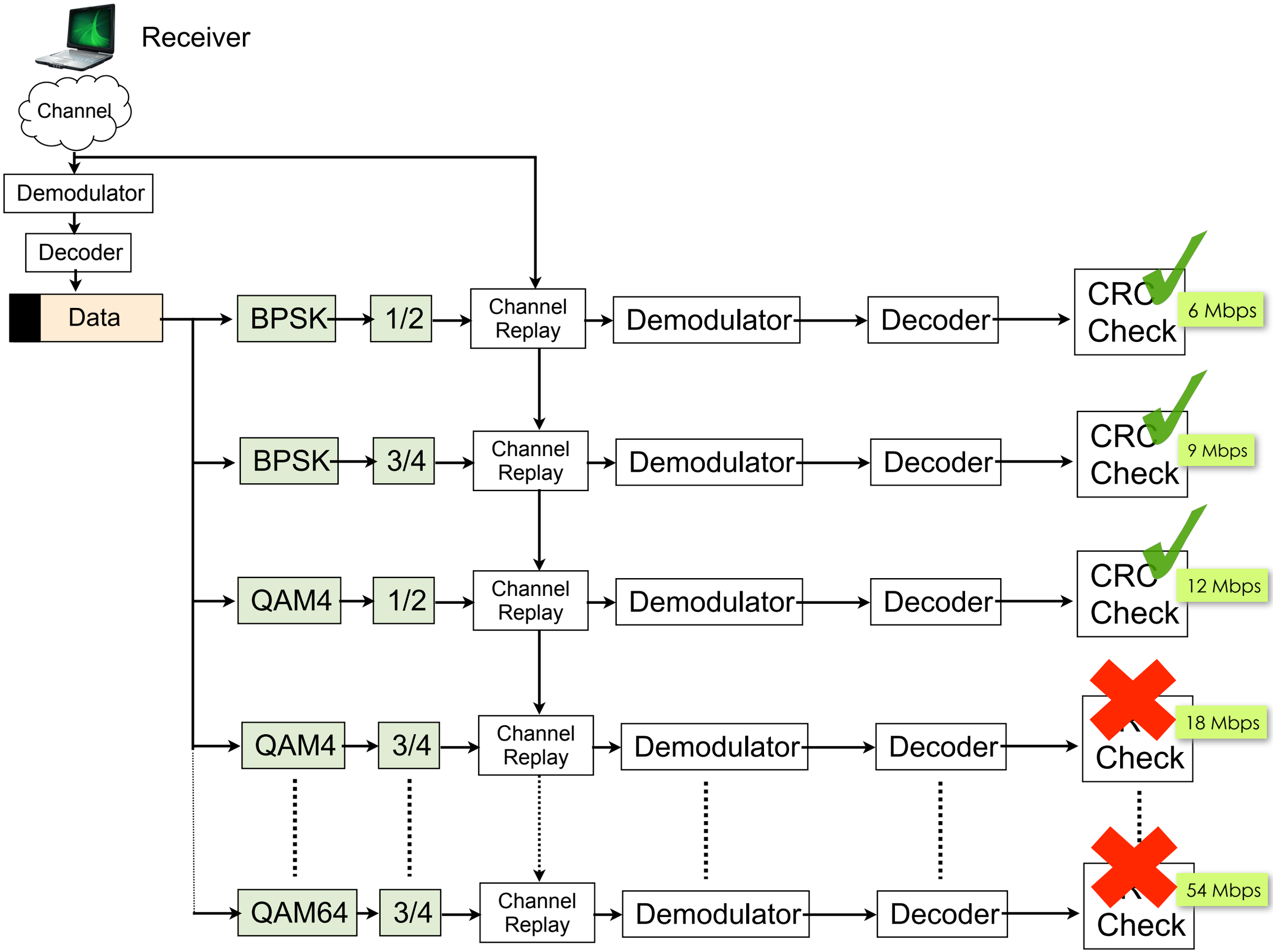
Can we find the optimal <modulation, coding> for a received packet?

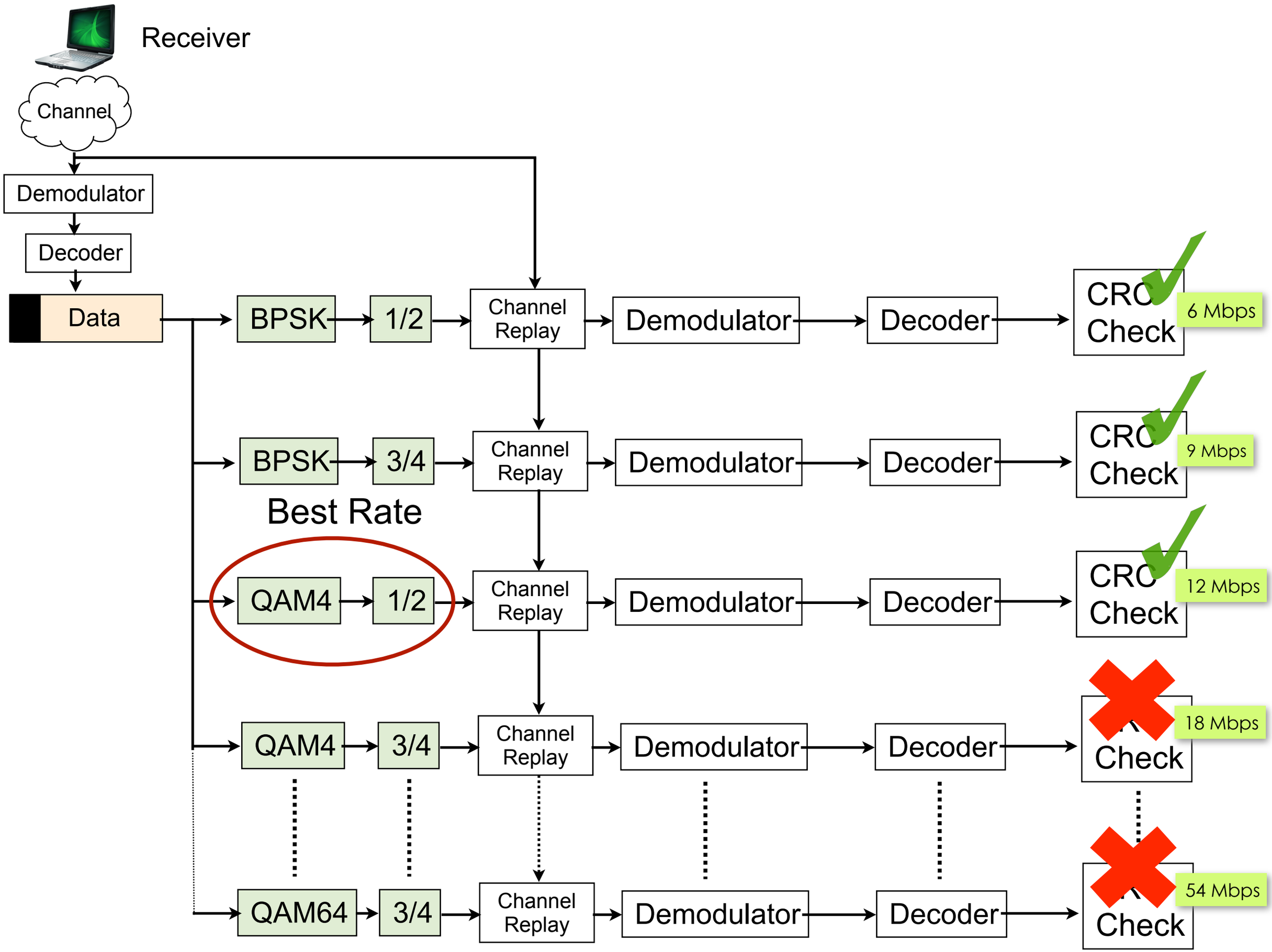

Receiver
Channel
Demodulator
Decoder
Data
BPSK
1/2
Channel Replay
Demodulator
Decoder
CRC Check
BPSK
3/4
Channel Replay
Demodulator
Decoder
CRC Check
QAM4
1/2
Channel Replay
Demodulator
Decoder
CRC Check
QAM4
3/4
Channel Replay
Demodulator
Decoder
CRC Check
QAM64
3/4
Channel Replay
Demodulator
Decoder
CRC Check


Receiver
Channel
Demodulator
Decoder
Data
BPSK
1/2
Channel Replay
Demodulator
Decoder
CRC Check
6 Mbps
BPSK
3/4
Channel Replay
Demodulator
Decoder
CRC Check
QAM4
1/2
Channel Replay
Demodulator
Decoder
CRC Check
QAM4
3/4
Channel Replay
Demodulator
Decoder
CRC Check
QAM64
3/4
Channel Replay
Demodulator
Decoder
CRC Check


Receiver
Channel
Demodulator
Decoder
Data
BPSK
1/2
Channel Replay
Demodulator
Decoder
CRC Check
6 Mbps
BPSK
3/4
Channel Replay
Demodulator
Decoder
CRC Check
9 Mbps
QAM4
1/2
Channel Replay
Demodulator
Decoder
CRC Check
QAM4
3/4
Channel Replay
Demodulator
Decoder
CRC Check
QAM64
3/4
Channel Replay
Demodulator
Decoder
CRC Check


Receiver
Channel
Demodulator
Decoder
Data
BPSK
1/2
Channel Replay
Demodulator
Decoder
CRC Check
6 Mbps
BPSK
3/4
Channel Replay
Demodulator
Decoder
CRC Check
9 Mbps
QAM4
1/2
Channel Replay
Demodulator
Decoder
CRC Check
12 Mbps
QAM4
3/4
Channel Replay
Demodulator
Decoder
CRC Check
QAM64
3/4
Channel Replay
Demodulator
Decoder
CRC Check

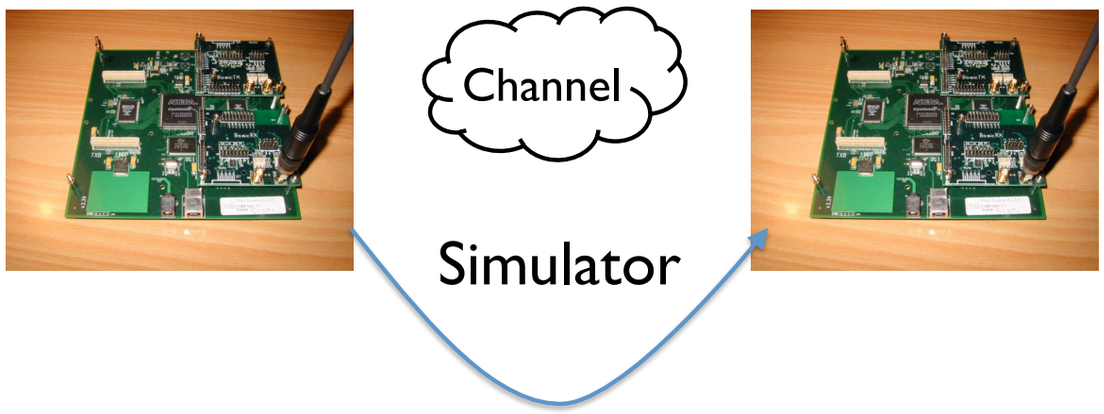

Receiver
Channel
Demodulator
Decoder
Data
BPSK
1/2
Channel Replay
Demodulator
Decoder
CRC Check
6 Mbps
BPSK
3/4
Channel Replay
Demodulator
Decoder
CRC Check
9 Mbps
QAM4
1/2
Channel Replay
Demodulator
Decoder
CRC Check
12 Mbps
QAM4
3/4
Channel Replay
Demodulator
Decoder
Check
18 Mbps
QAM64
3/4
Channel Replay
Demodulator
Decoder
Check
54 Mbps


Receiver
Channel
Demodulator
Decoder
Data
BPSK
1/2
Channel Replay
Demodulator
Decoder
CRC Check
6 Mbps
BPSK
3/4
Channel Replay
Demodulator
Decoder
CRC Check
9 Mbps
Best Rate
QAM4
1/2
Channel Replay
Demodulator
Decoder
CRC Check
12 Mbps
QAM4
3/4
Channel Replay
Demodulator
Decoder
Check
18 Mbps
QAM64
3/4
Channel Replay
Demodulator
Decoder
Check
54 Mbps

Performance Evaluation

- Used 802.11 like Tx and Rx design on USRP/GnuRadio
  - Modulation: BPSK, QPSK, 16QAM, 64QAM
  - Coding: Convolution coding with puncturing with rate 1/2, 3/4
  - Compare with Softrate, SNR-based

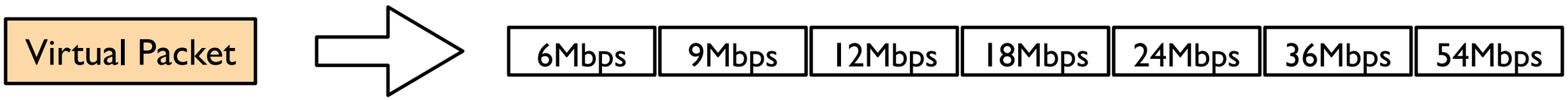
- Testbed
  - 10 traces at walking speed
  - Trace based evaluation



- Simulation
  - Characterize AccuRate's performance under high mobility
  - Raleigh fading channel simulator ported to GnuRadio

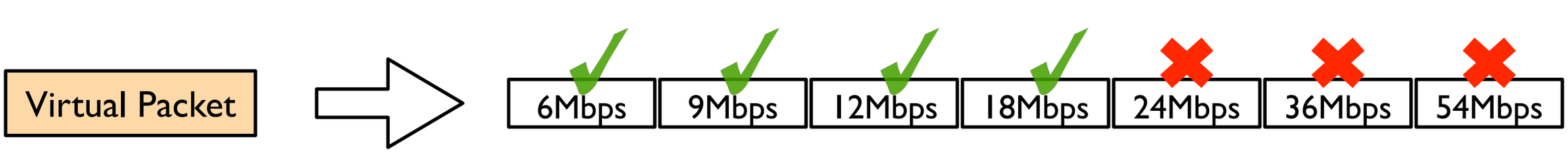
What is the True Optimal Rate?

- Testbed
  - Using train of packets (Virtual Packet)
  - Each Virtual Packet consists of data packets at all bit-rates
  - Similar method as Softrate



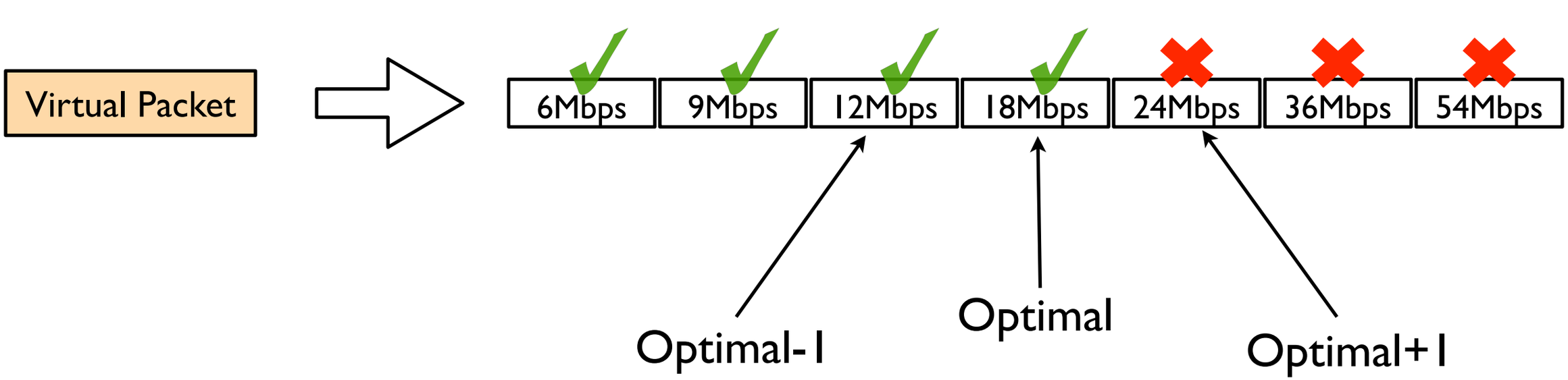
What is the True Optimal Rate?

- Testbed
  - Using train of packets (Virtual Packet)
  - Each Virtual Packet consists of data packets at all bit-rates
  - Similar method as Softrate



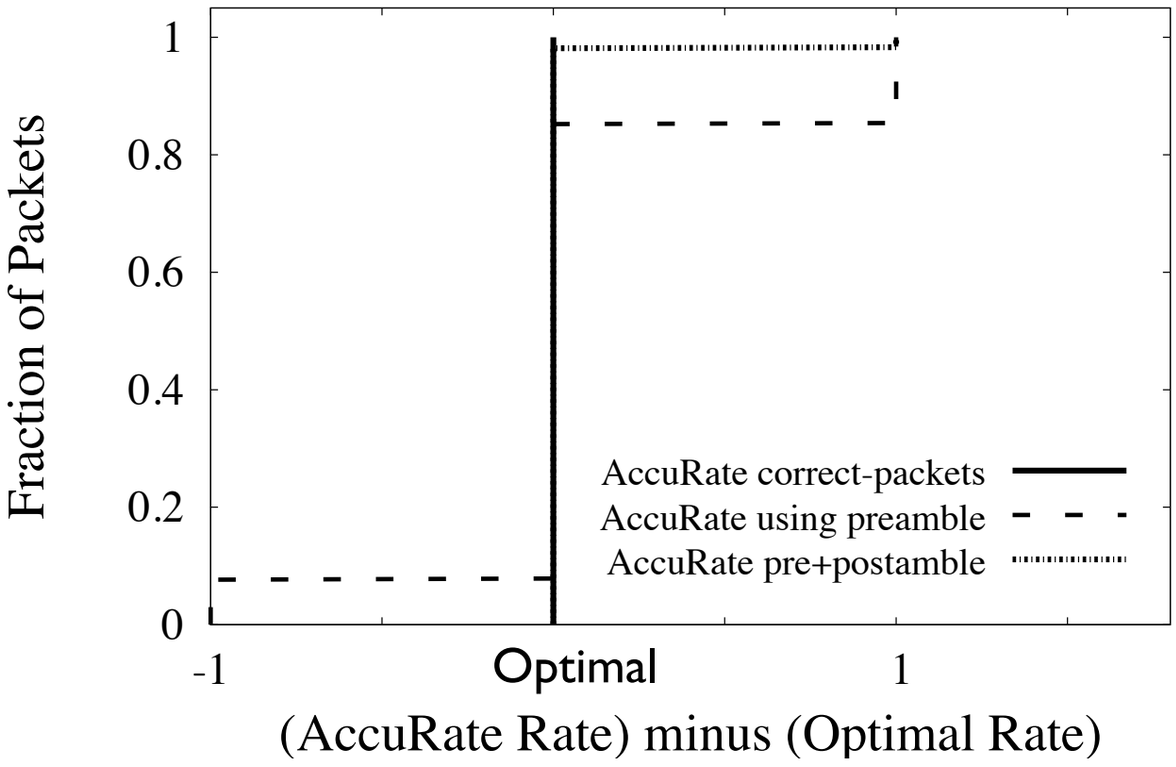
What is the True Optimal Rate?

- Testbed
  - Using train of packets (Virtual Packet)
  - Each Virtual Packet consists of data packets at all bit-rates
  - Similar method as Softrate

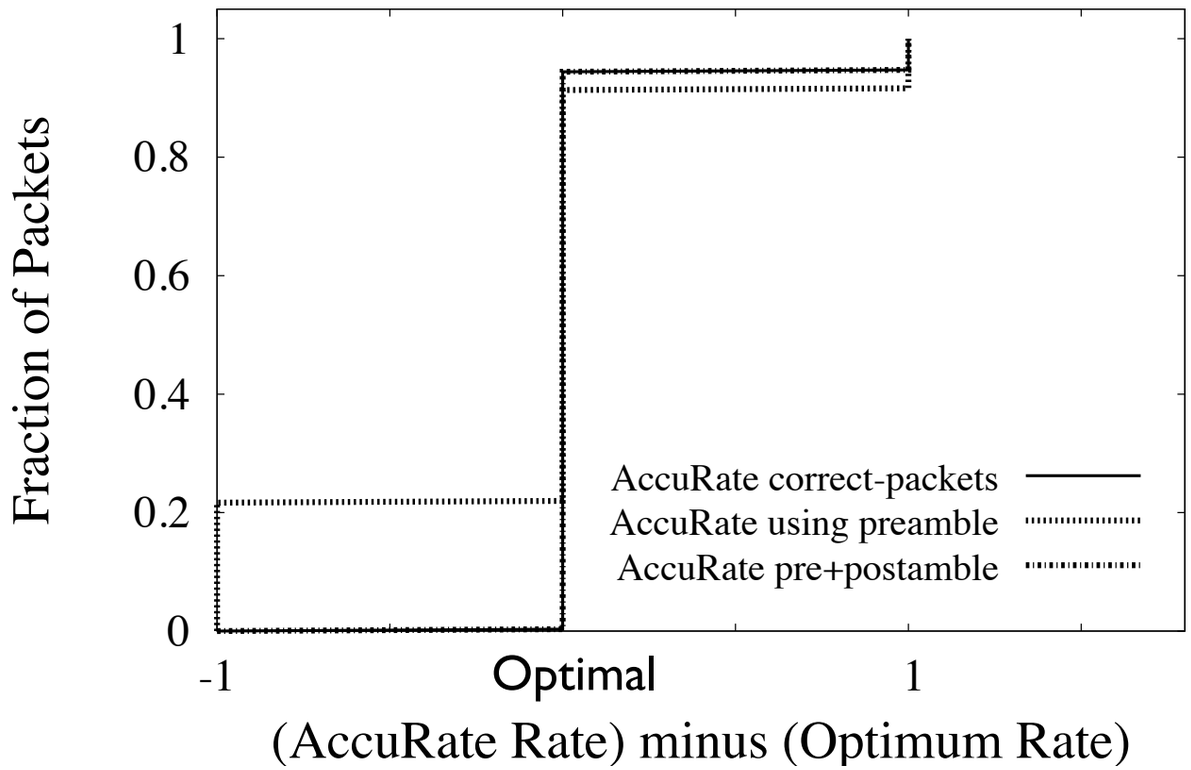


Can we estimate the optimal rate?

Simulation



Testbed



For correctly received packets,
100% in Simulation,
95% in Testbed

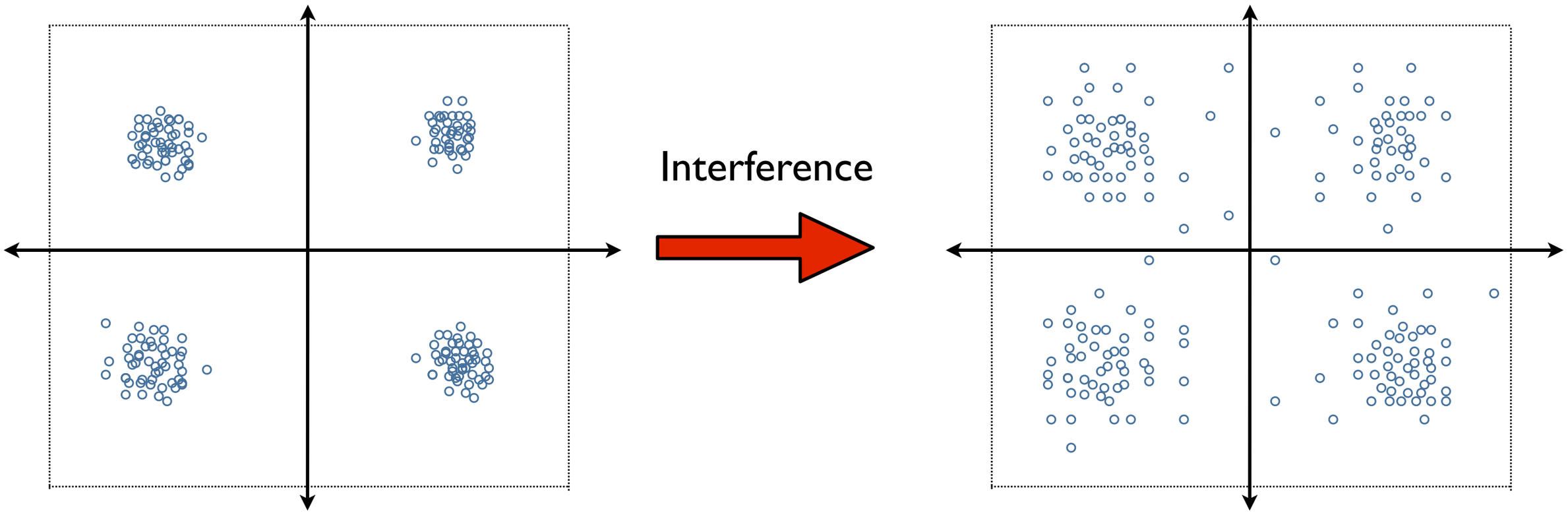
AccuRate needs to detect Interference

AccuRate needs to detect Interference

Rate selection needs to be independent of interference

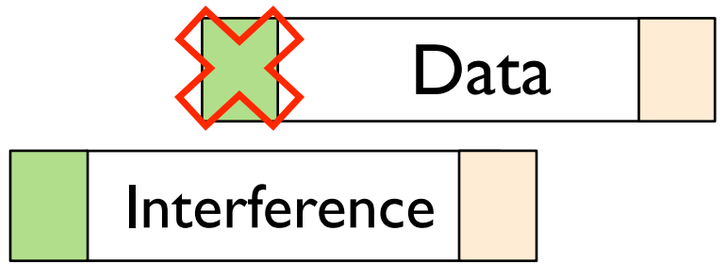
How to Detect Interference?

- Interference causes substantial symbol dispersion

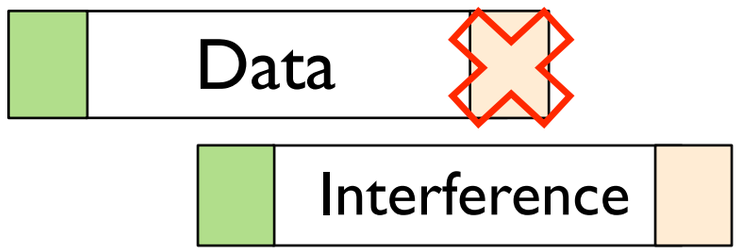


How to Detect Interference?

- Interference starts first: Preamble with high dispersion

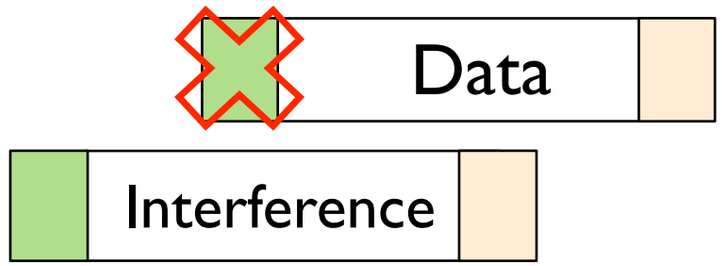


- Interference starts second: Postamble with high dispersion

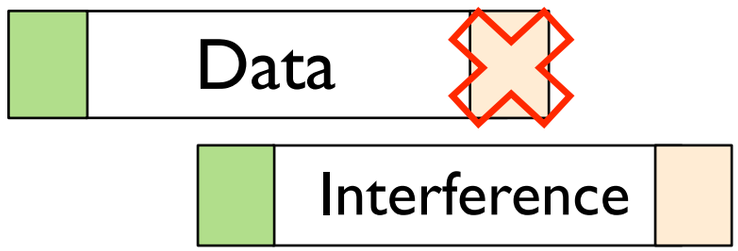


How to Detect Interference?

- Interference starts first: Preamble with high dispersion

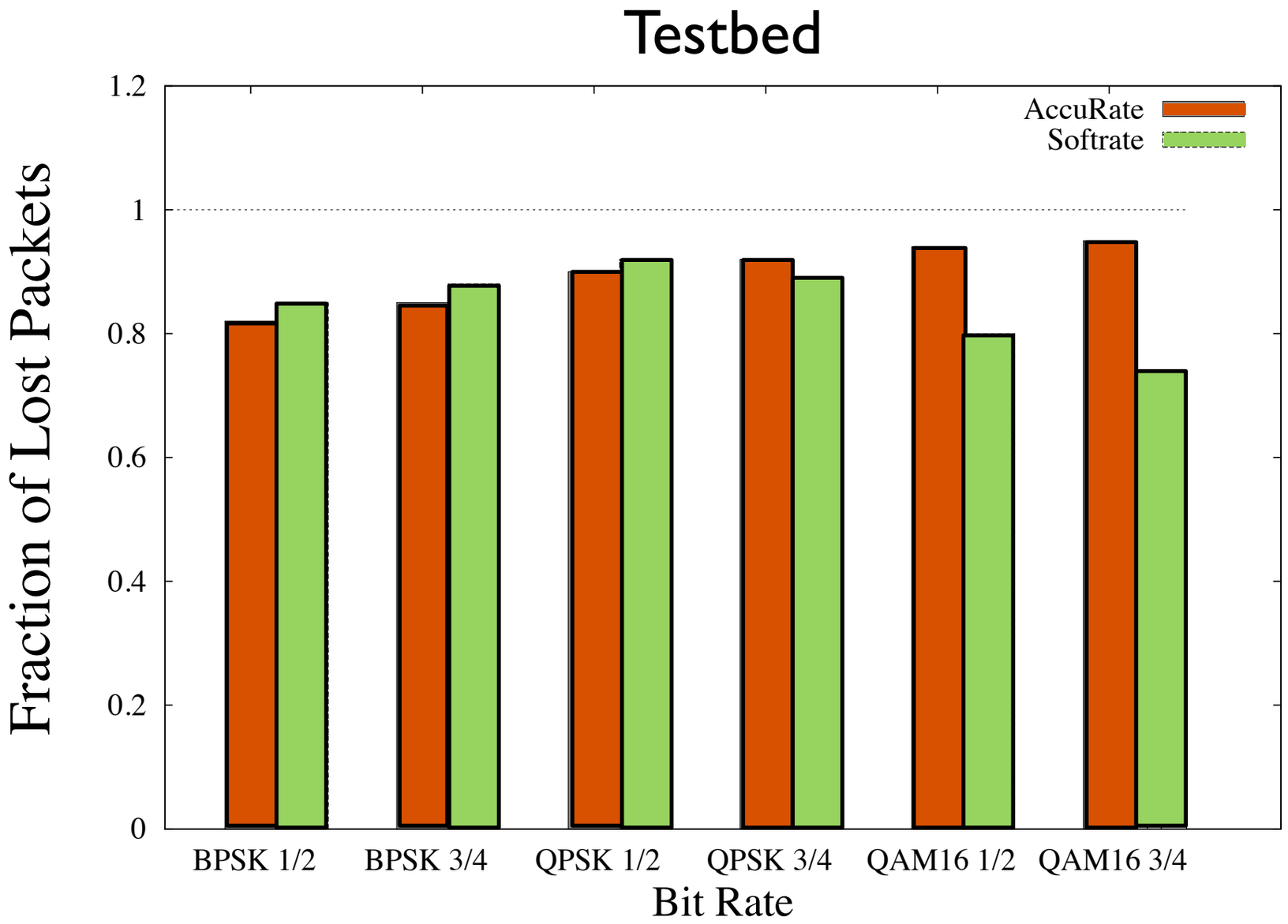


- Interference starts second: Postamble with high dispersion

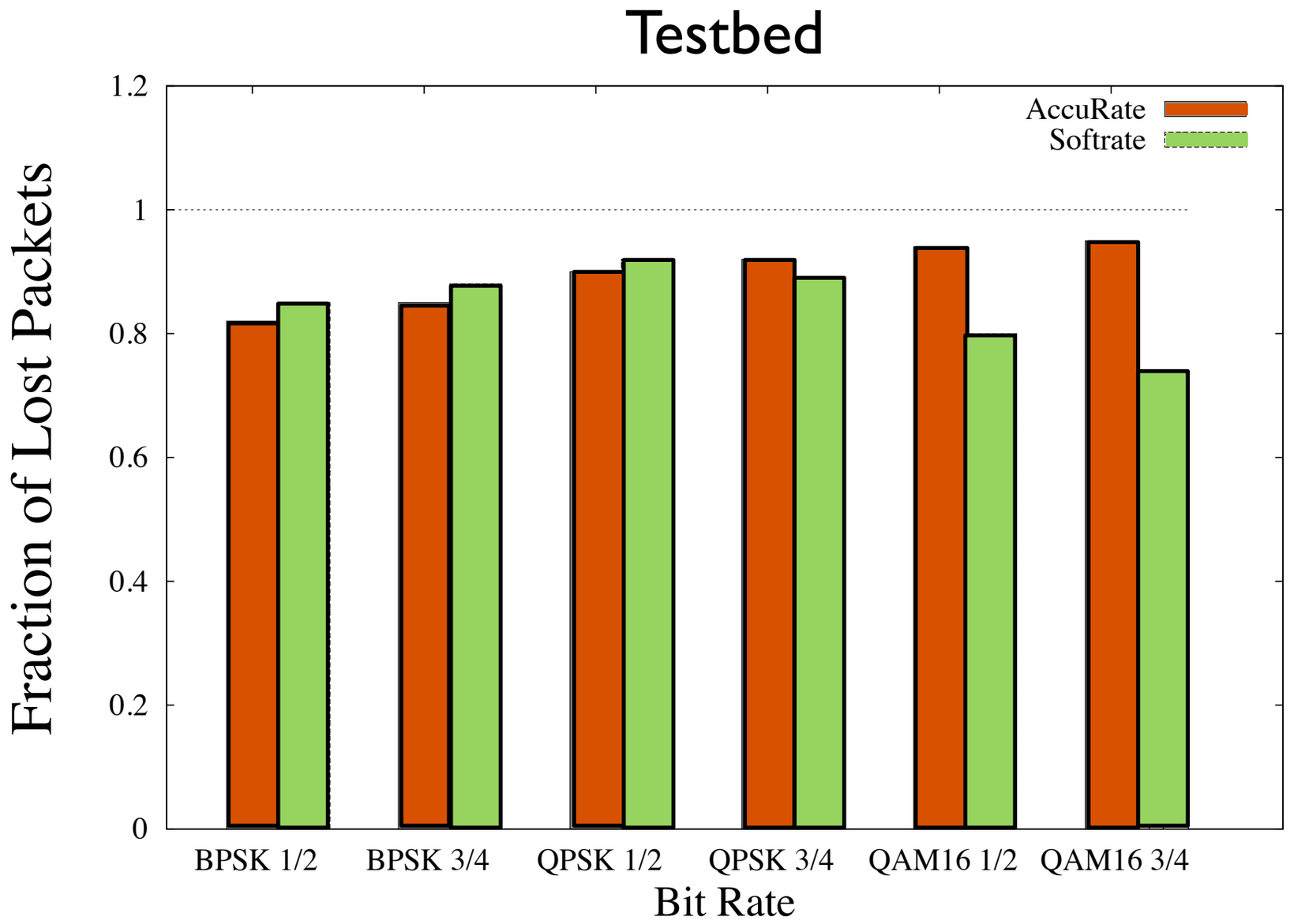


Compare preamble with postamble dispersion

Interference Detection Accuracy

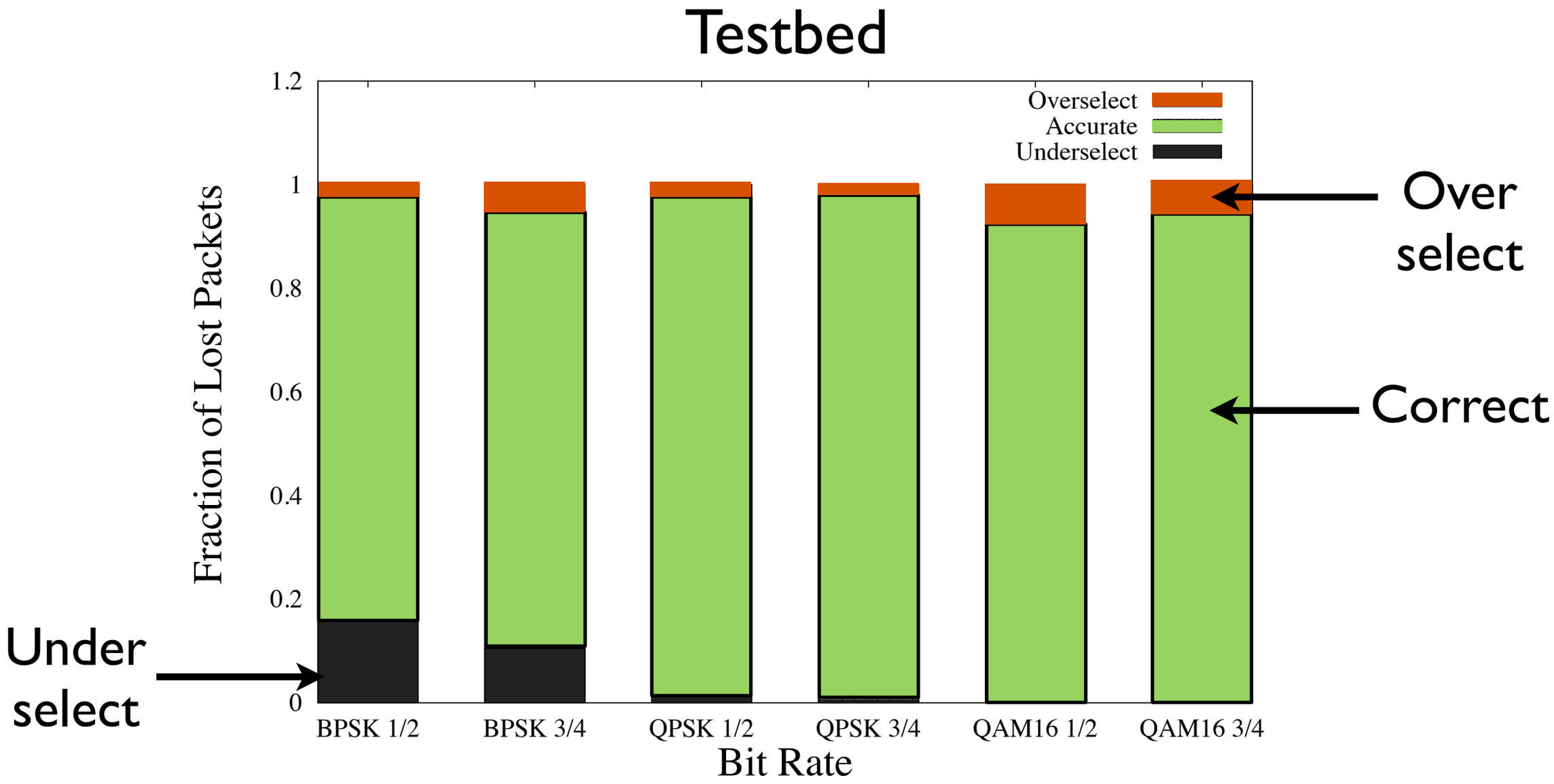


Interference Detection Accuracy

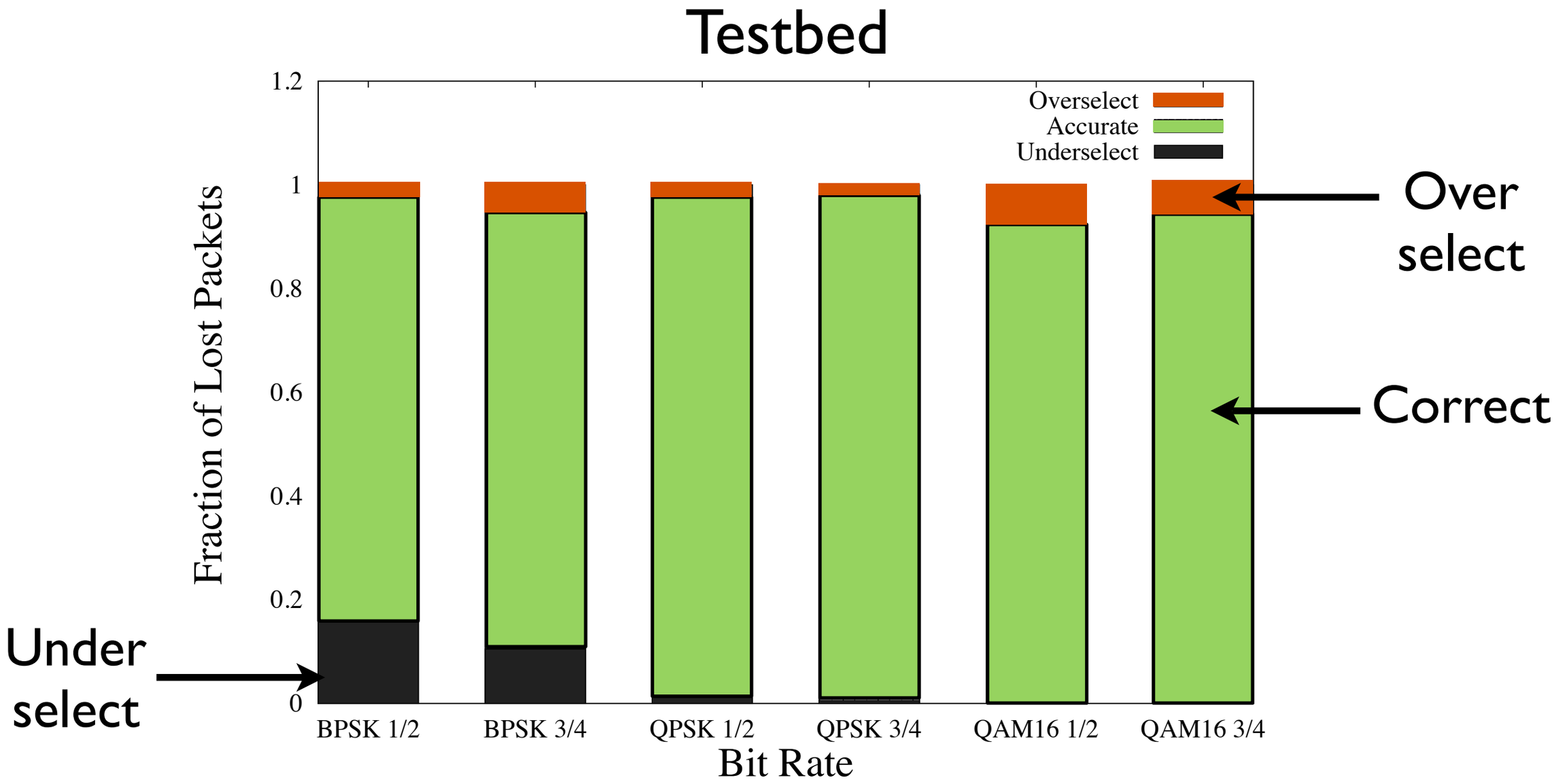


Detection Accuracy is better at higher rates (95%)

Estimation Performance with Interference



Estimation Performance with Interference

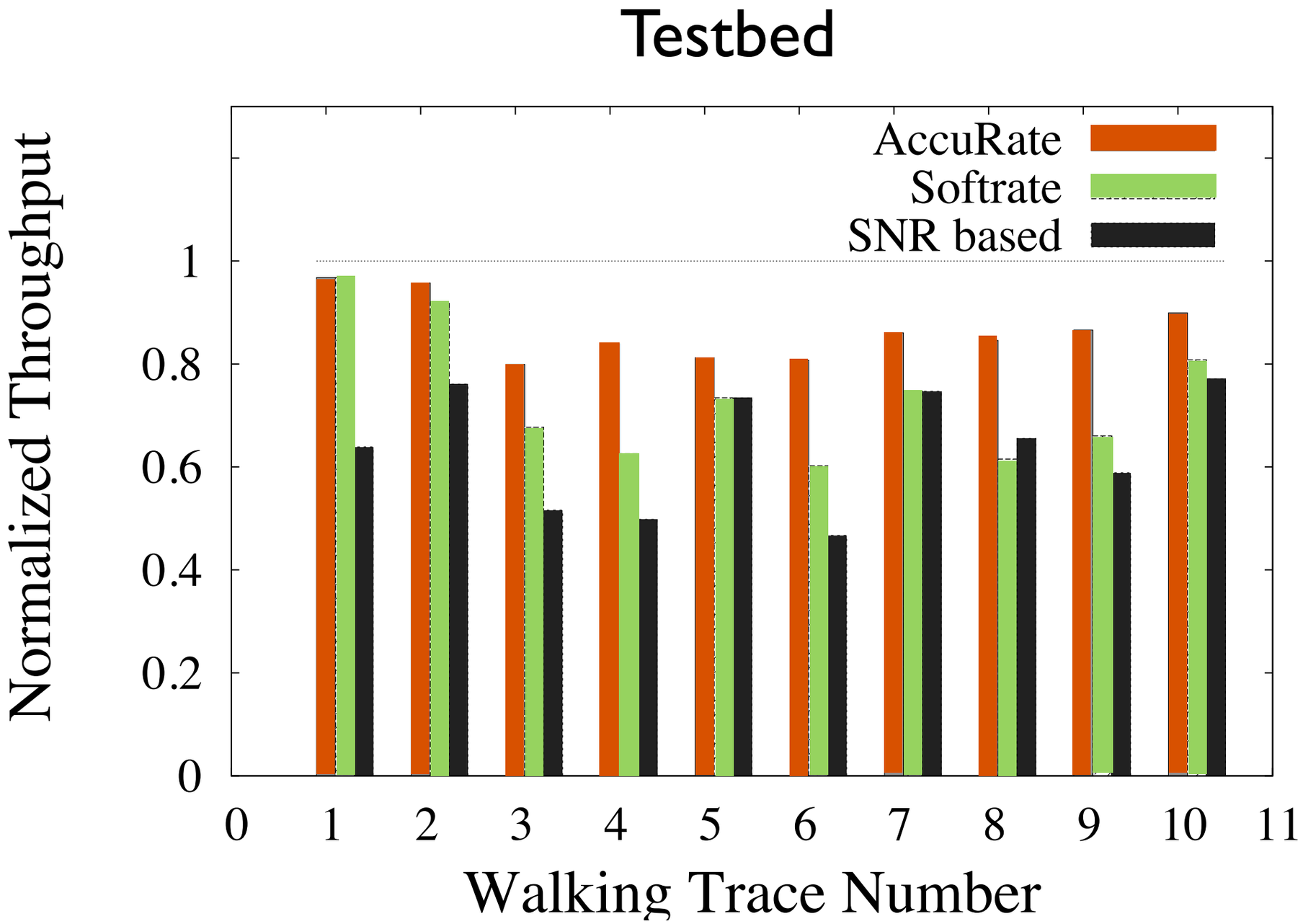


91% accuracy in Optimal rate selection

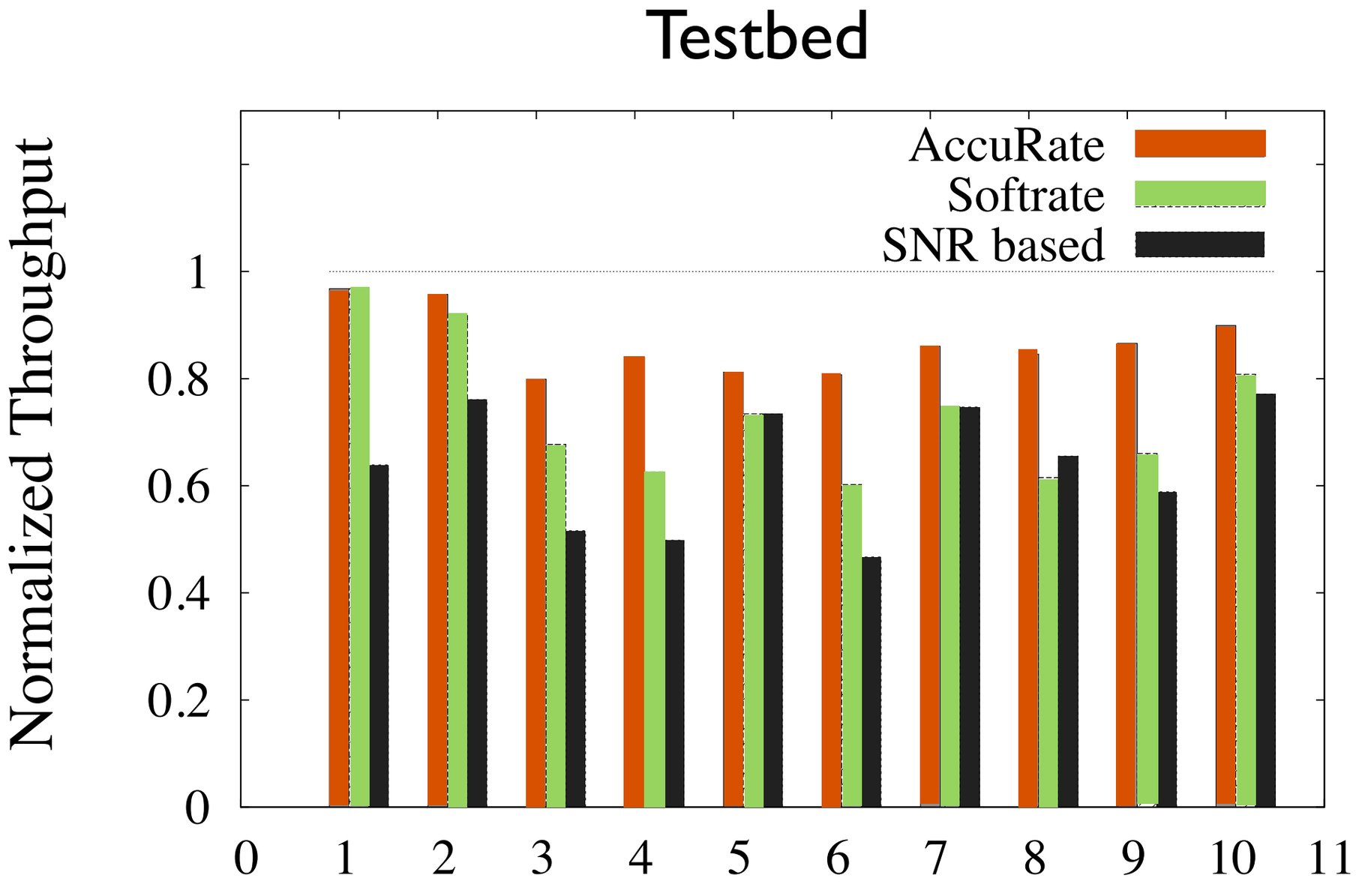
AccuRate estimates the optimal rate for an already received packet

What is the performance if the next transmission uses this rate?

Throughput at Walking Speeds

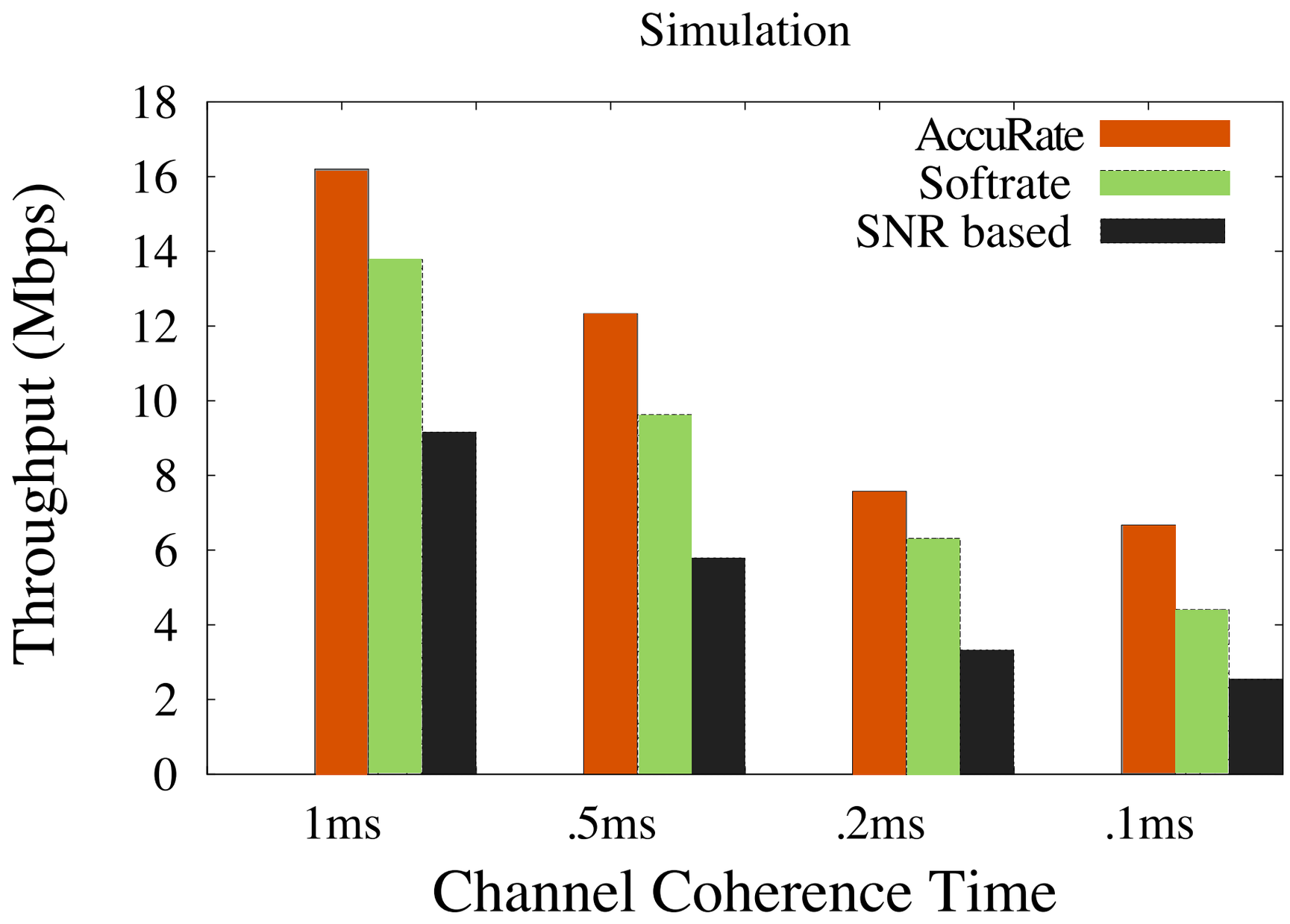


Throughput at Walking Speeds



AccuRate achieves 87% of the optimal throughput

Throughput under Mobility



AccuRate performs well even under high mobility

Limitations

- Hardware Complexity
  - AccuRate targets optimal rate estimation
  - Does not consider implementation cost
- Rate estimation sub-optimal under packet failure
  - Pre/Post amble based estimation achieves 93% accuracy
  - Improvements possible with midamble
- Interfering packet may engulf or be engulfed by data
  - AccuRate unable to detect such cases

Summary

- AccuRate uses symbol dispersion to estimate bit-rate
  - Symbol dispersion is a measure of channel behavior
- AccuRate replays this channel on different bit-rates
  - The max rate that “passes” this replay is declared optimal
- The optimal rate is prescribed for subsequent transmissions
  - USRP testbed results show 87% of optimal throughput
- **SoftRate capable of choosing very good bit-rates**
  - **AccuRate pushes rate estimation towards optimality**

Questions, Comments?

Thank You

Duke SyNRG Research Group

http://synrg.ee.duke.edu