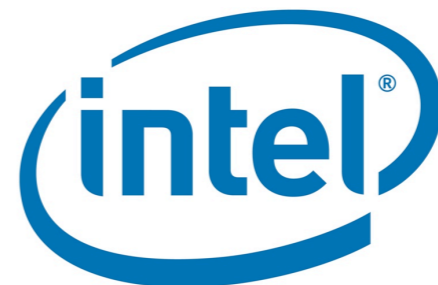


Predictable 802.11 Packet Delivery from Wireless Channel Measurements

Daniel Halperin

Wenjun Hu, Anmol Sheth, David Wetherall



802.11 Wi-Fi technology

- **Fast** - 600 Mbps in 802.11n represents a 300x speedup in 12 years
- **Reliable** - vehicular speeds, extended range, stable hardware and software
- **Ubiquitous** - few dollars per chip allows integration everywhere

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New, exciting apps on the horizon

New apps stress network



**Wireless
Display**



**Mobile
Wireless**



**Wireless
Input**

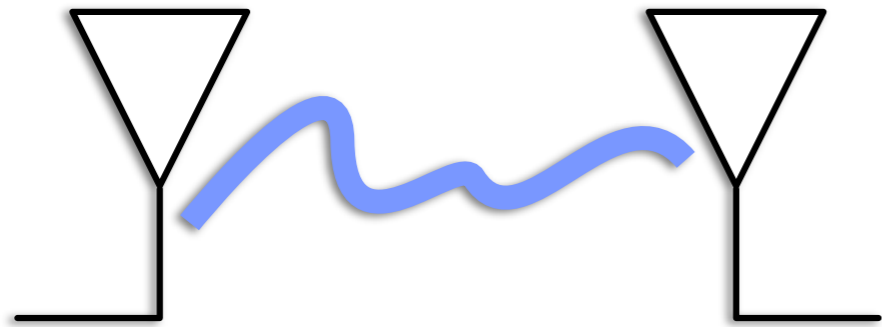
New apps stress network



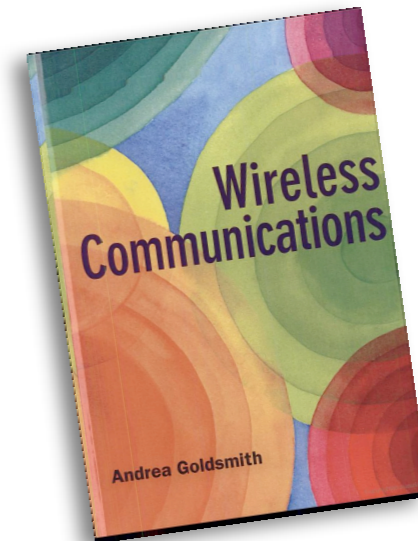
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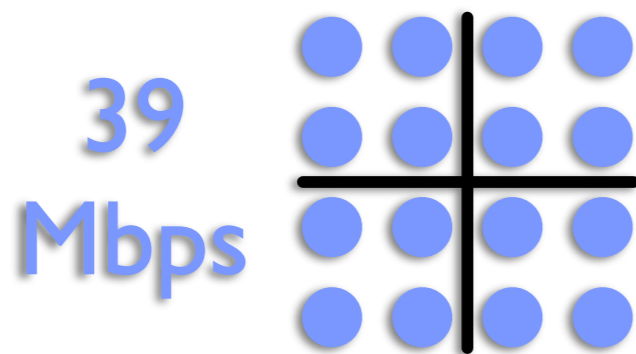
Performance – *in theory*



Channel Measurements

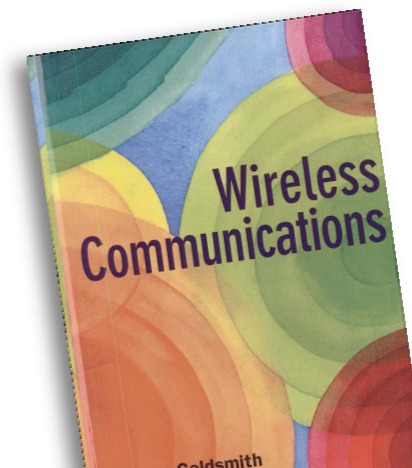
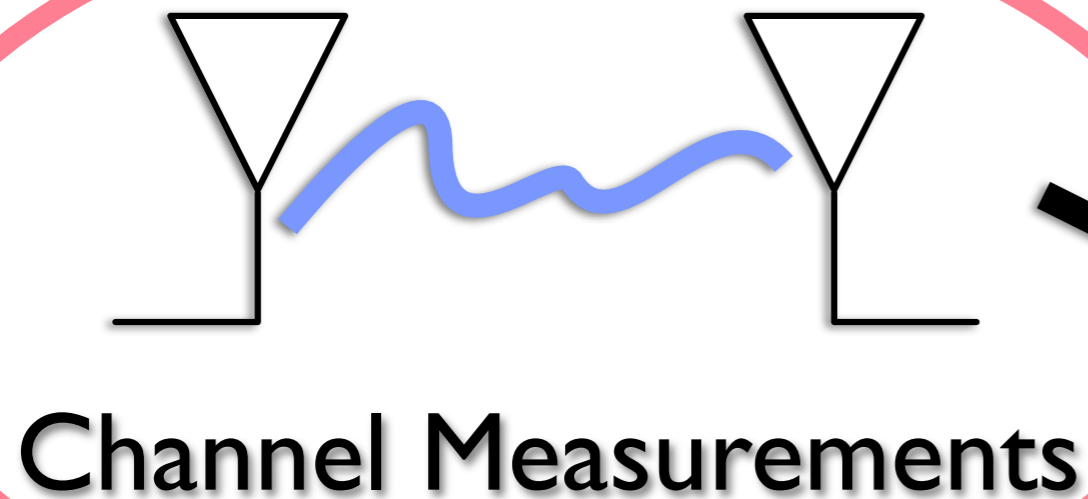


Textbook Algorithms



Rate Selection

Performance – *in theory*



In practice, this has never worked!



Performance – *In practice*



65 Mbps?

Nope!

65 Mbps?

Nope!

65 Mbps?

Nope!

52 Mbps?

Nope!

13 Mbps?

Okay!



**Statistics-based
Adaptation**

Problem: Convergence time

- *Dynamic environments*
- *Large search spaces*
 - >300 tx configs in 802.11n
 - Combined rate & power

Both are trends

Goals: Bridging Theory and Practice

- Accurately predict performance over real channels
- Agile response to changing channels
- Leverage measurements available in real NICs
- Extend to 802.11n and more applications

Key: an accurate channel metric

Goals: Bridging Theory and Practice

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Key: an accurate channel metric

Today's talk

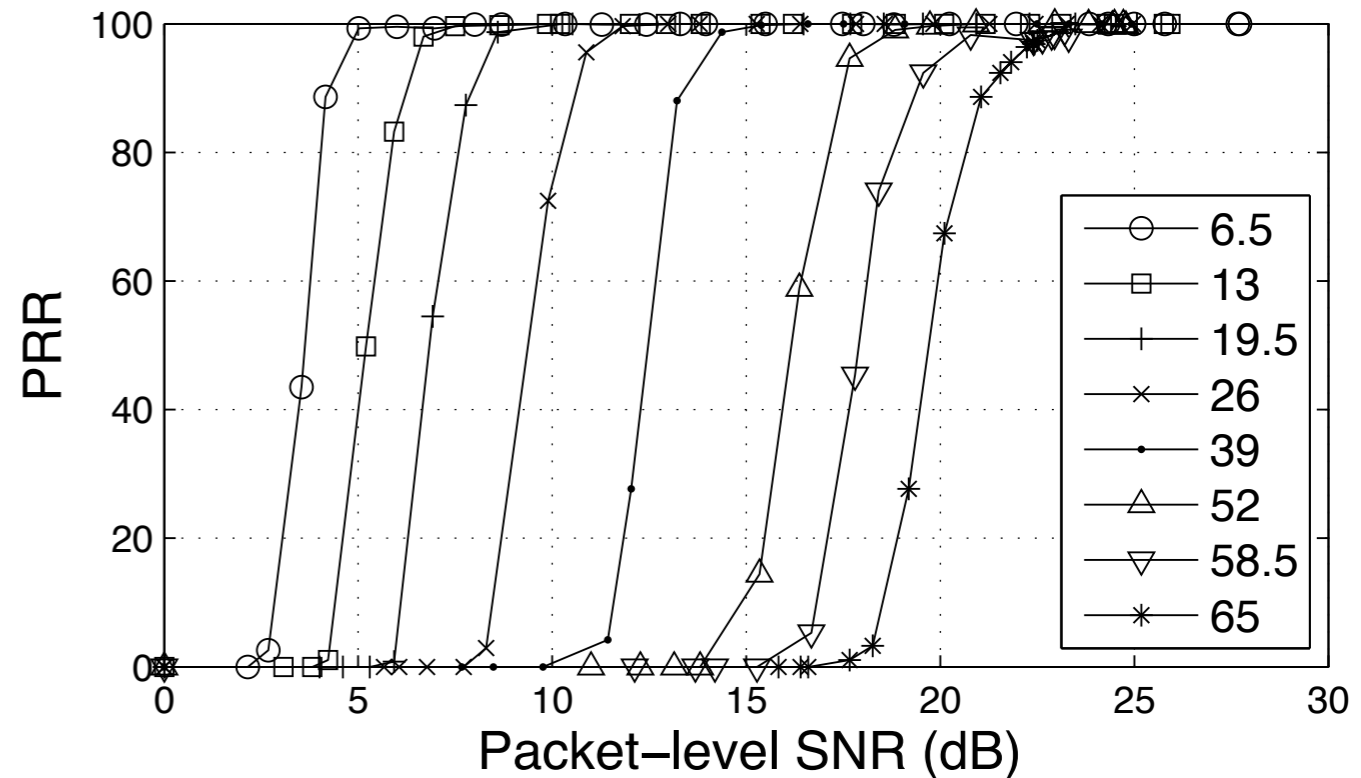
- Why it's hard to predict performance with RF measurements today
- Our solution: an accurate channel metric using ***Effective SNR***
- Evaluation of Effective SNR in Wi-Fi Networks

Today's talk

- Why it's hard to predict performance with RF measurements today
- Our solution: an accurate channel metric using ***Effective SNR***
- Evaluation of Effective SNR in Wi-Fi Networks

SNR based on RSSI

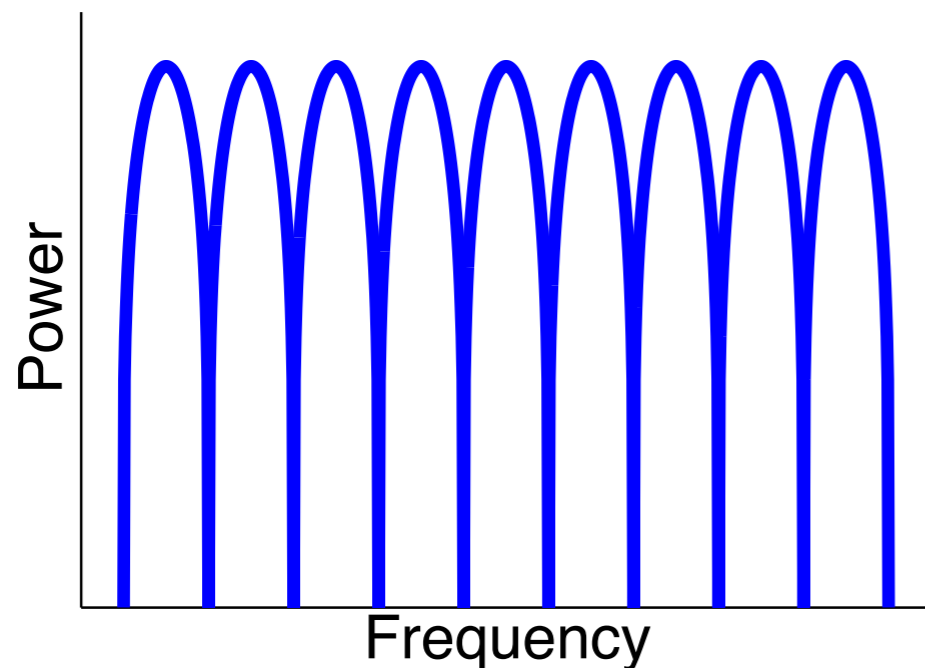
- **Received Signal Strength Indicator**
 - Measures total power received in packet
 - With Noise, gives SNR for packet
- *Treated as if directly reflects performance*
E.g., NIC manufacturers list per-rate ‘sensitivity’



- In practice, **SNR** at which a rate starts to work can **vary more than 10 dB** for real links

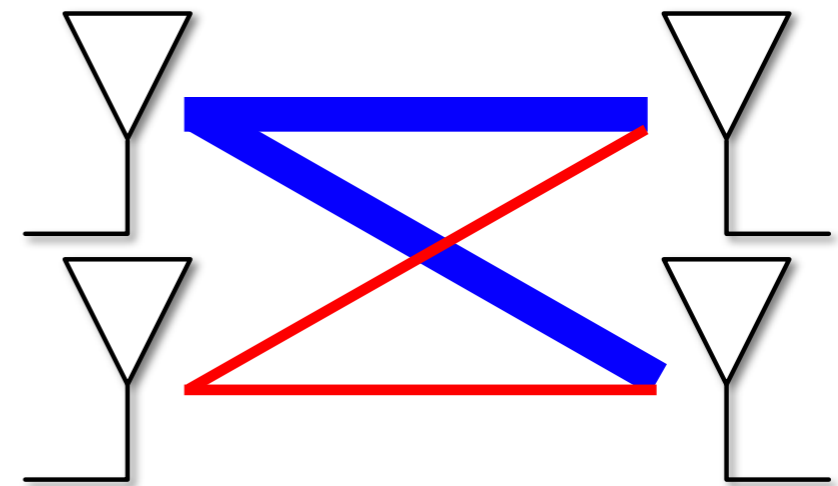
802.11: OFDM and MIMO

Orthogonal Frequency Division Multiplexing



Frequency-selective fading

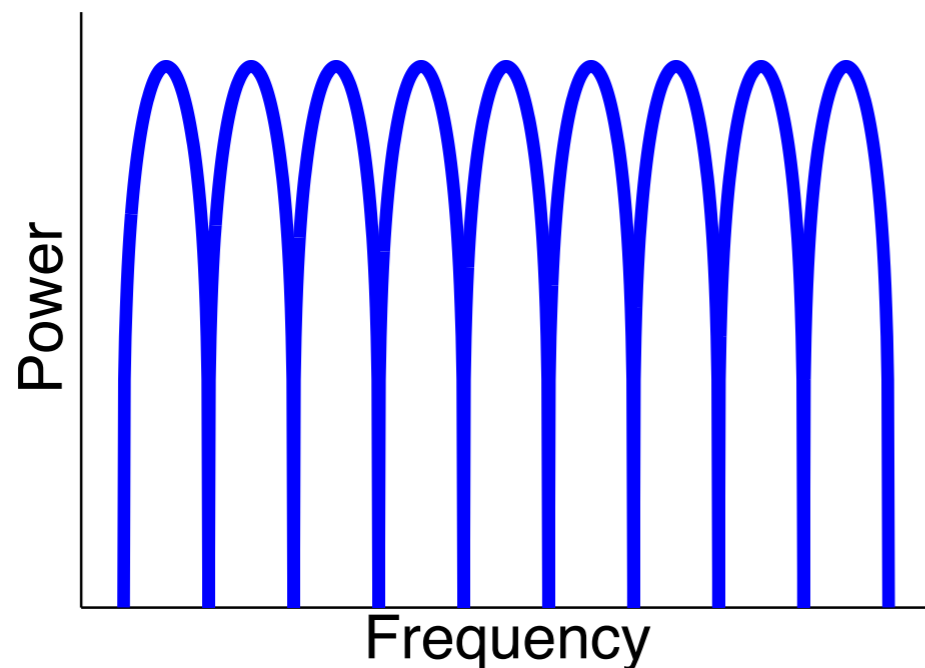
Multiple-Input Multiple-Output



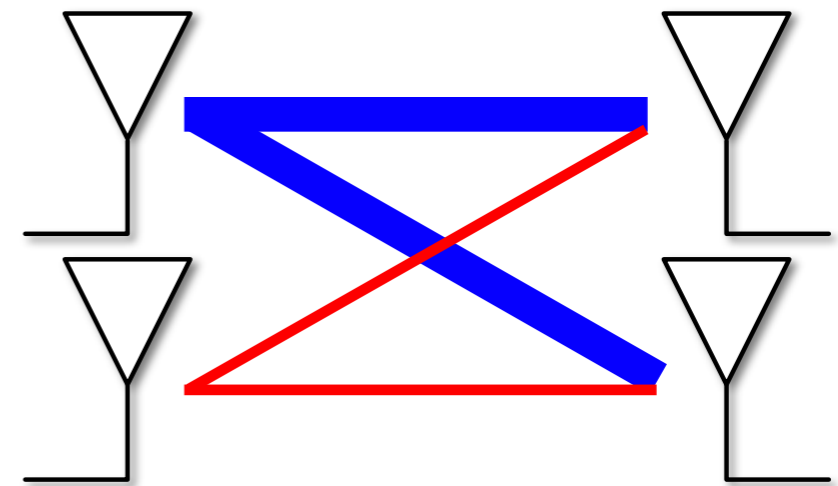
Spatial diversity

802.11: OFDM and MIMO

Orthogonal Frequency Division Multiplexing

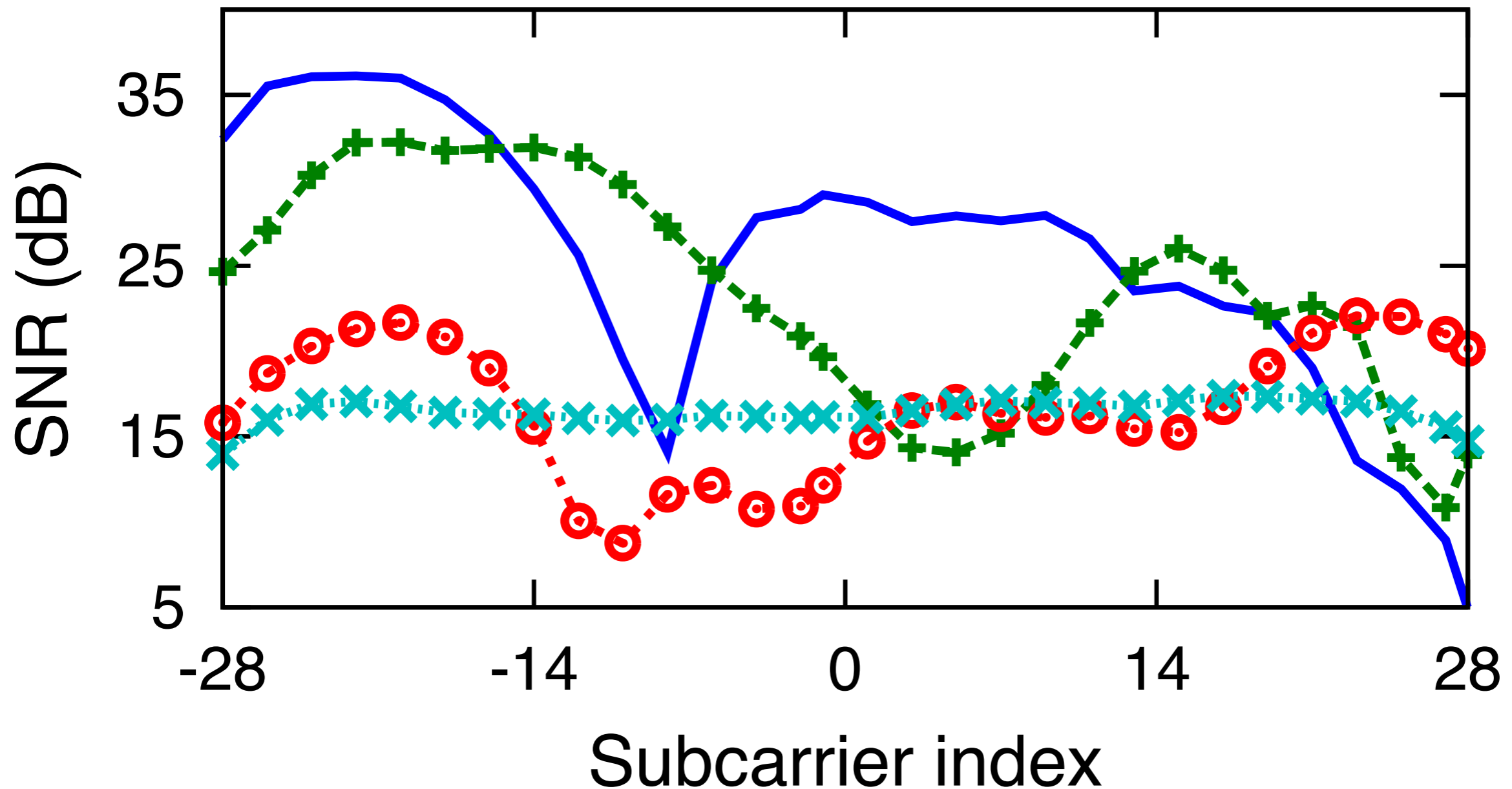


Multiple-Input Multiple-Output

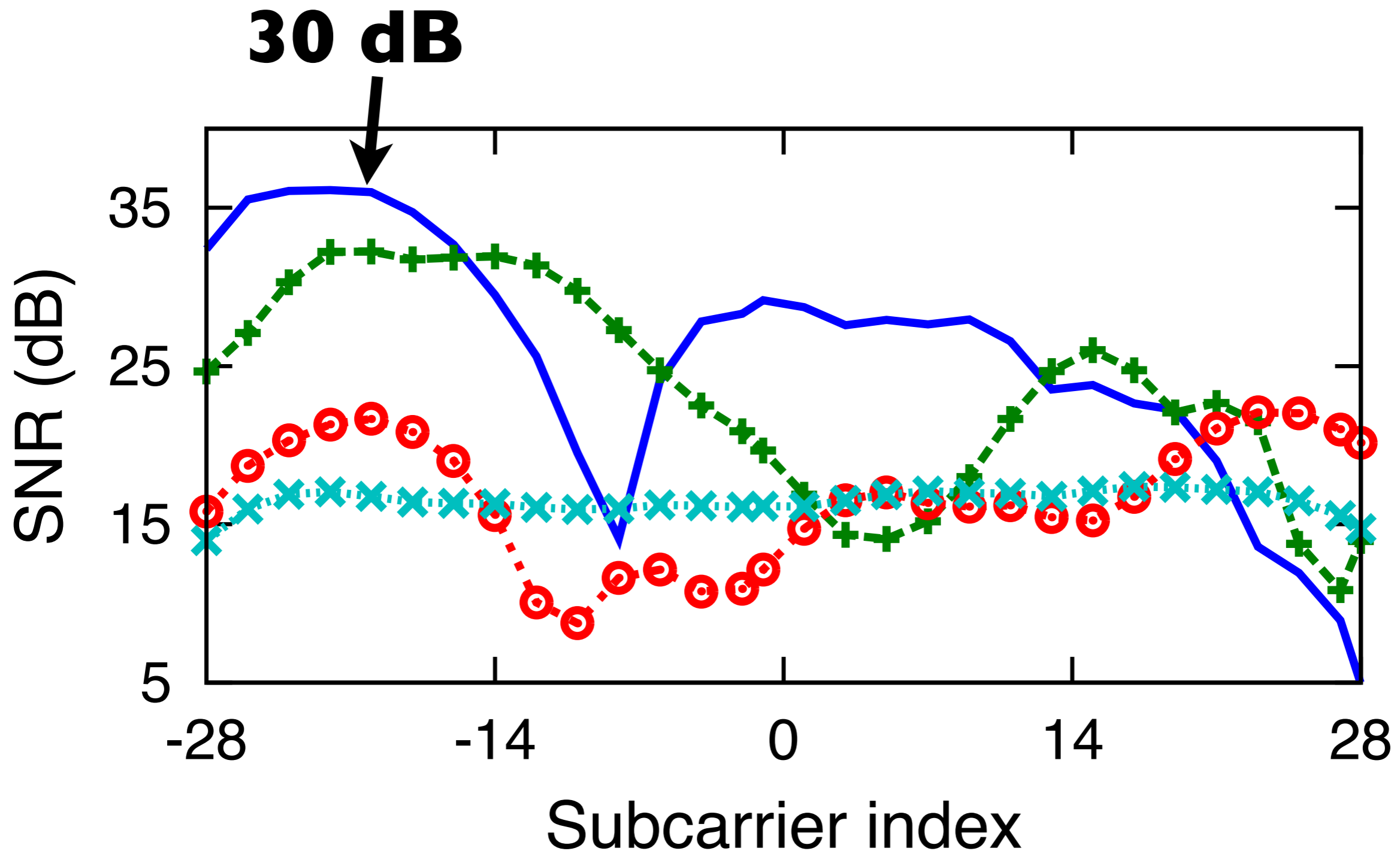


Key: Different subchannels have different SNRs

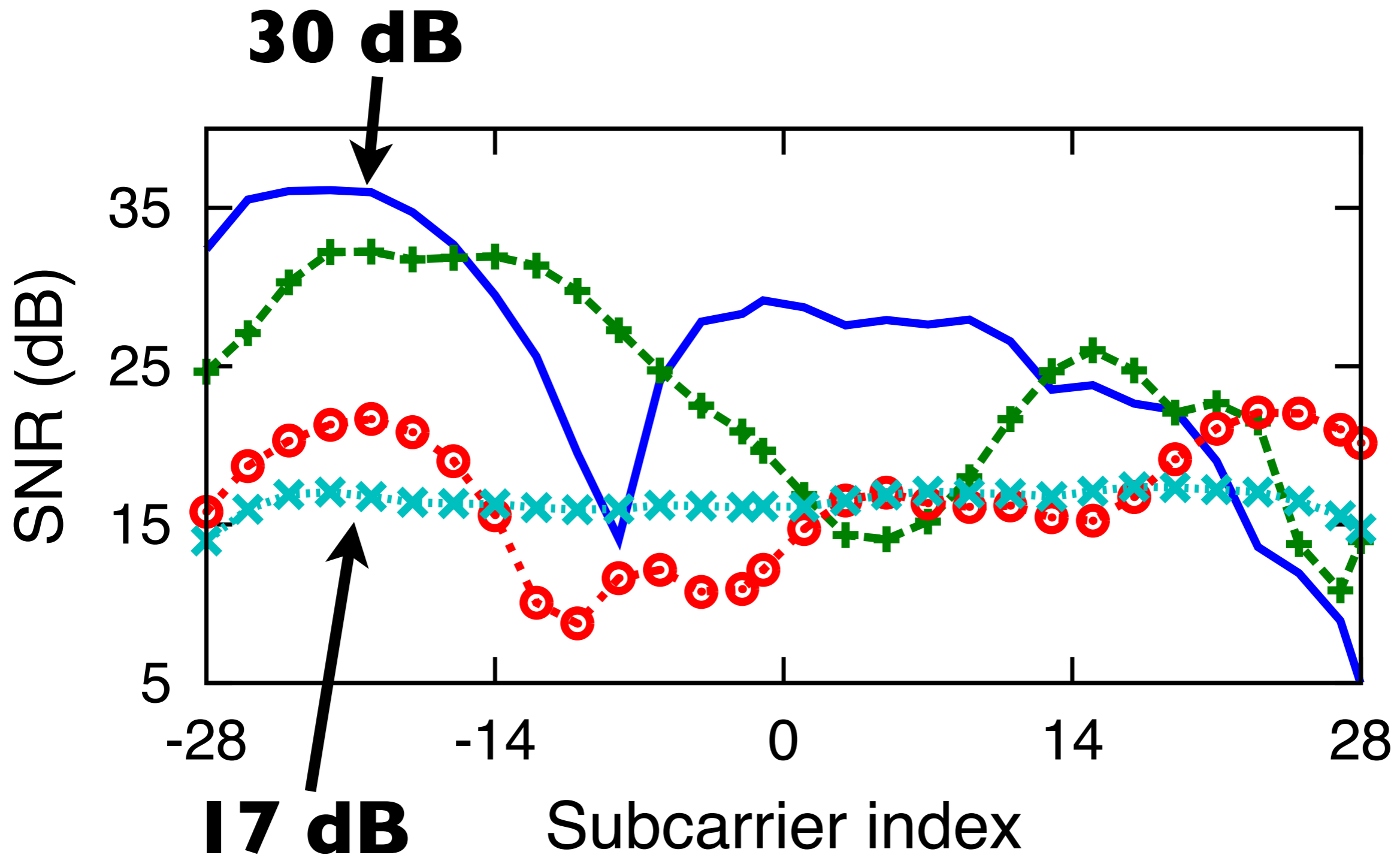
Packet SNR for 4 faded links



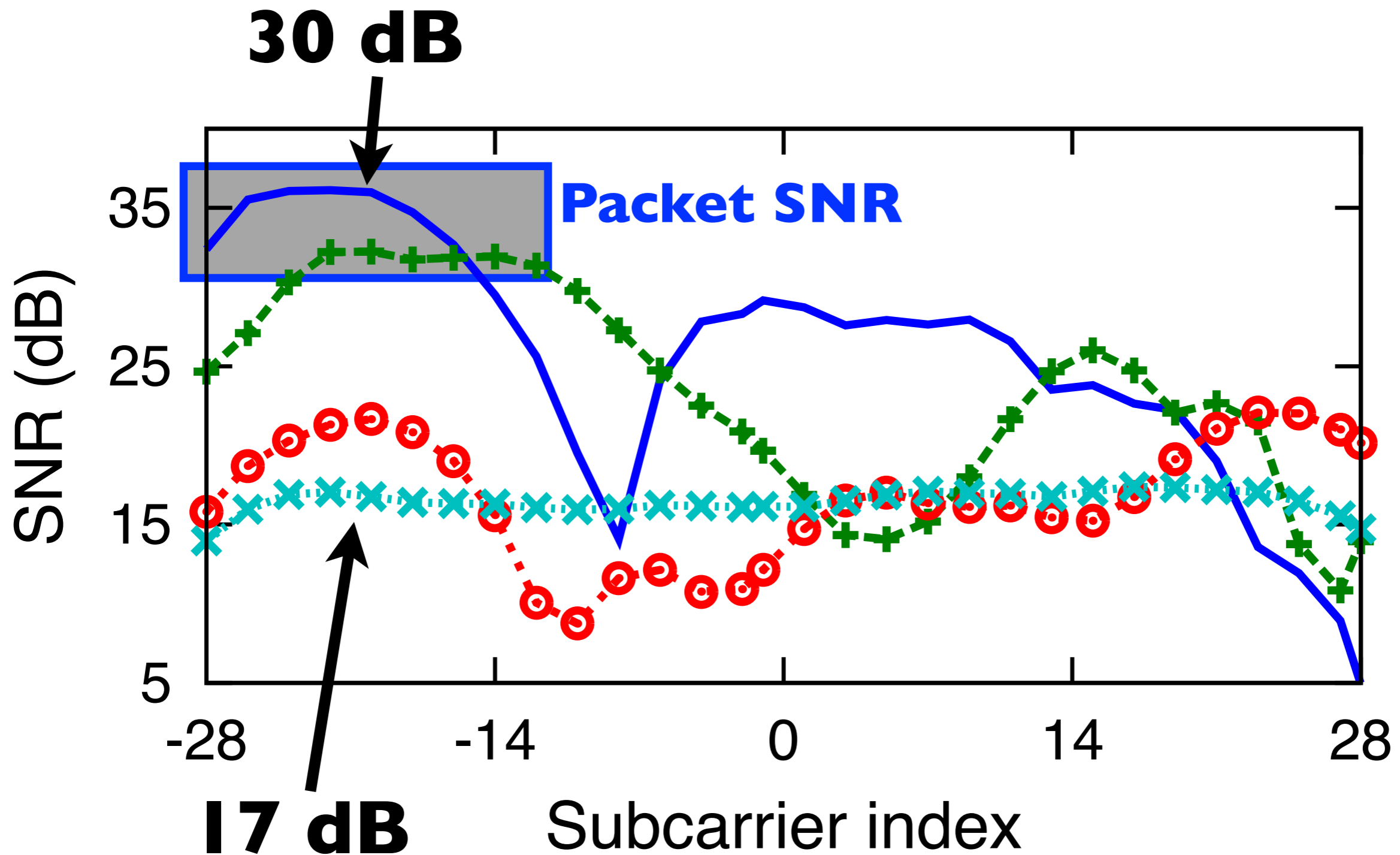
Packet SNR for 4 faded links



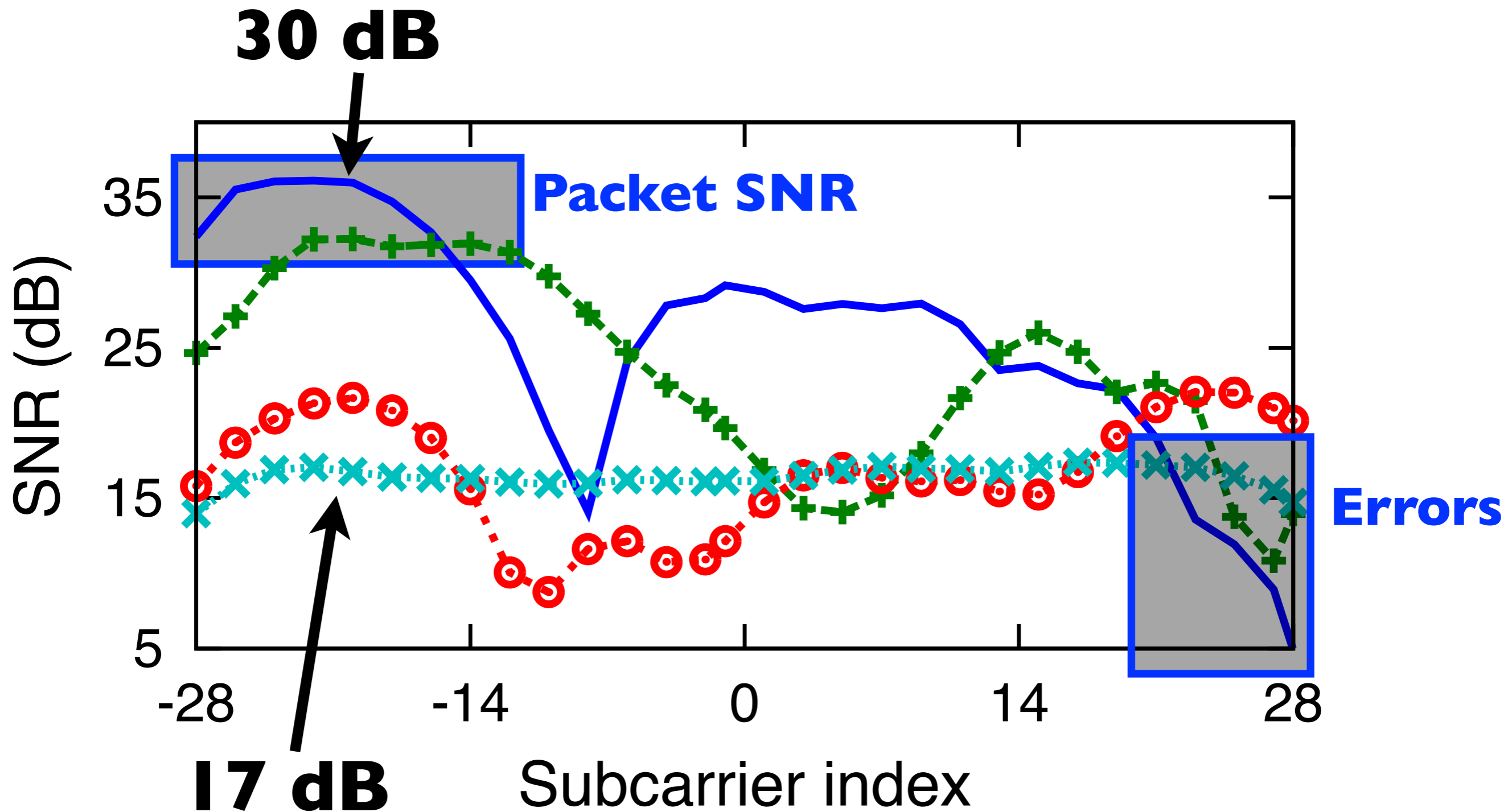
Packet SNR for 4 faded links



Packet SNR for 4 faded links

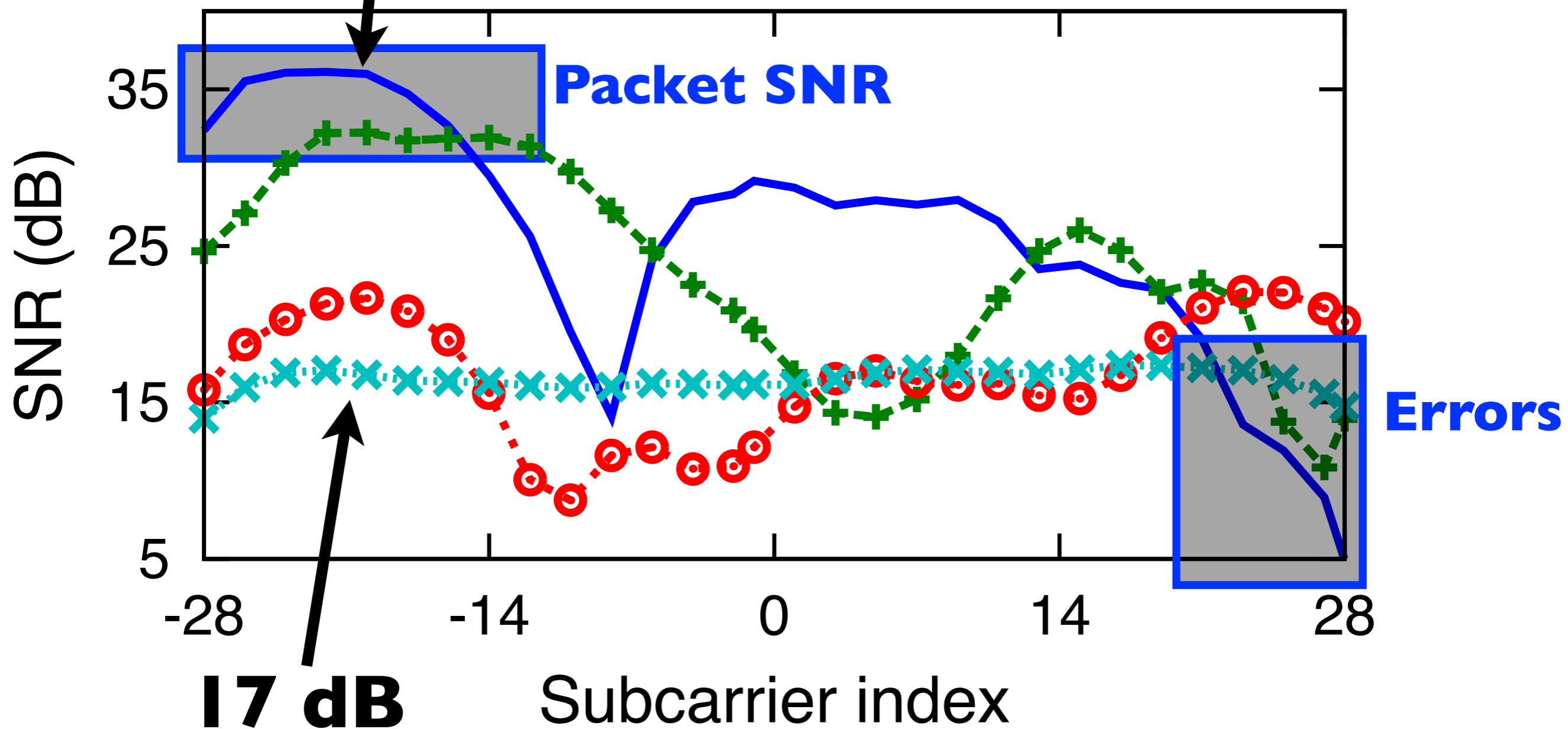


Packet SNR for 4 faded links



Packet SNR for 4 faded links

Fundamental SNR mismatch



An 802.11n opportunity

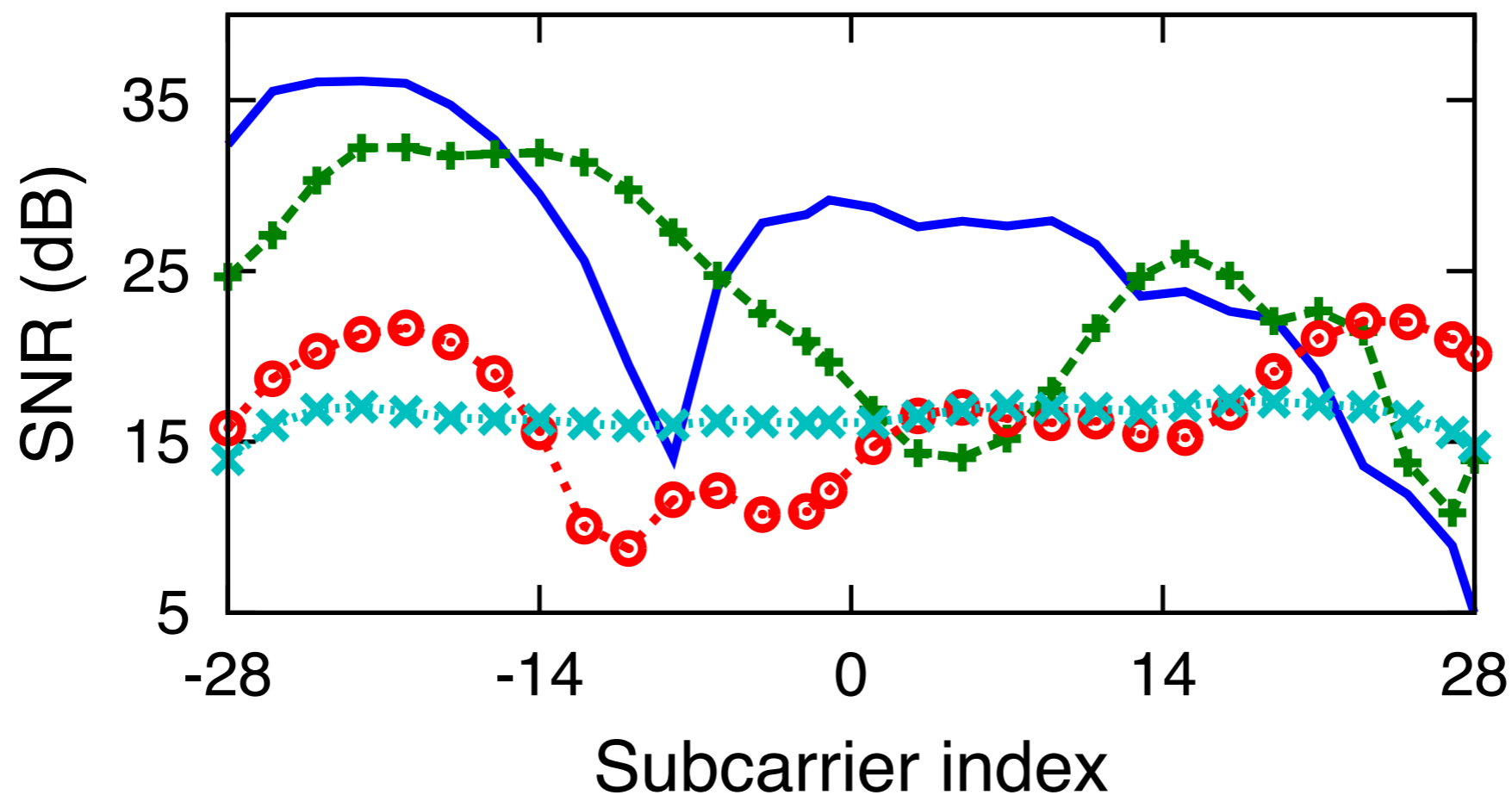
- *802.11n provides detailed channel measurements*
Used for advanced MIMO techniques
- ***Channel State Information (CSI) measures MIMO and OFDM!***
 - Matrix captures per-antenna paths
 - One matrix per subcarrier
- *Can we use it to predict packet delivery?*
In theory? In practice?

Today's talk

- Why it's hard to predict performance with RF measurements today
- Our solution: an accurate channel metric using ***Effective SNR***
- Evaluation of Effective SNR in Wi-Fi Networks

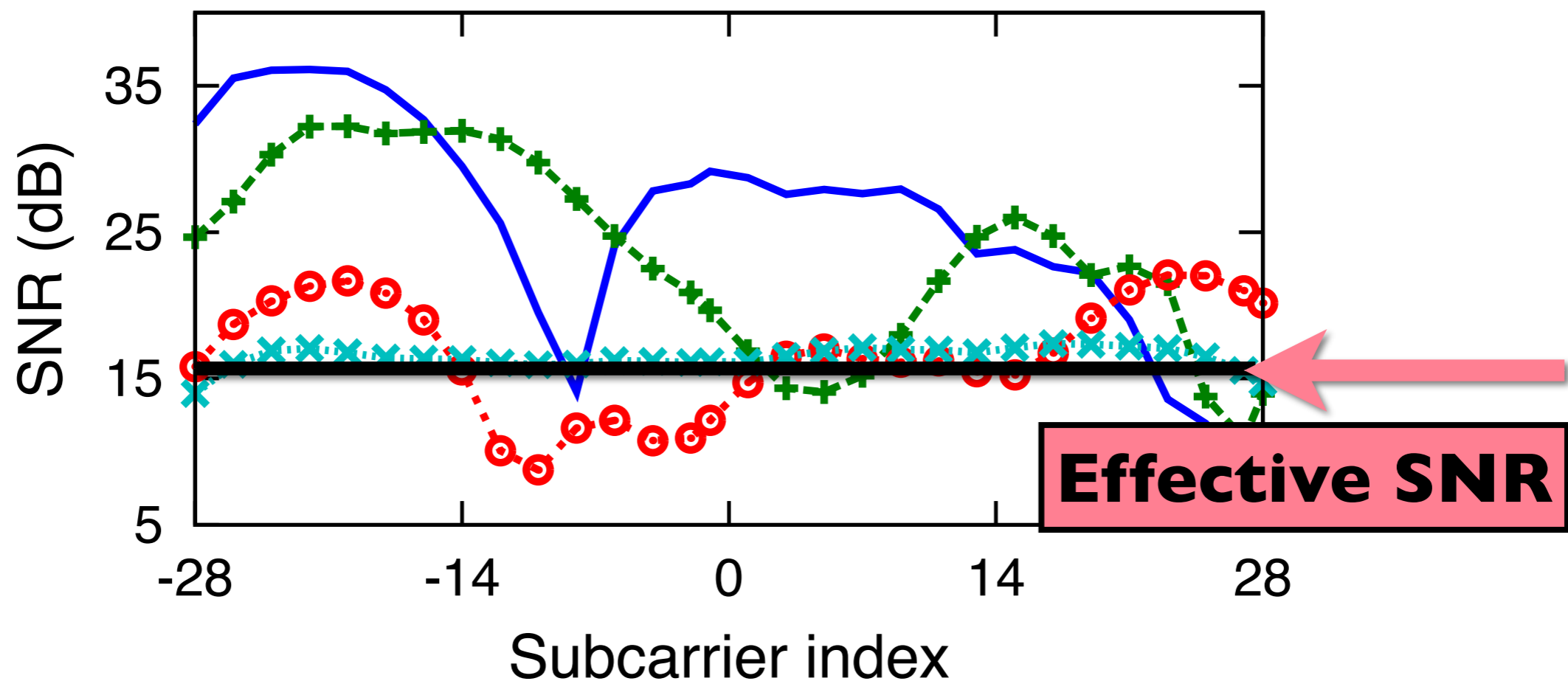
Effective SNR

- Introduced by Nanda and Rege in 1998
- **Packet SNR:** total power in the link
- **Effective SNR:** useful power in the link

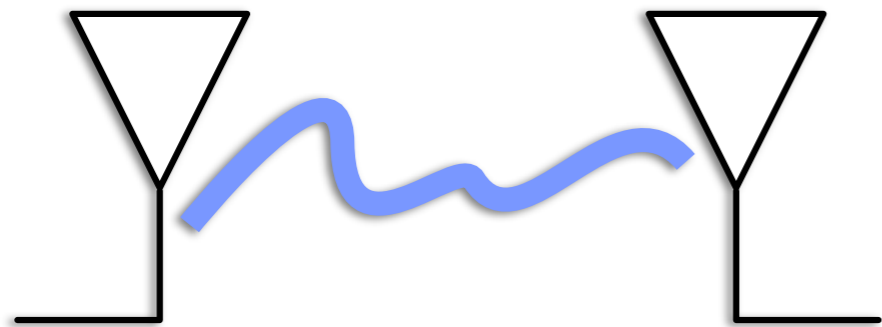


Effective SNR

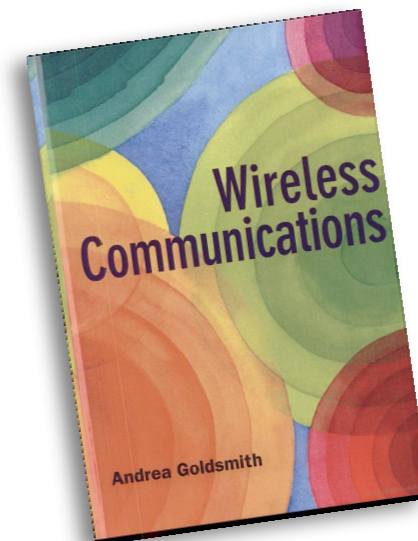
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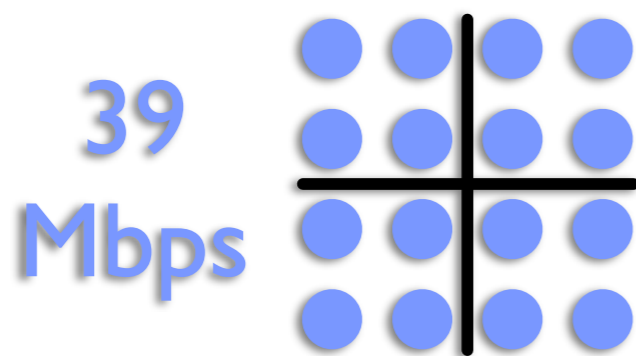
Using Effective SNR



Channel Measurements

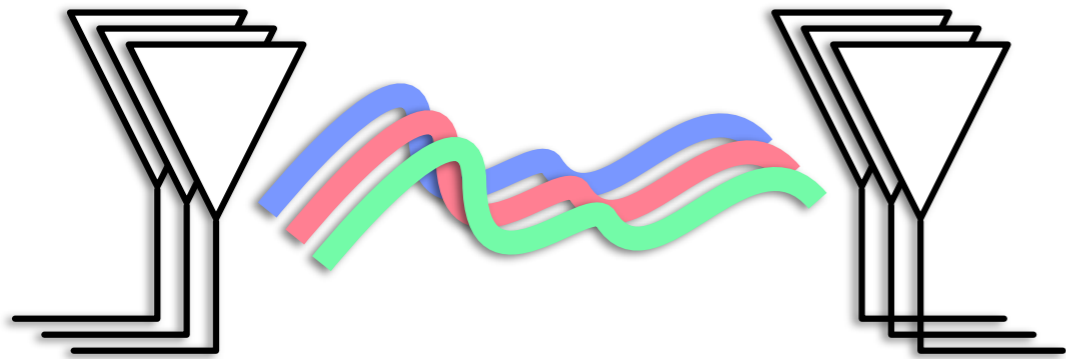


Textbook Algorithms

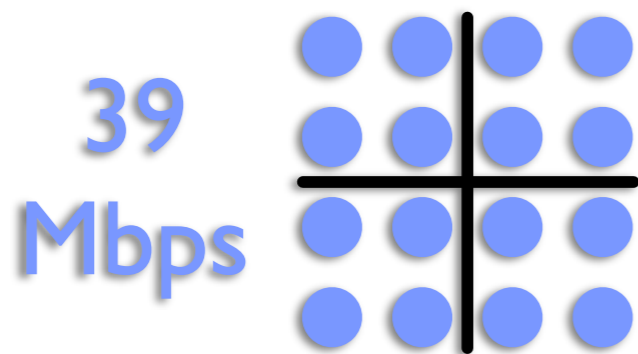


Rate Selection

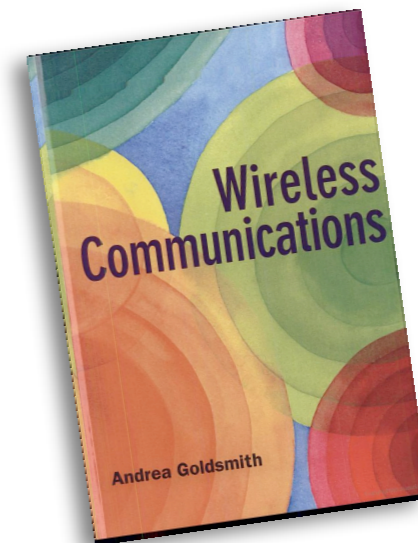
Using Effective SNR



Channel State Information
(MIMO & OFDM)

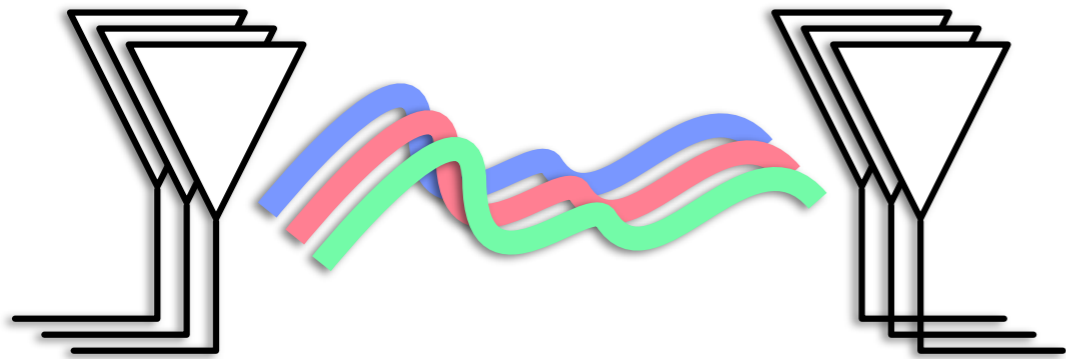


Rate Selection

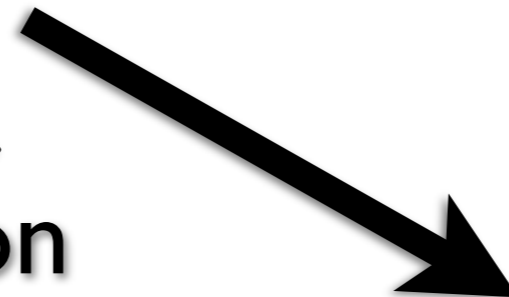


Textbook Algorithms

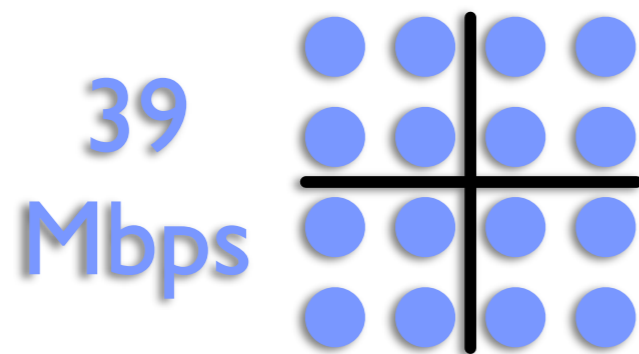
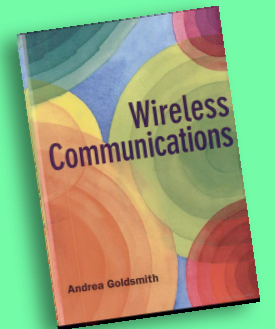
Using Effective SNR



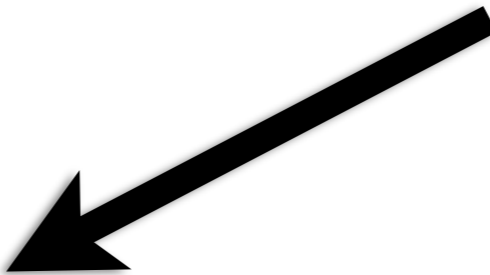
Channel State Information
(MIMO & OFDM)



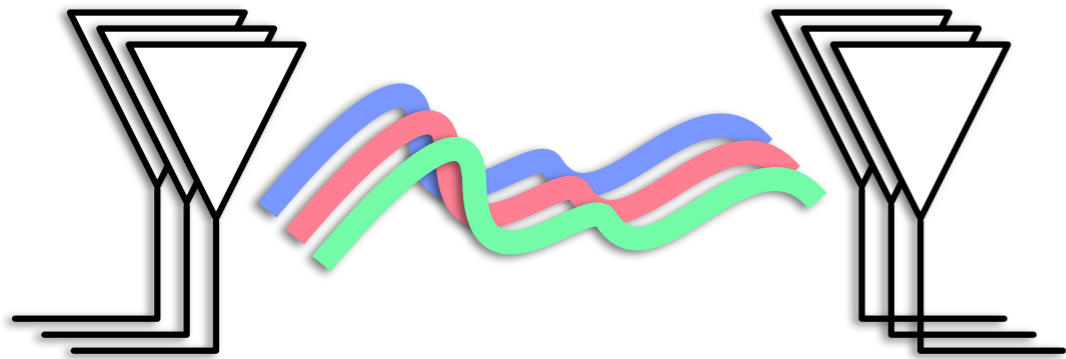
**Effective
SNR Model**



Rate Selection



Using Effective SNR

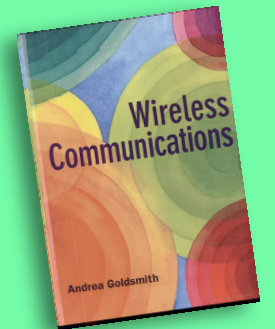


Channel State Information
(MIMO & OFDM)

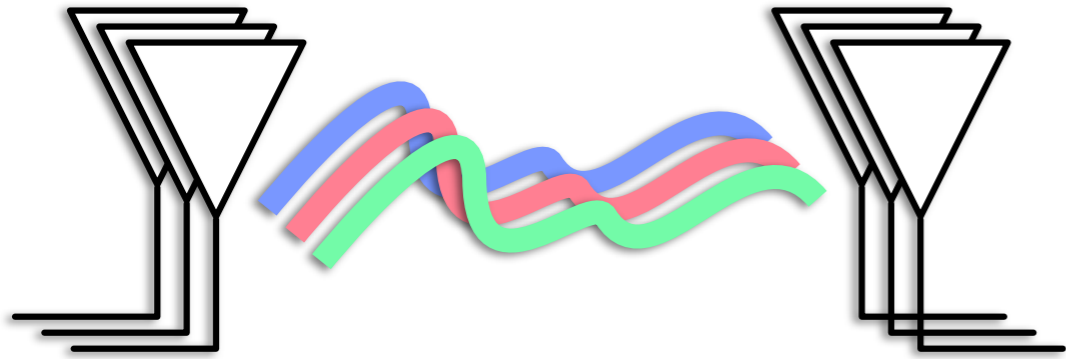
1x65	X
1x52	X
2x26	✓
3x13	✓

Working Configurations;
Application Decision

**Effective
SNR Model**

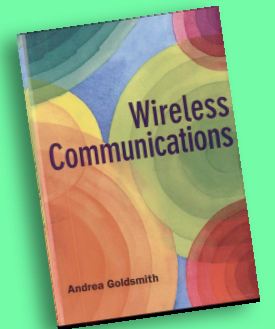


Using Effective SNR



Channel State Information
(MIMO & OFDM)

**Effective
SNR Model**

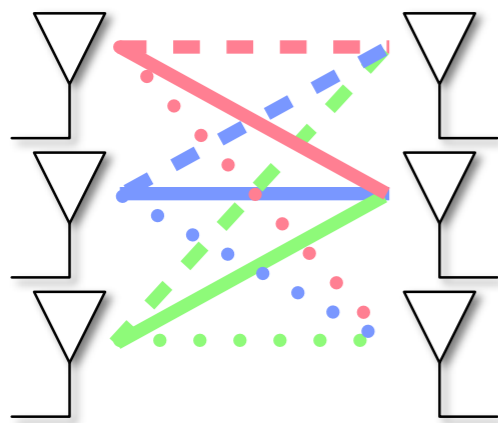


1x65 X
1x52 X
2x26 ✓
3x13 ✓

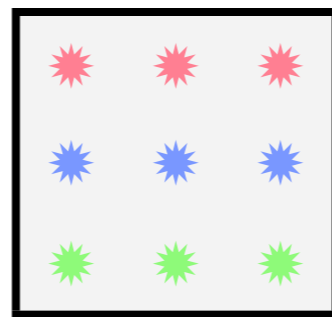
Working Configurations;
Application Decision

Obtaining CSI

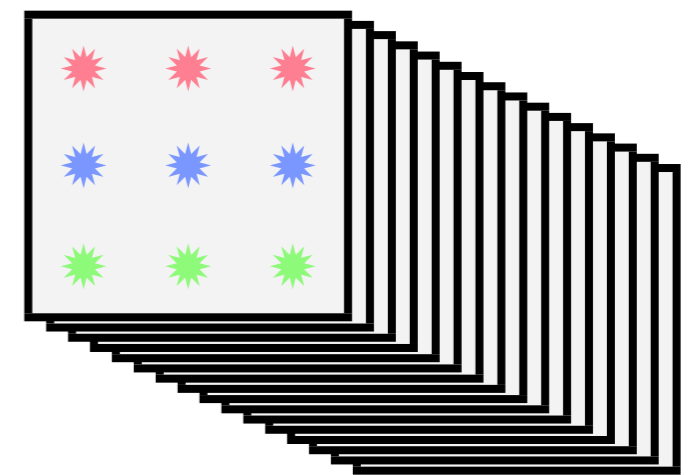
- *RX measures CSI* from packet preamble
NICs do this for MIMO/OFDM operation
- *For every received frame*
Measures ***all antennas + subcarriers*** used



3-antenna Link

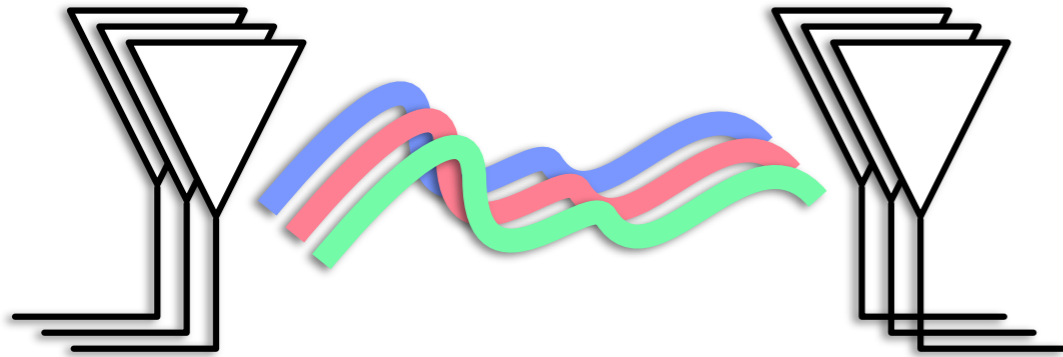


3x3 Matrix



One matrix
per Subcarrier

Using Effective SNR

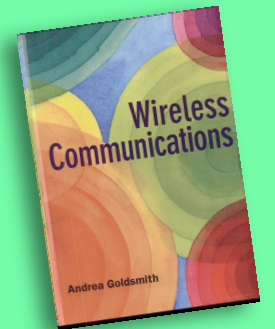


Channel State Information
(MIMO & OFDM)

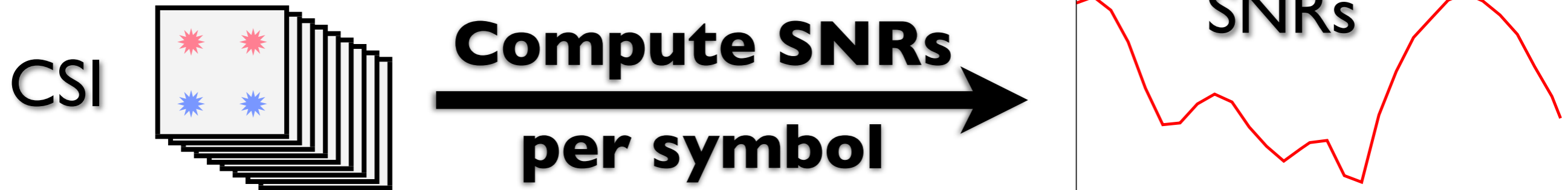
- 1x65 ✗
- 1x52 ✗
- 2x26 ✓
- 3x13 ✓

Working Configurations;
Application Decision

**Effective
SNR Model**

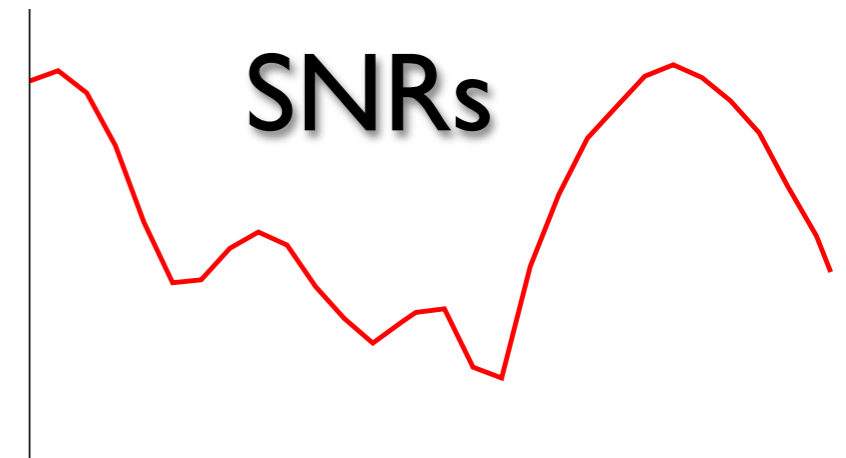
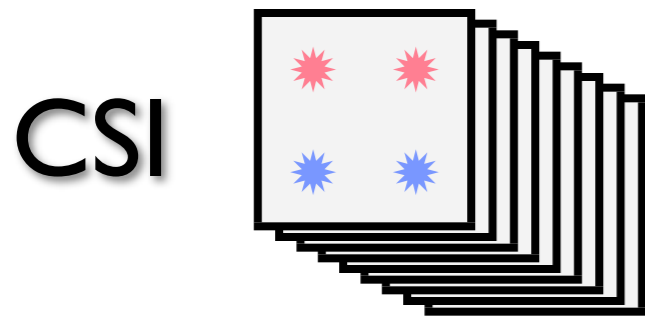


Computing Effective SNR



- *Single antenna link (1×1)*
CSI gives the per-symbol SNR
- *Multiple RX antennas ($1 \times N$)*
Maximal-ratio combining
- *MIMO link ($M \times N$)*
Minimum mean-square error (**MMSE**)

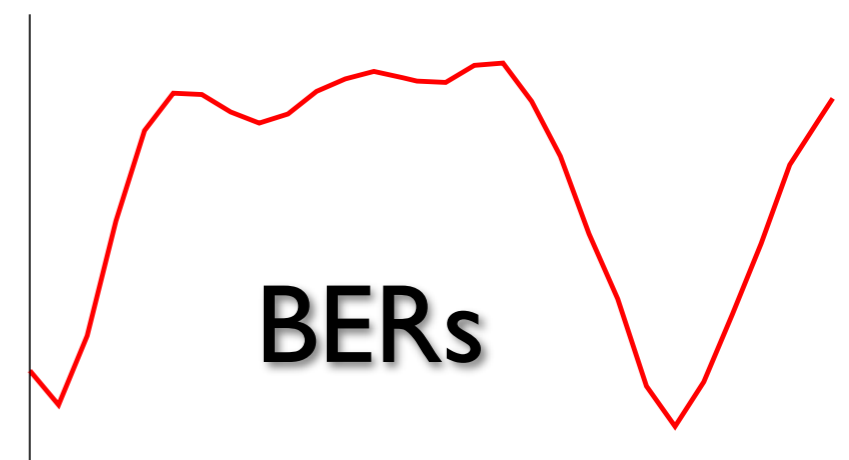

Computing Effective SNR



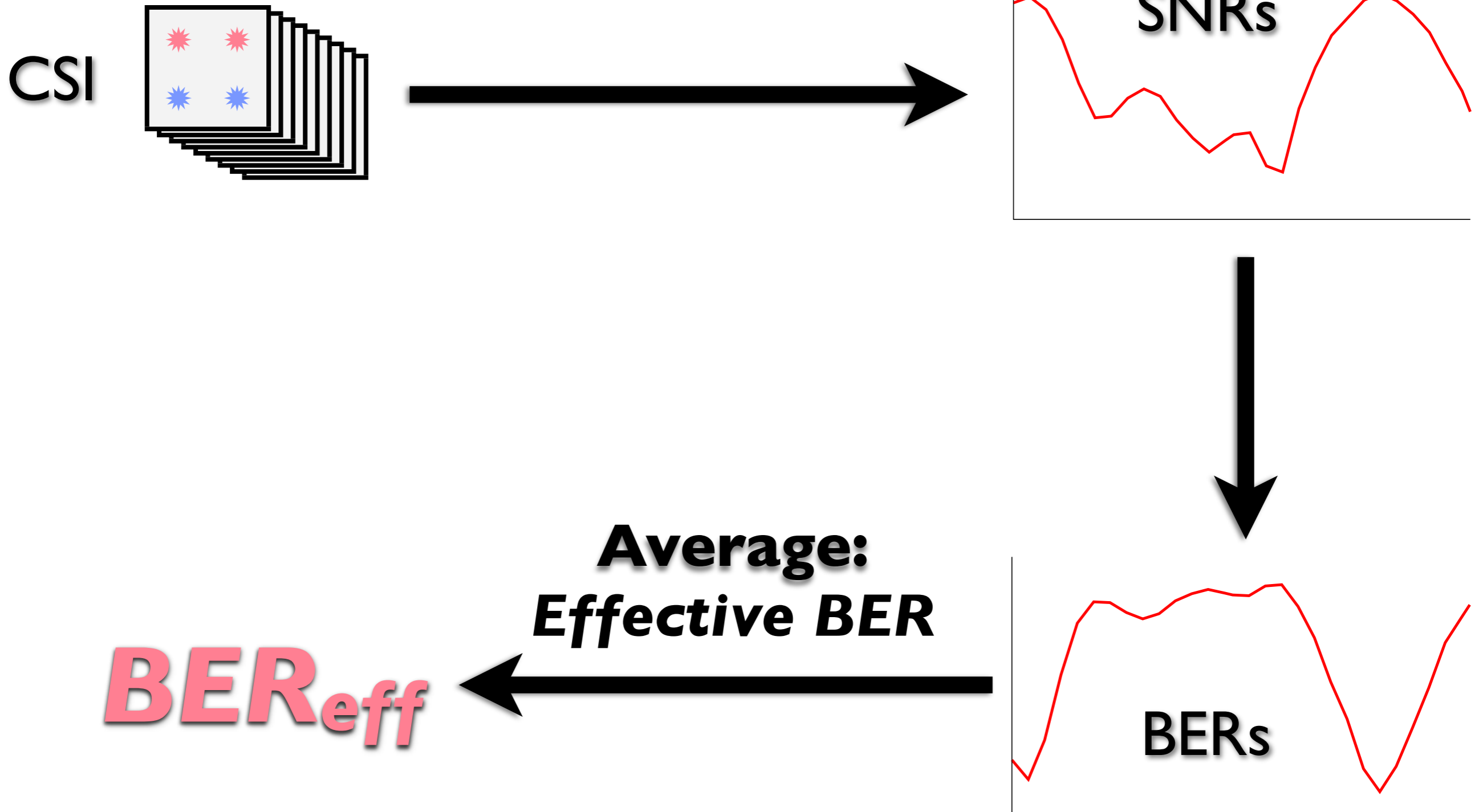
Modulation	BER(ρ)
BPSK	$Q(\sqrt{2\rho})$
QPSK	$Q(\sqrt{\rho})$
QAM-16	$Q(\sqrt{\rho/5})$
QAM-64	$Q(\sqrt{\rho/21})$

**Textbook
formulas**

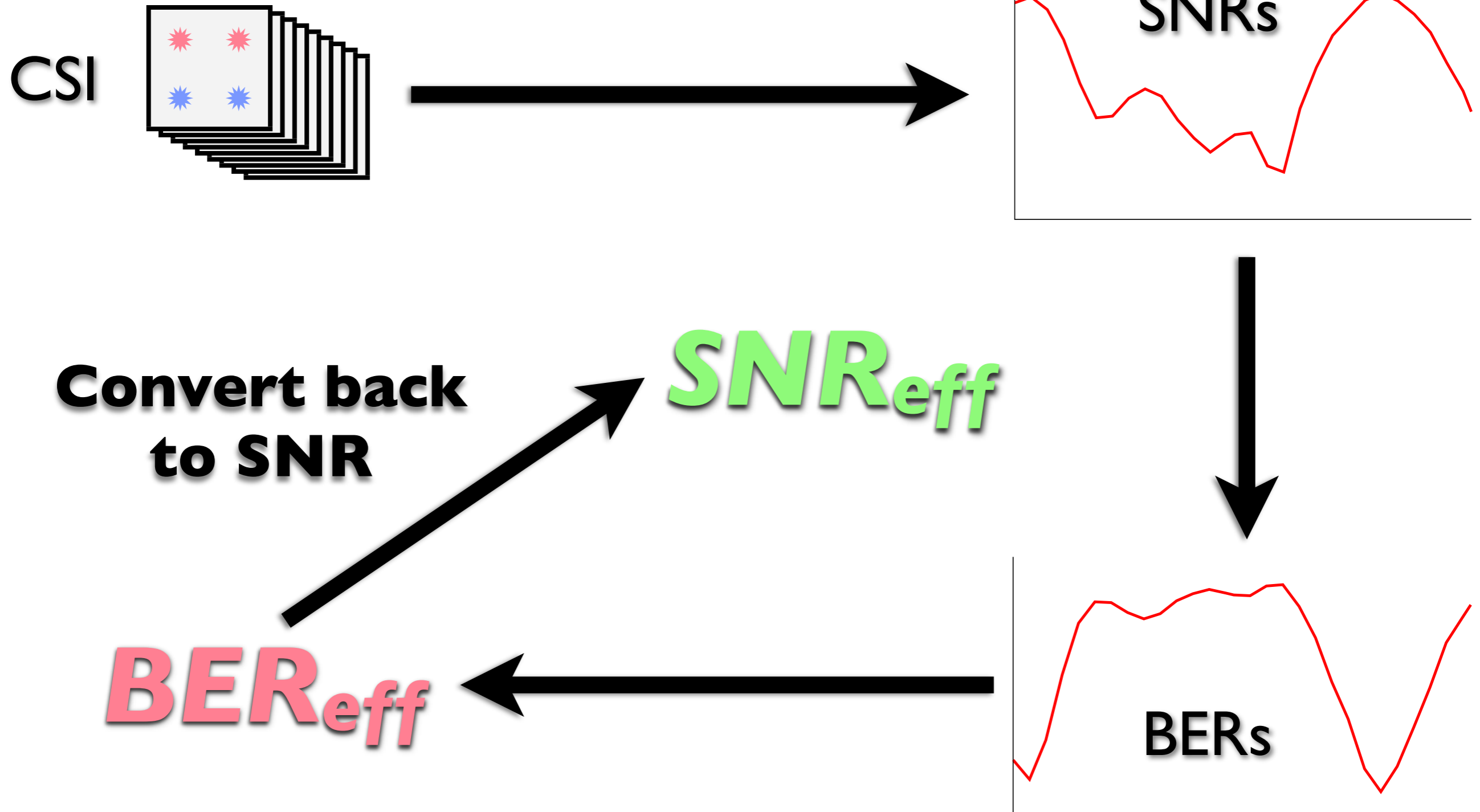
**Compute
BERs
per symbol**



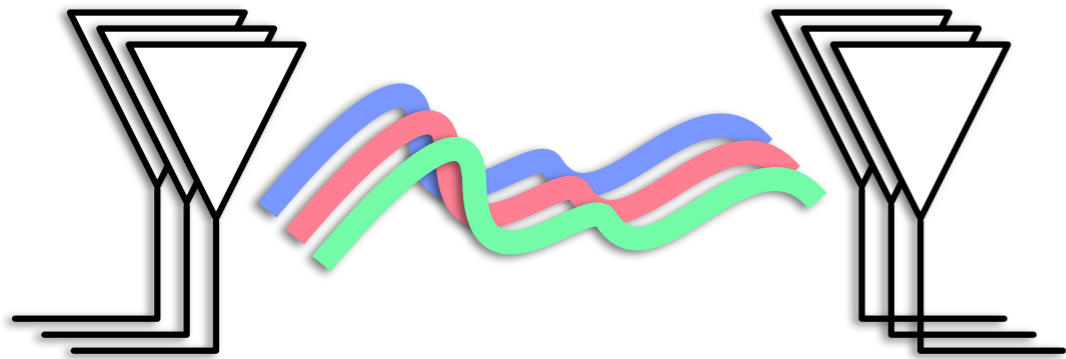
Computing Effective SNR



Computing Effective SNR

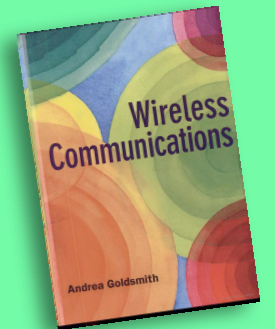


Using Effective SNR



Channel State Information
(MIMO & OFDM)

**Effective
SNR Model**



1x65	X
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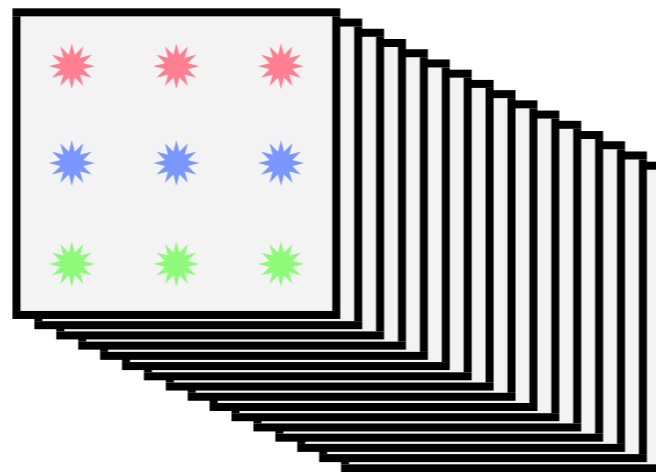
Working Configurations;
Application Decision

Predicting Packet Delivery

- ***Effective SNR thresholds*** for each rate
 - Threshold per ***NIC implementation***, not per NIC or per channel
- Adds ***flexibility*** to handle real NICs
 - *Hard vs soft decoding*
 - *Other special techniques*
e.g., use optimal Maximum Likelihood receiver only for small modulations

Example Applications

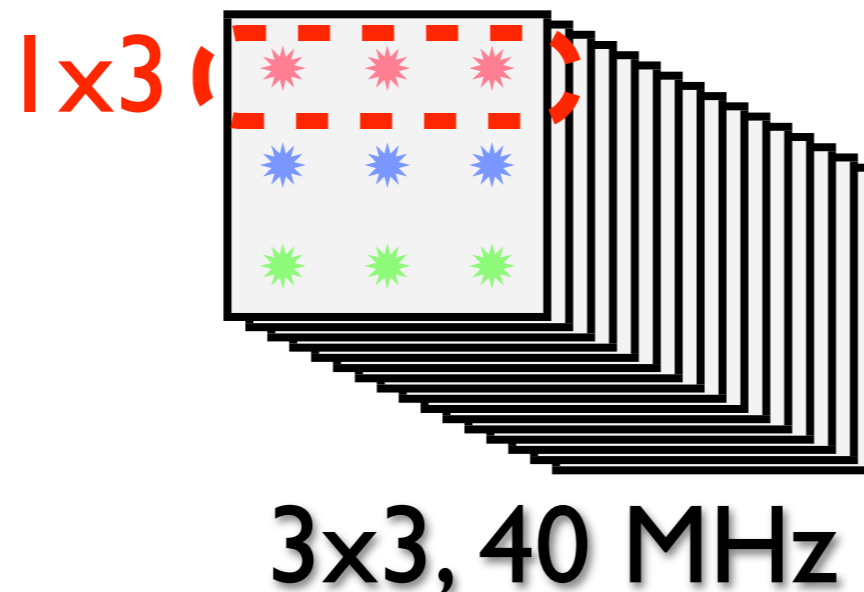
- **Rate/MIMO/Channel width selection:**
What is the fastest configuration for this link?



3x3, 40 MHz

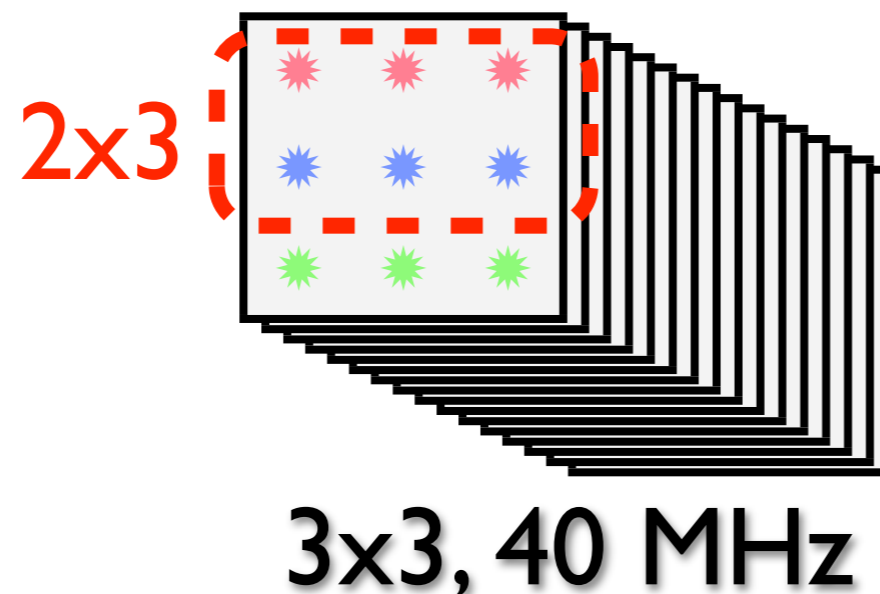
Example Applications

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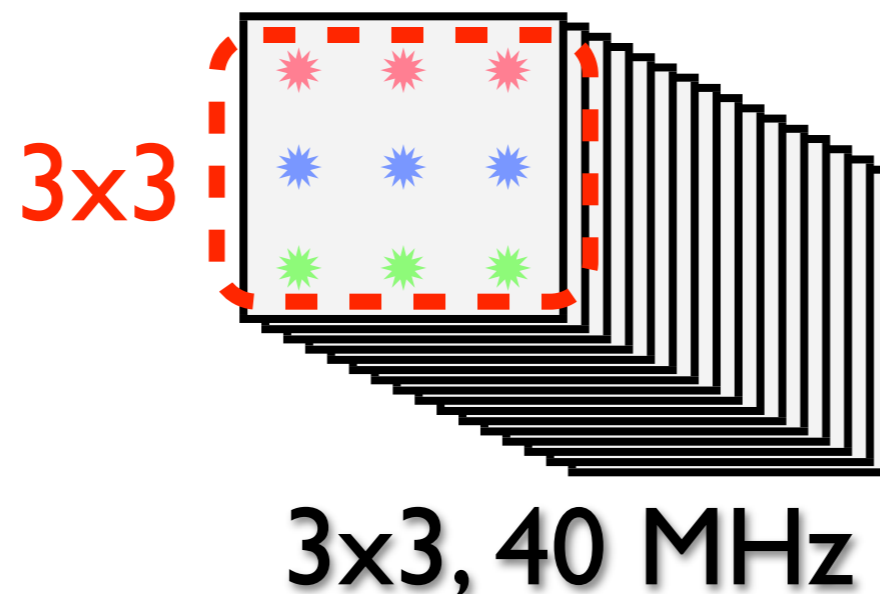
Example Applications

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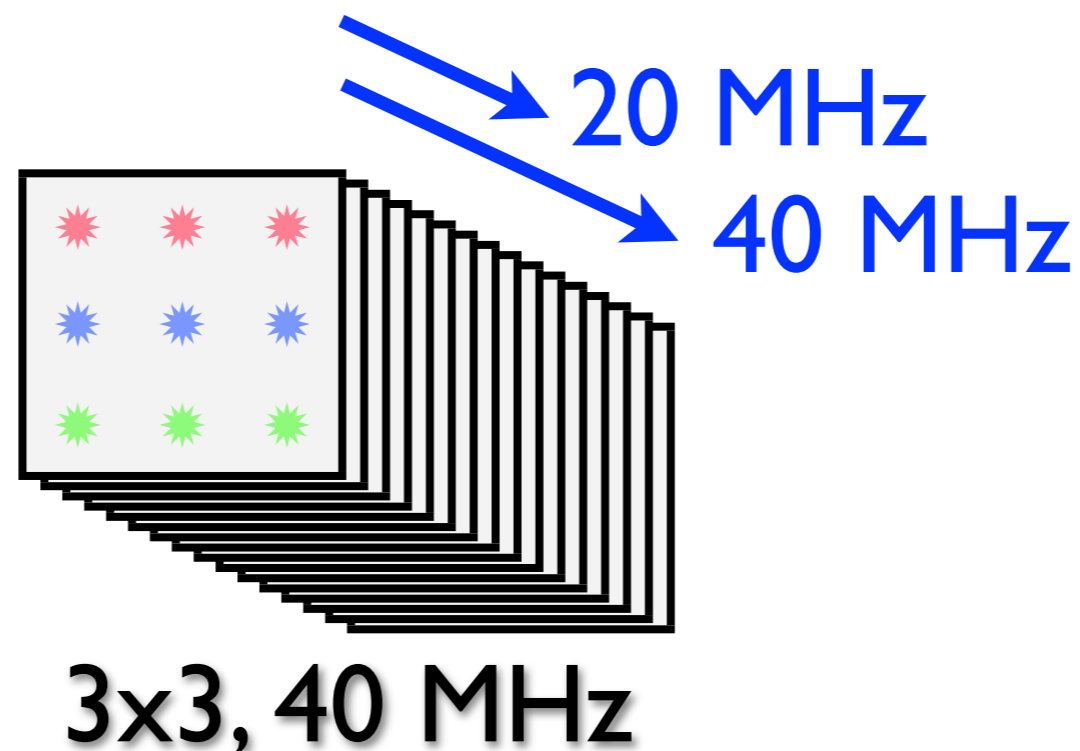
Example Applications

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Example Applications

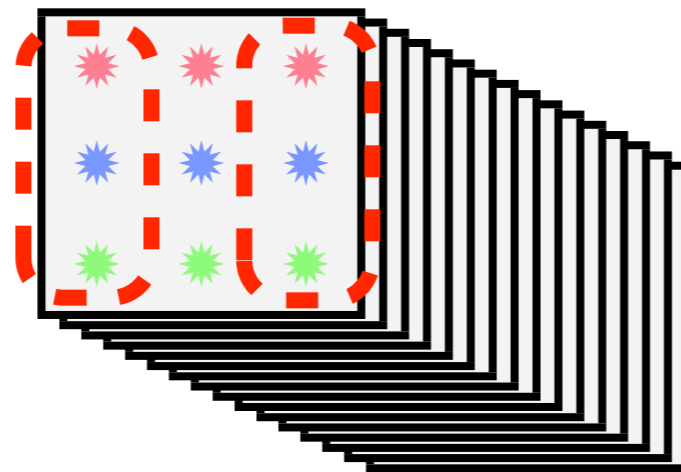
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What is the fastest configuration for this link?



Example Applications

- **Power Consumption:**
Which receive antenna is best to disable to save power?

RX Antenna
Selection



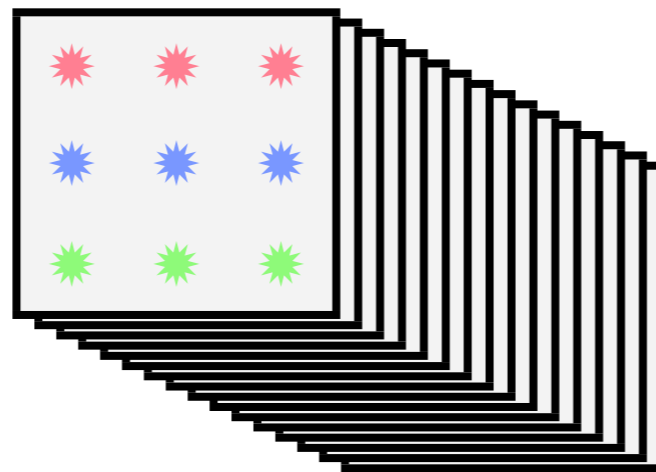
3x3, 40 MHz

Example Applications

- **Spatial Reuse:**

What is the lowest transmit power at which I can support 100 Mbps bitrate?

Power ×

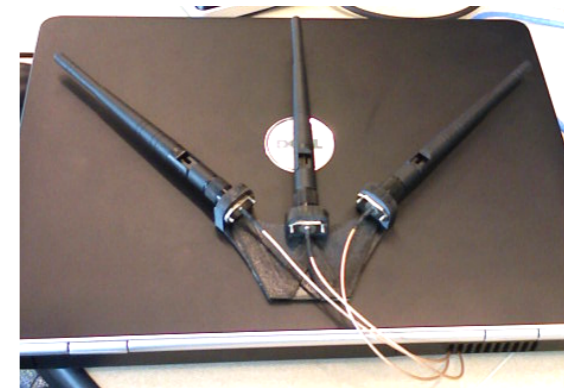
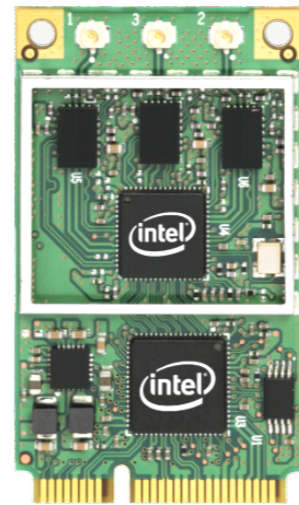


3x3, 40 MHz

Today's talk

- Why it's hard to predict performance with RF measurements
- Our solution building a better metric using ***Effective SNR***
- Evaluation of Effective SNR in Wi-Fi Networks

Implemented in Intel NIC



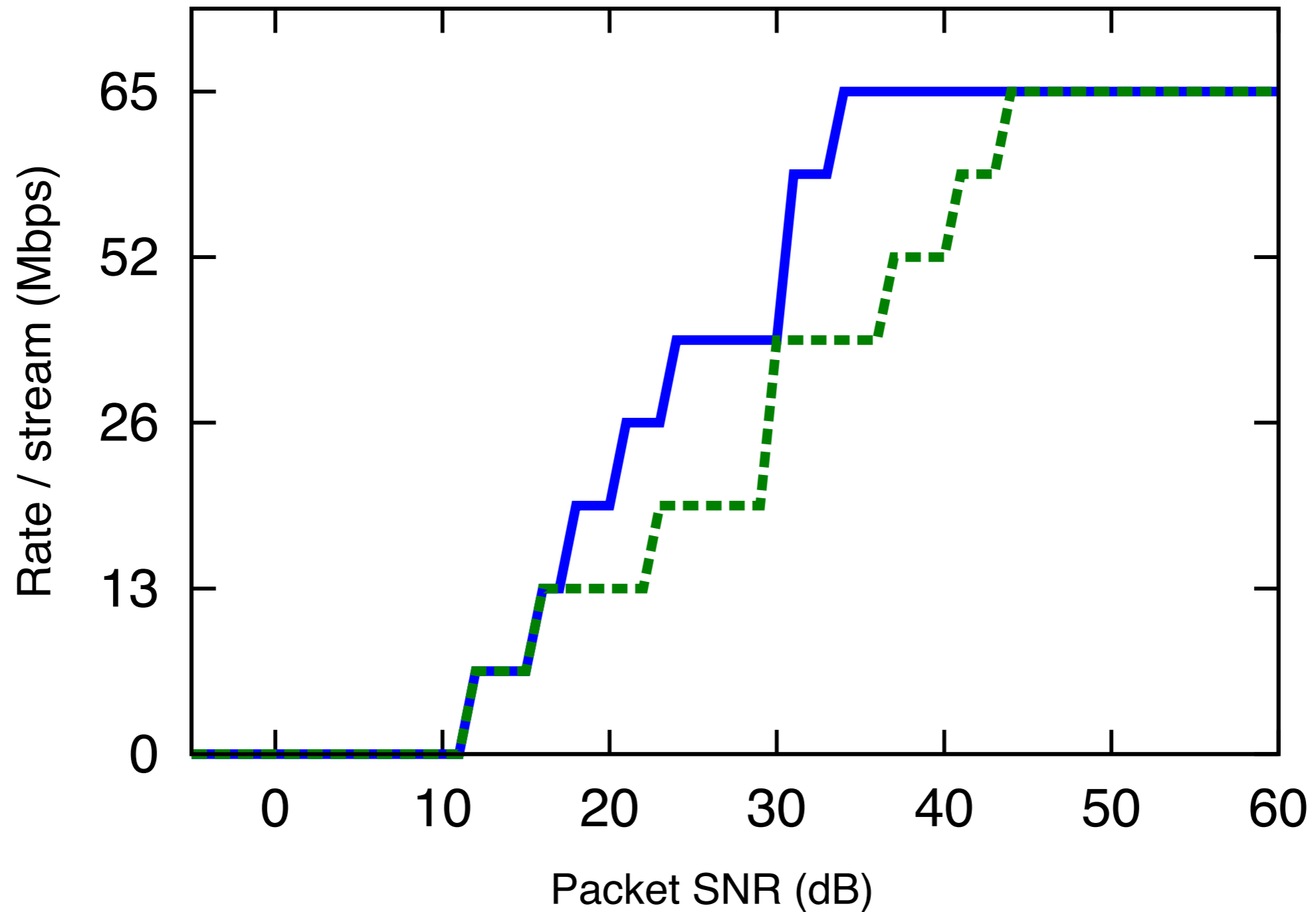
- Intel Wi-Fi Link 5300 NIC (3x3, 450 Mbps)
- Two testbeds with > 200 widely varying links
- Linux (2.6.35-rc3) open source ***iwlwifi*** driver
- Firmware ***debug mode***: send CSI to RX host
- Real-time computation: **$\sim 4 \mu\text{s}$** per 3x3 CSI

Evaluation Questions

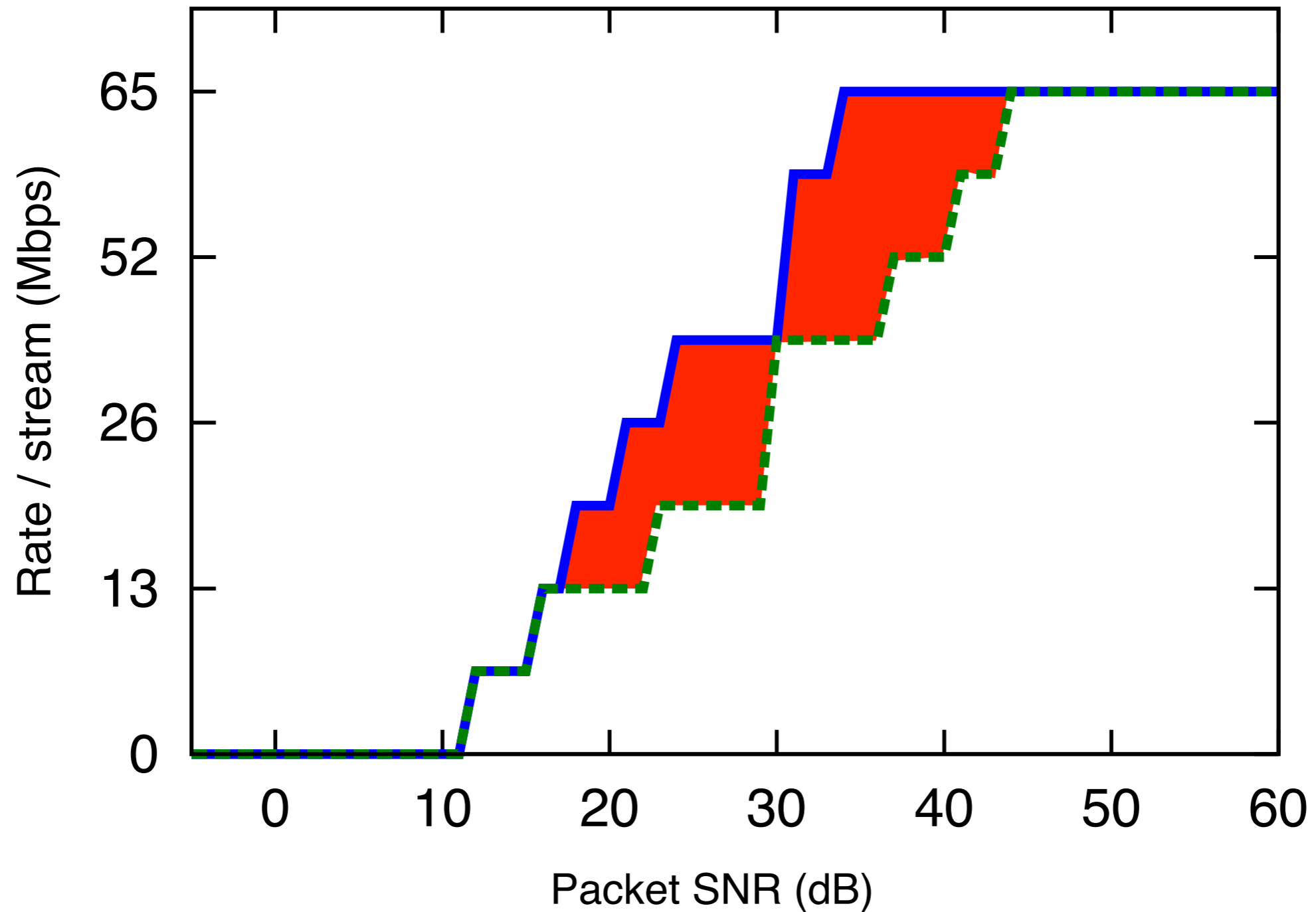
- **Does Effective SNR accurately predict packet delivery?**
- **Does an Effective SNR rate selection algorithm perform well?**
- More results in the paper
 - *Wireless link transition region*
 - *Transmit power control*
 - *Collisions*

Predicting Optimal 3x3 Rate

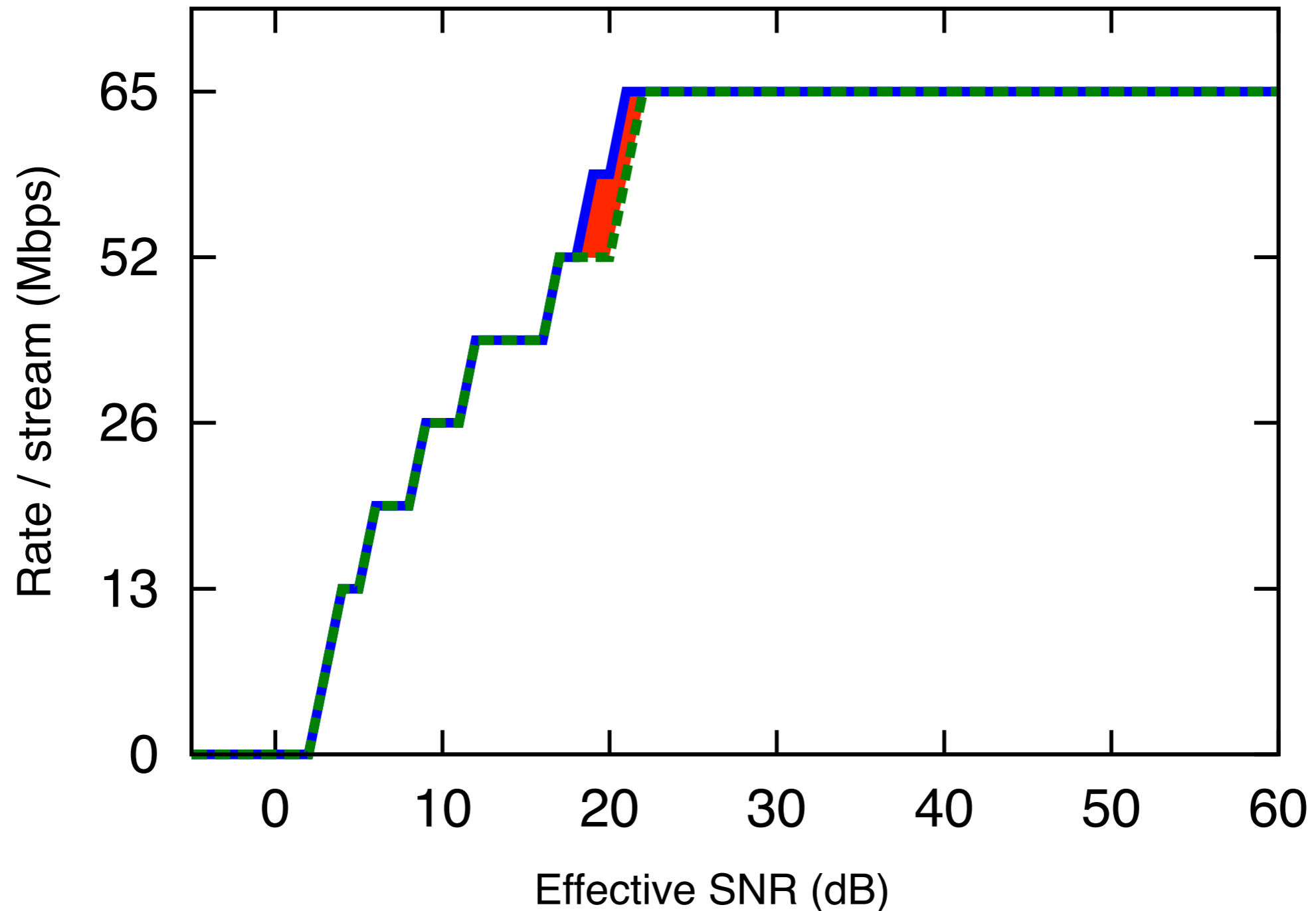
Predicting Optimal 3x3 Rate



Predicting Optimal 3x3 Rate



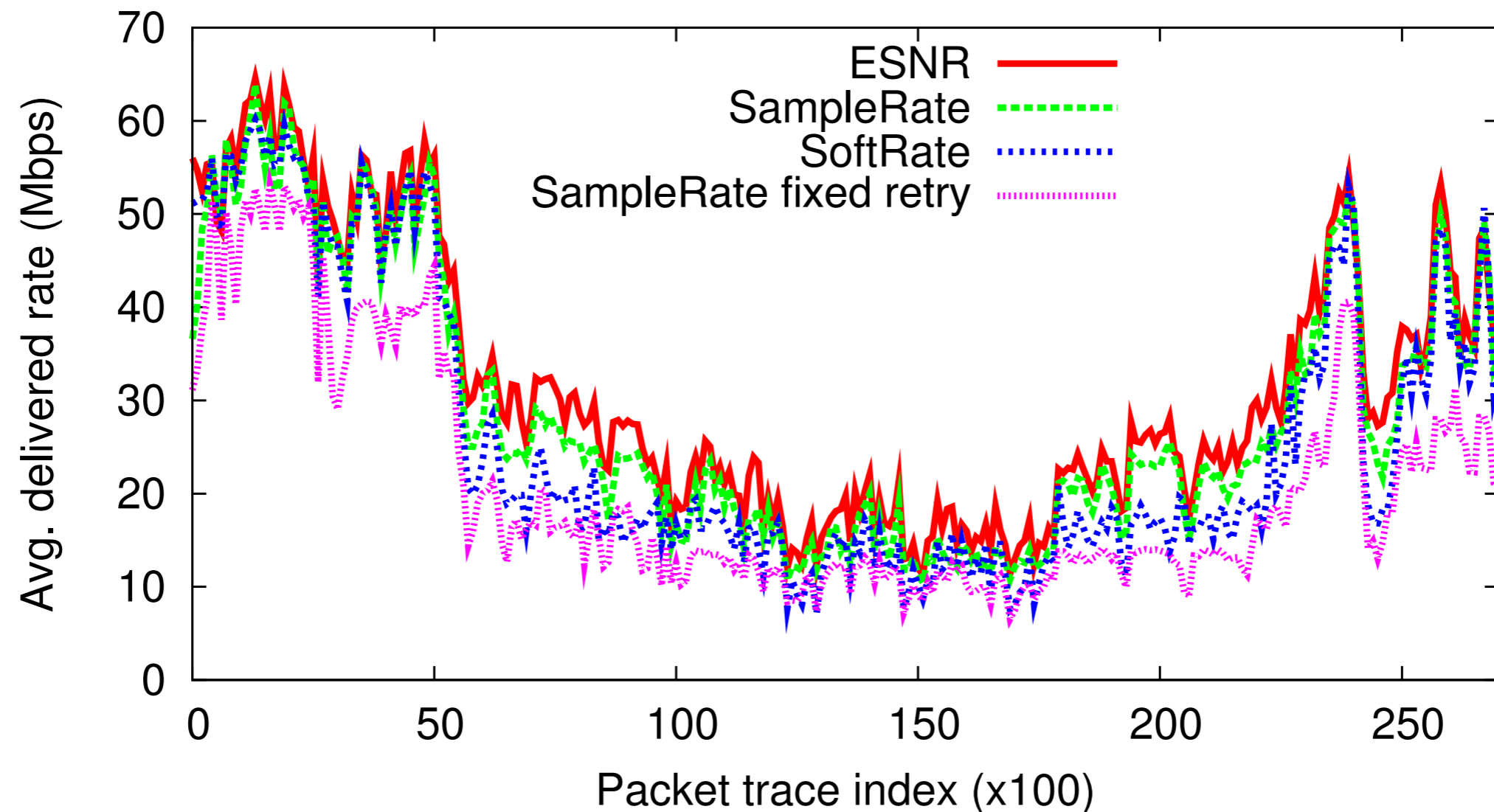
Predicting Optimal 3x3 Rate



Rate control evaluation

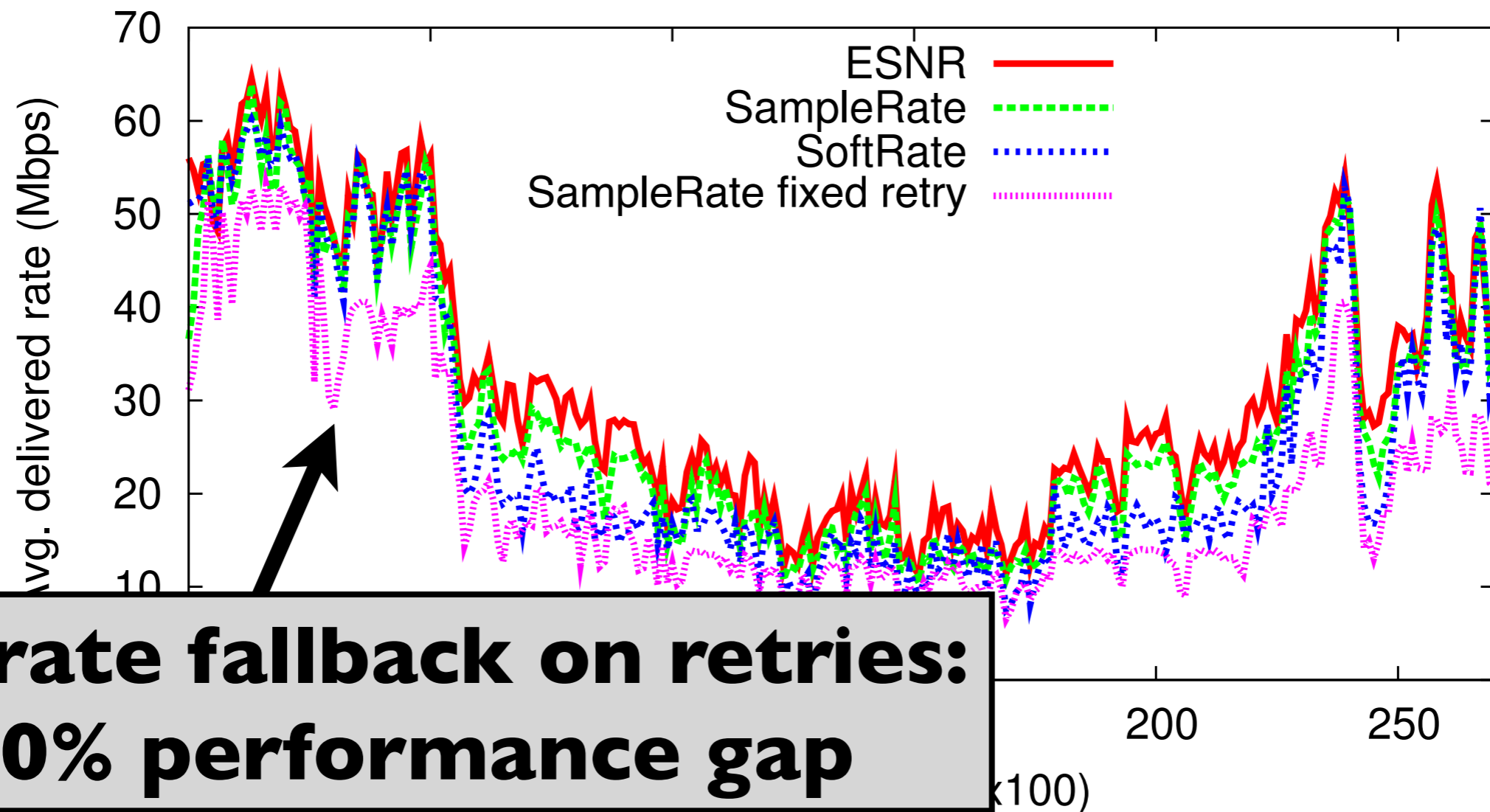
- **802.11a:** Does *Effective SNR* match related work?
ESNR versus SampleRate, SoftRate, OPT
- **802.11n:** Does *Effective SNR* extend to 802.11n?
ESNR versus OPT
- **Channel simulation over mobile trace**
to compare against related work & vary speed
 - MATLAB simulation + SoftRate GNU Radio
 - Effective SNR algorithm gets corrupted CSI

Effective SNR for 802.11a



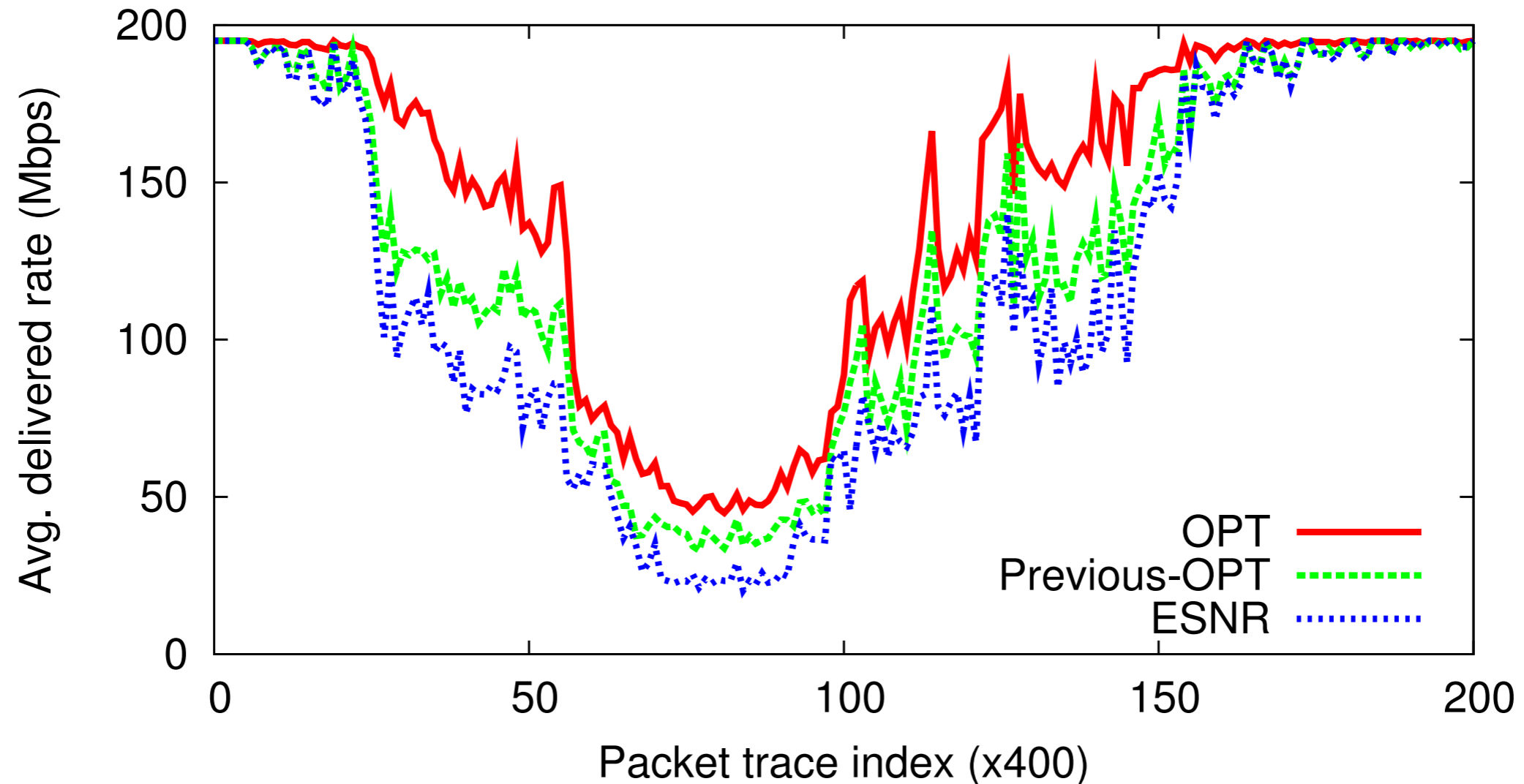
- ***Matches or beats 802.11a algorithms***
- **All within 15% of OPT**

Effective SNR for 802.11a



- ***Matches or beats 802.11a algorithms***
- **All within 15% of OPT**

ESNR extends to MIMO



- 80% accuracy, 10% overselection
- 24 rates vs 8, larger gap vs Previous-OPT

Related work

Related work

802.11a

SoftRate
(2009)



AccuRate
(2010)



Error Estim.
Codes (2010)



**Effective
SNR**



Related work

	802.11a	MIMO & Ant Sel.	TX Power	Channel Width	Real NICs
SoftRate (2009)	✓				
AccuRate (2010)	✓		✓	✓	
Error Estim. Codes (2010)	✓				✓
Effective SNR	✓	✓	✓	✓	✓

Conclusions

- For the first time, we can use **measurements available in real NICs** to **predict packet delivery over real channels**
- **Matches good performance** of existing rate adaptation algorithms and **extends to 802.11n**
- Applies to a **broad problem space** and provides a **simple, practical API** for protocols
- *Lots more in the paper!*

Thanks! Questions?

dhalperi@cs.washington.edu