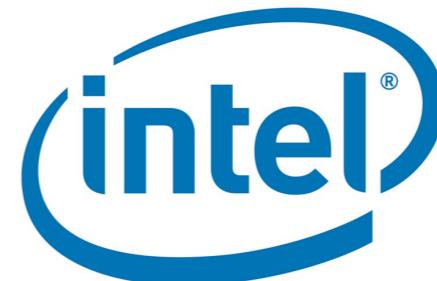


Predictable 802.11 Packet Delivery from Wireless Channel Measurements

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

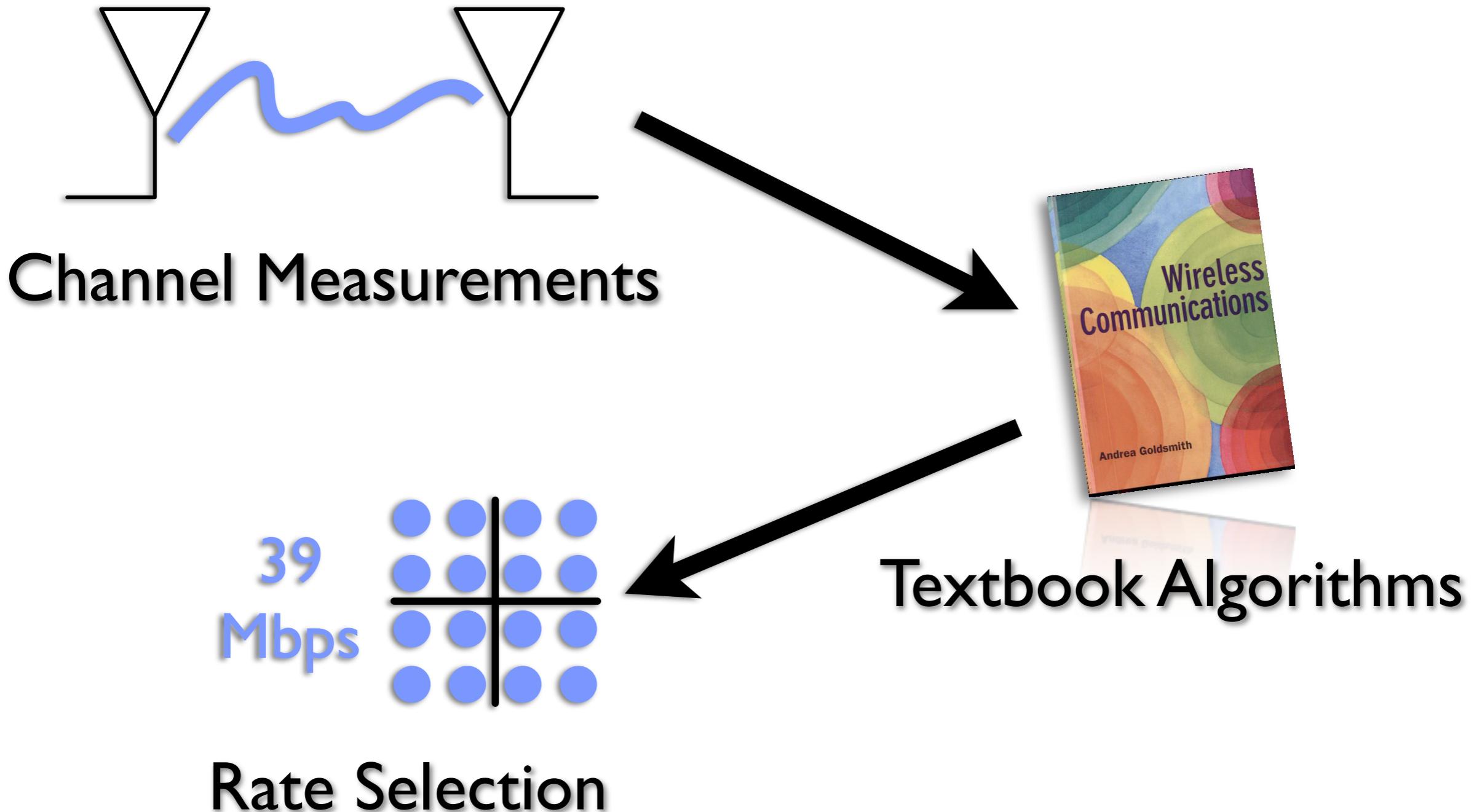
New apps stress network



New apps stress network



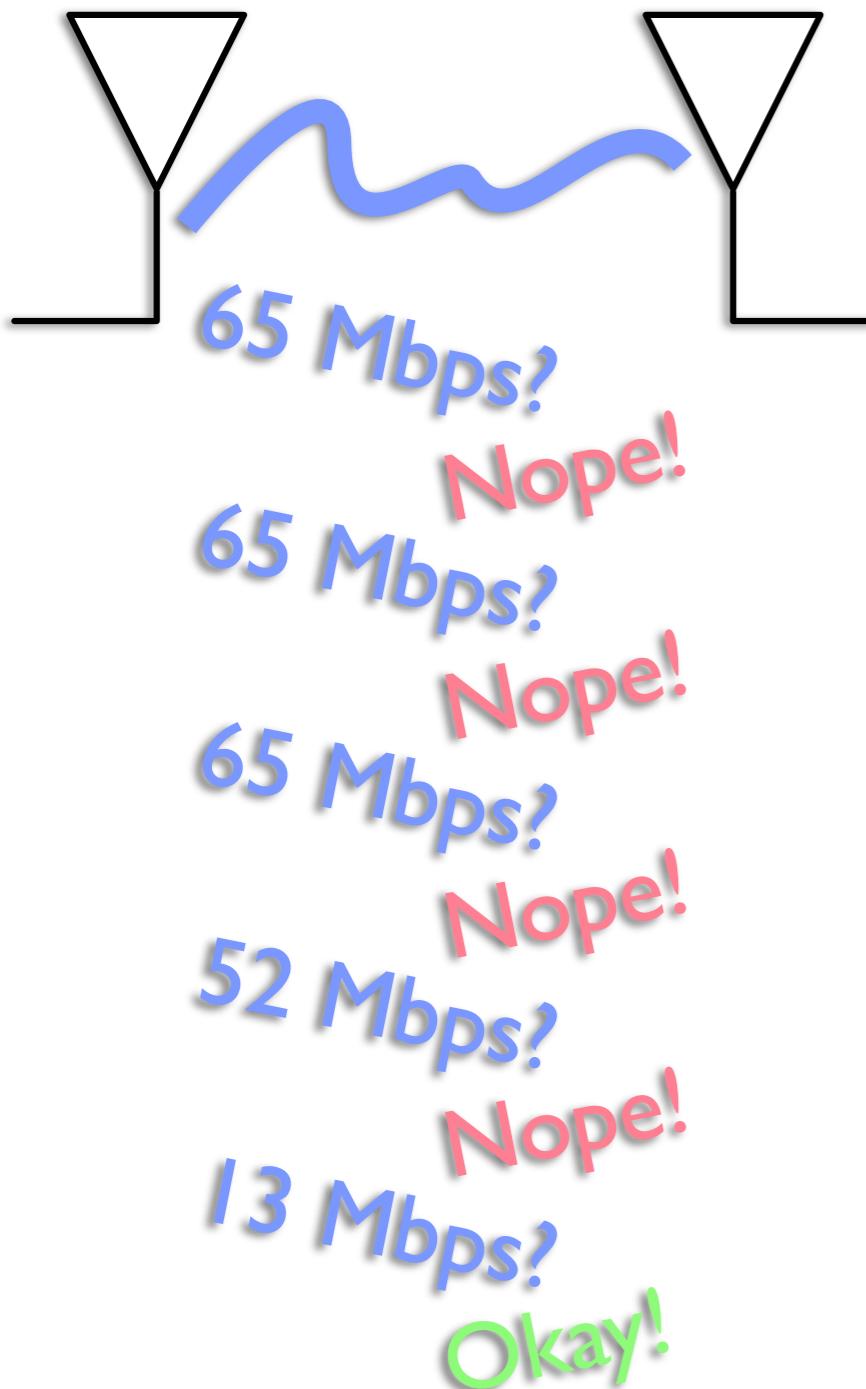
Performance – *in theory*



Performance – *in theory*



Performance – In practice



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

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Key: an accurate channel metric

Today's talk

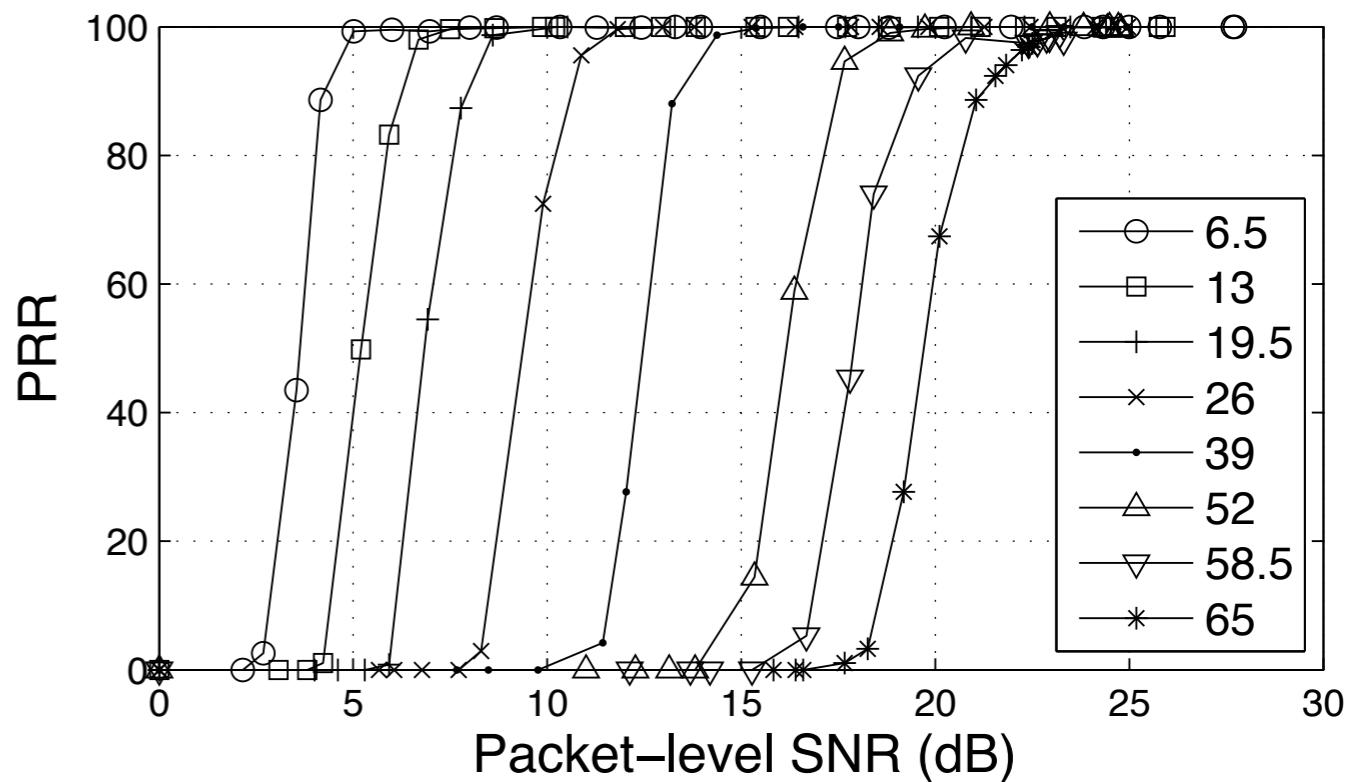
- Why it's hard to predict performance with RF measurements today
- Our solution: an accurate channel metric using **Effective SNR**
- Evaluation of Effective SNR in Wi-Fi Networks

Today's talk

- Why it's hard to predict performance with RF measurements today
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SNR based on RSSI

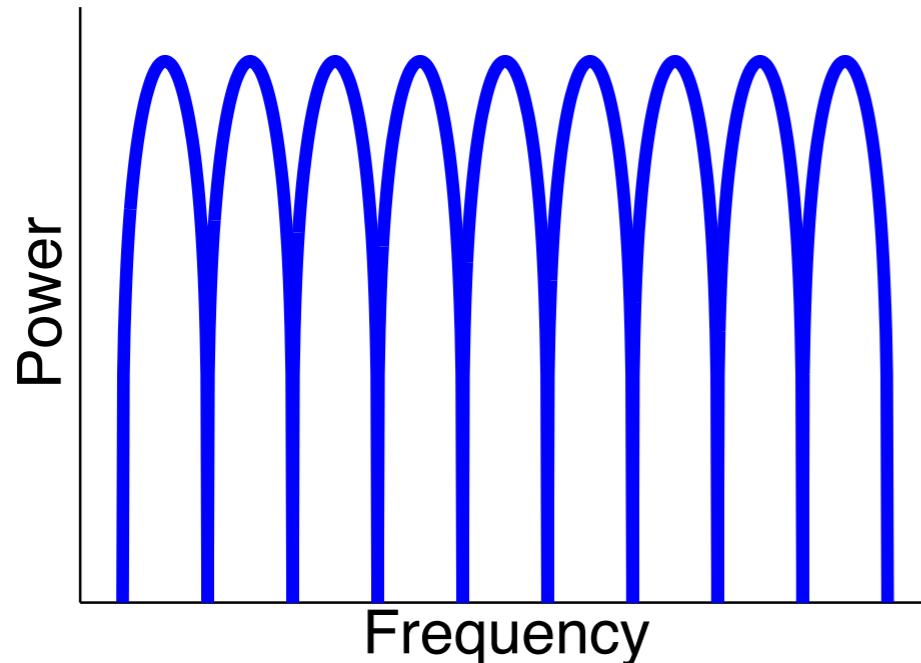
- **Received Signal Strength Indicator**
 - Measures total power received in packet
 - With Noise, gives SNR for packet
- *Treated as if directly reflects performance*
E.g., NIC manufacturers list per-rate ‘sensitivity’



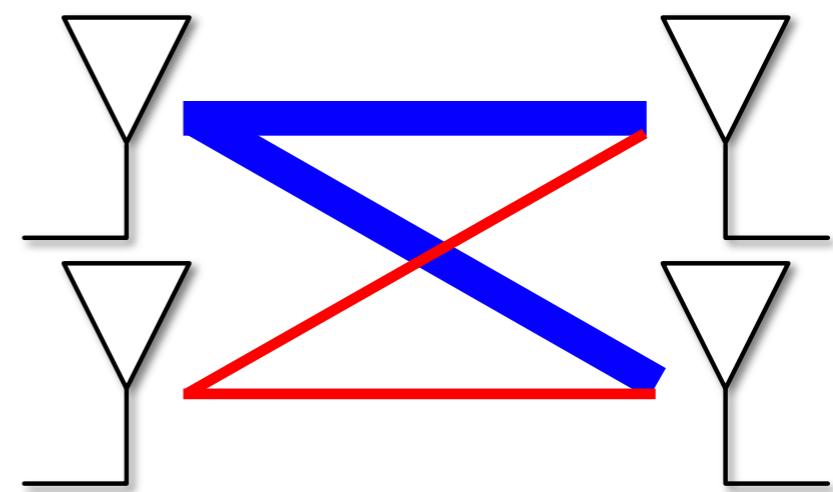
- In practice, **SNR** at which a rate starts to work can **vary more than 10 dB** for real links

802.11: OFDM and MIMO

Orthogonal Frequency Division Multiplexing



Multiple-Input Multiple-Output

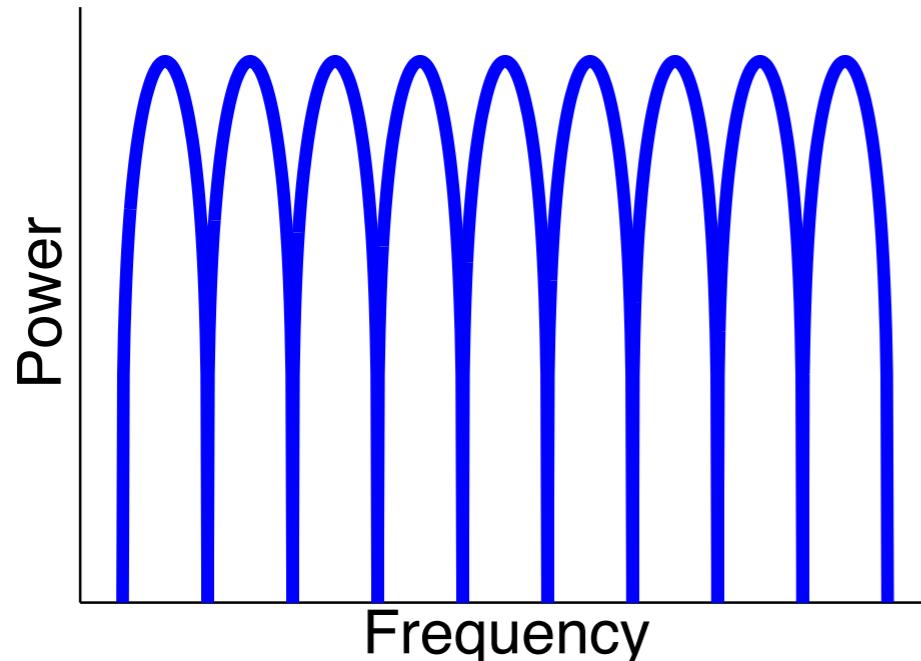


Frequency-selective fading

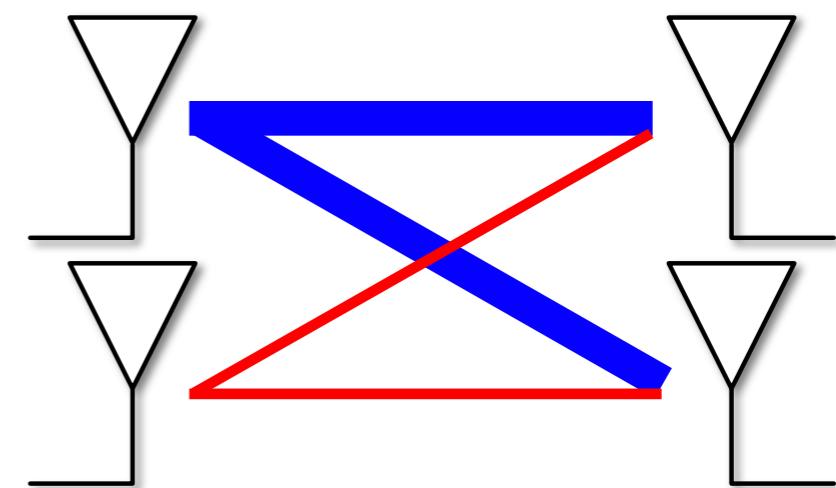
Spatial diversity

802.11: OFDM and MIMO

Orthogonal Frequency Division Multiplexing

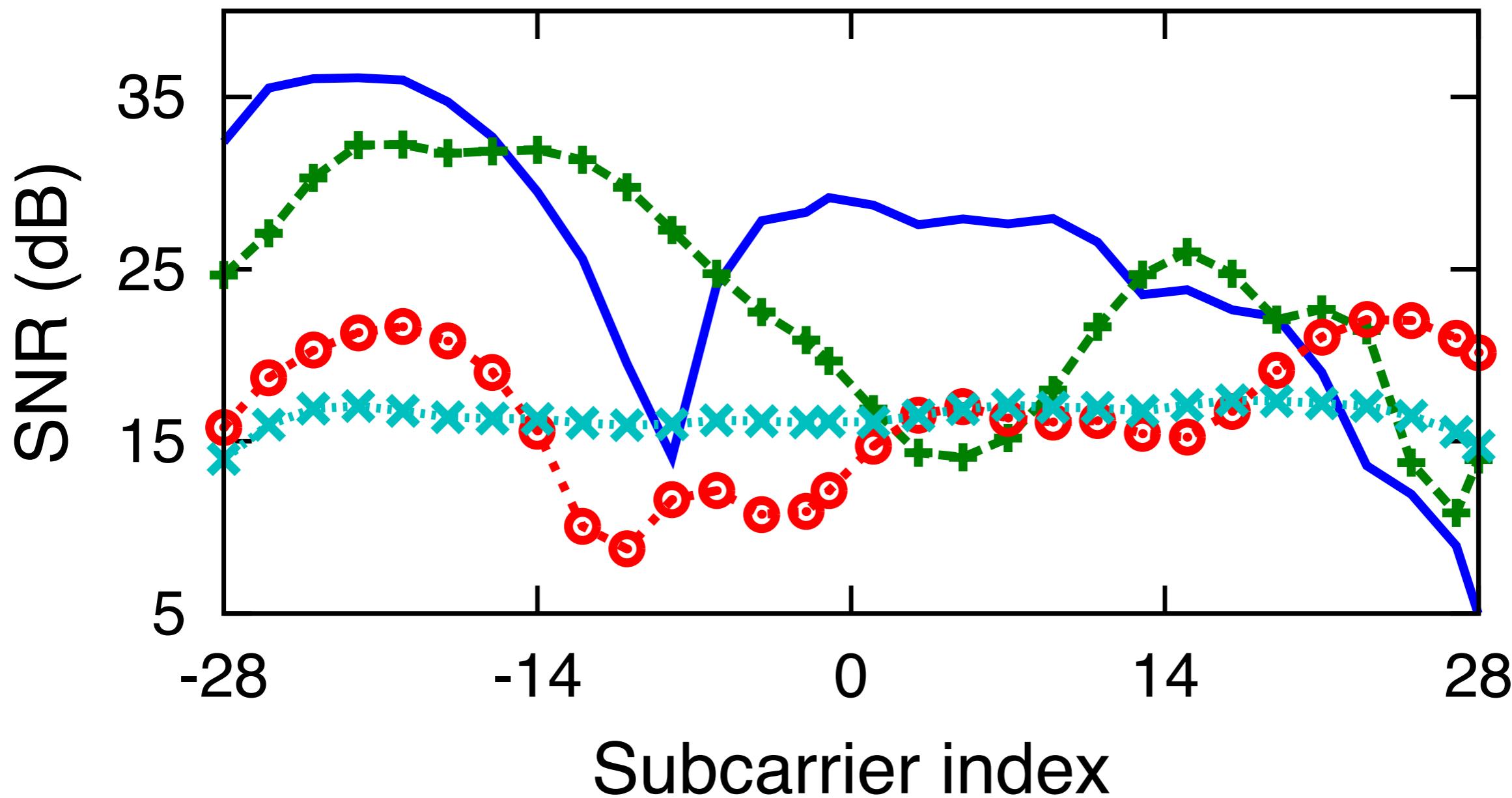


Multiple-Input Multiple-Output

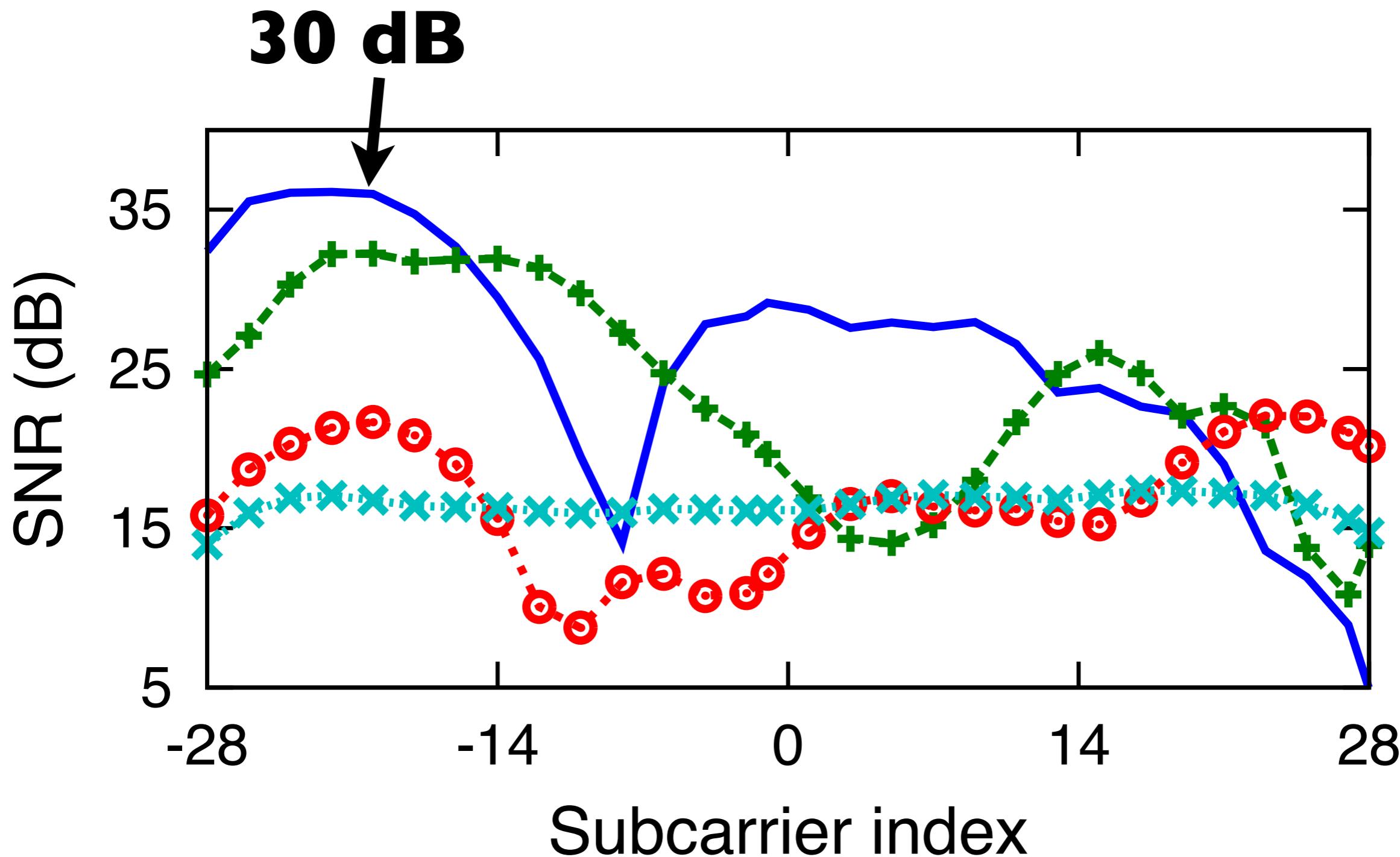


Key: Different subchannels
have different SNRs

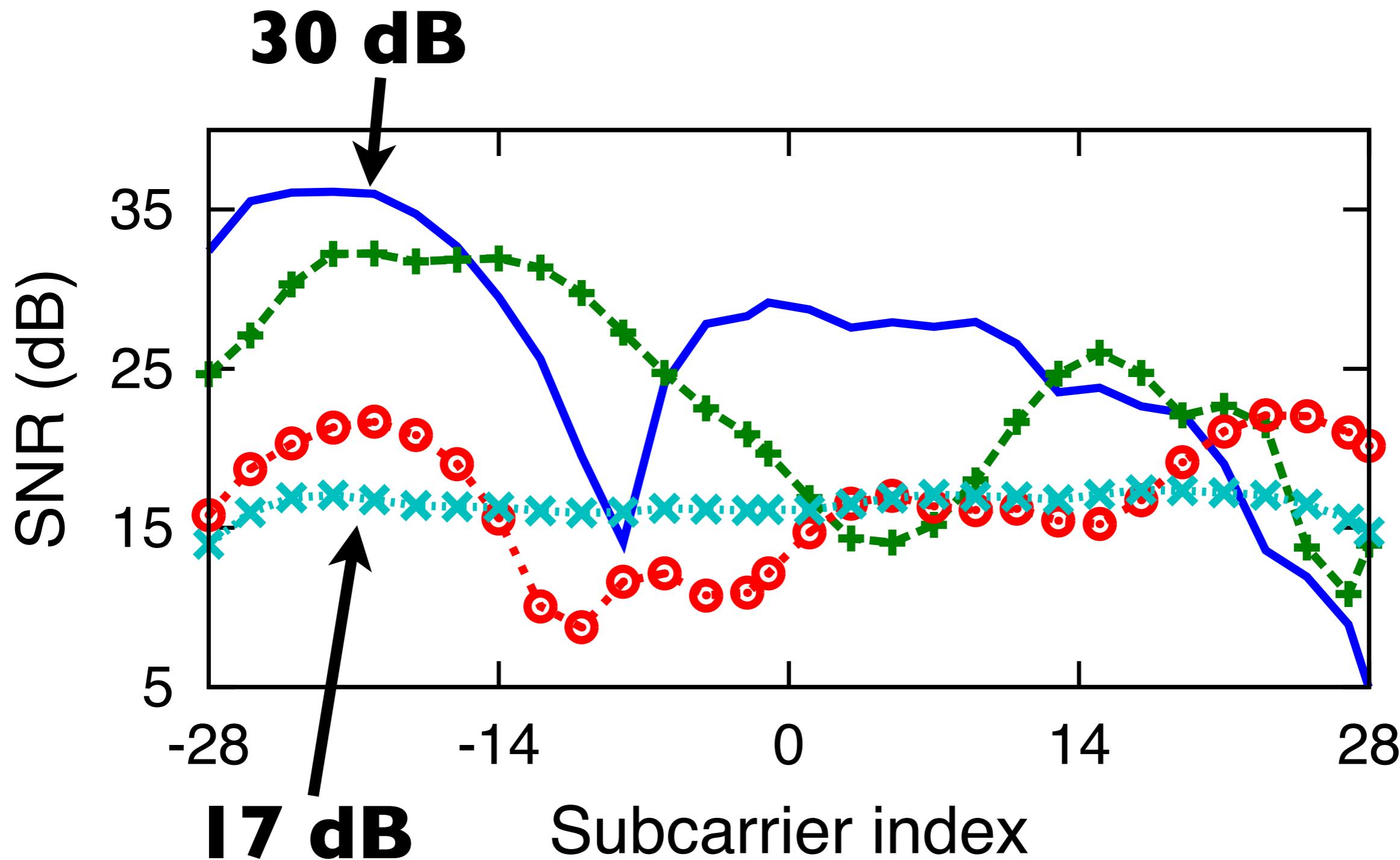
Packet SNR for 4 faded links



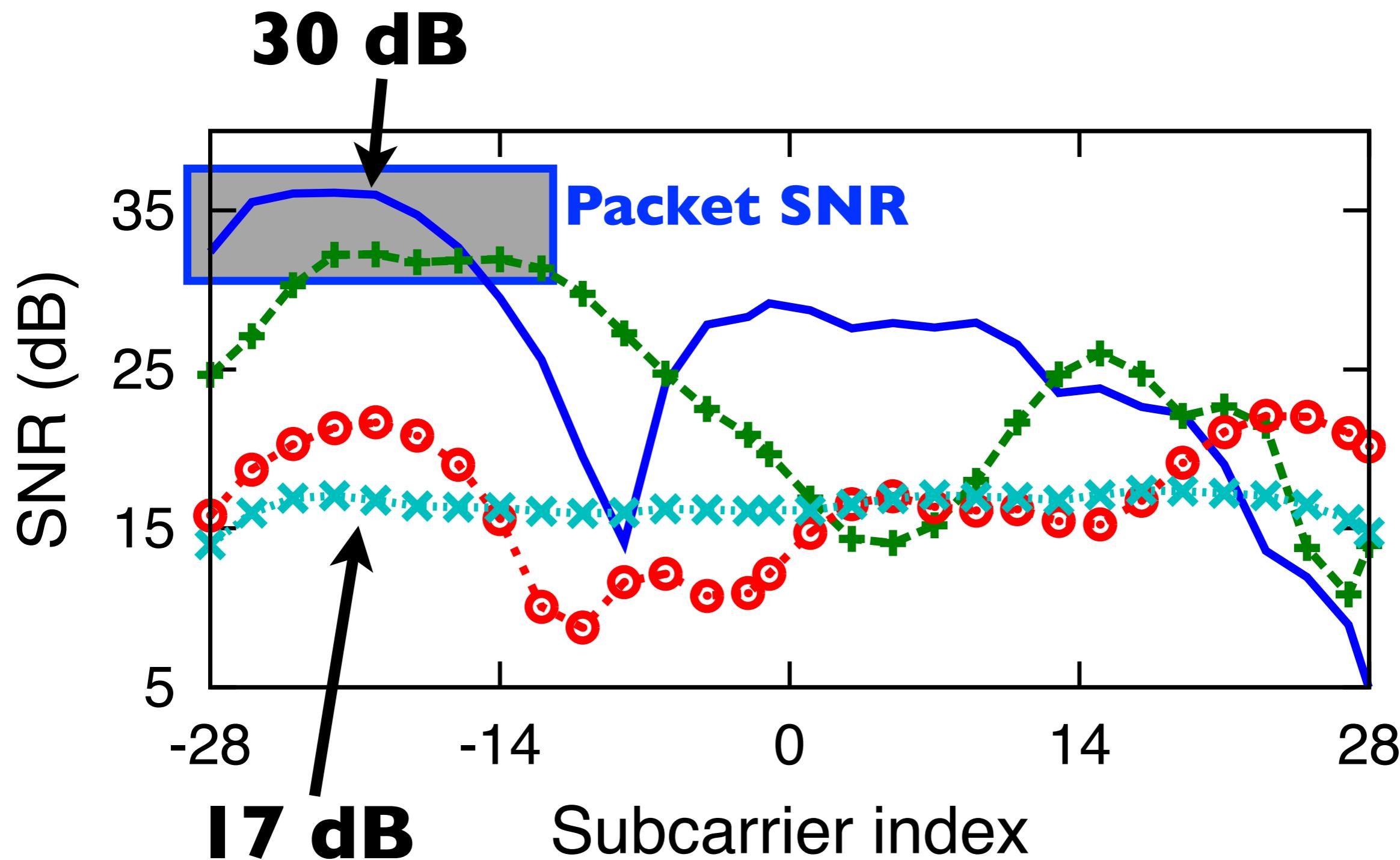
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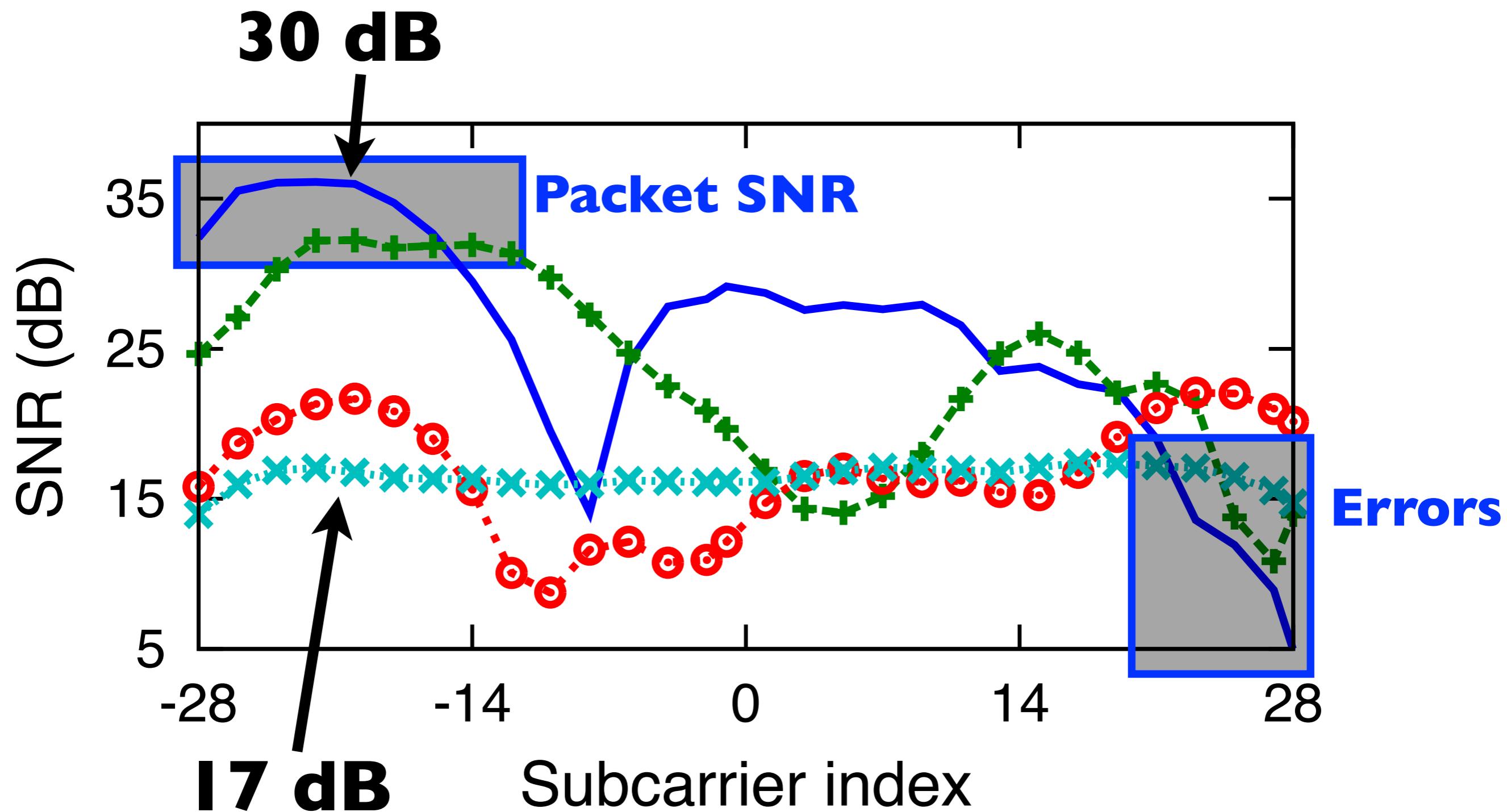
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Packet SNR for 4 faded links

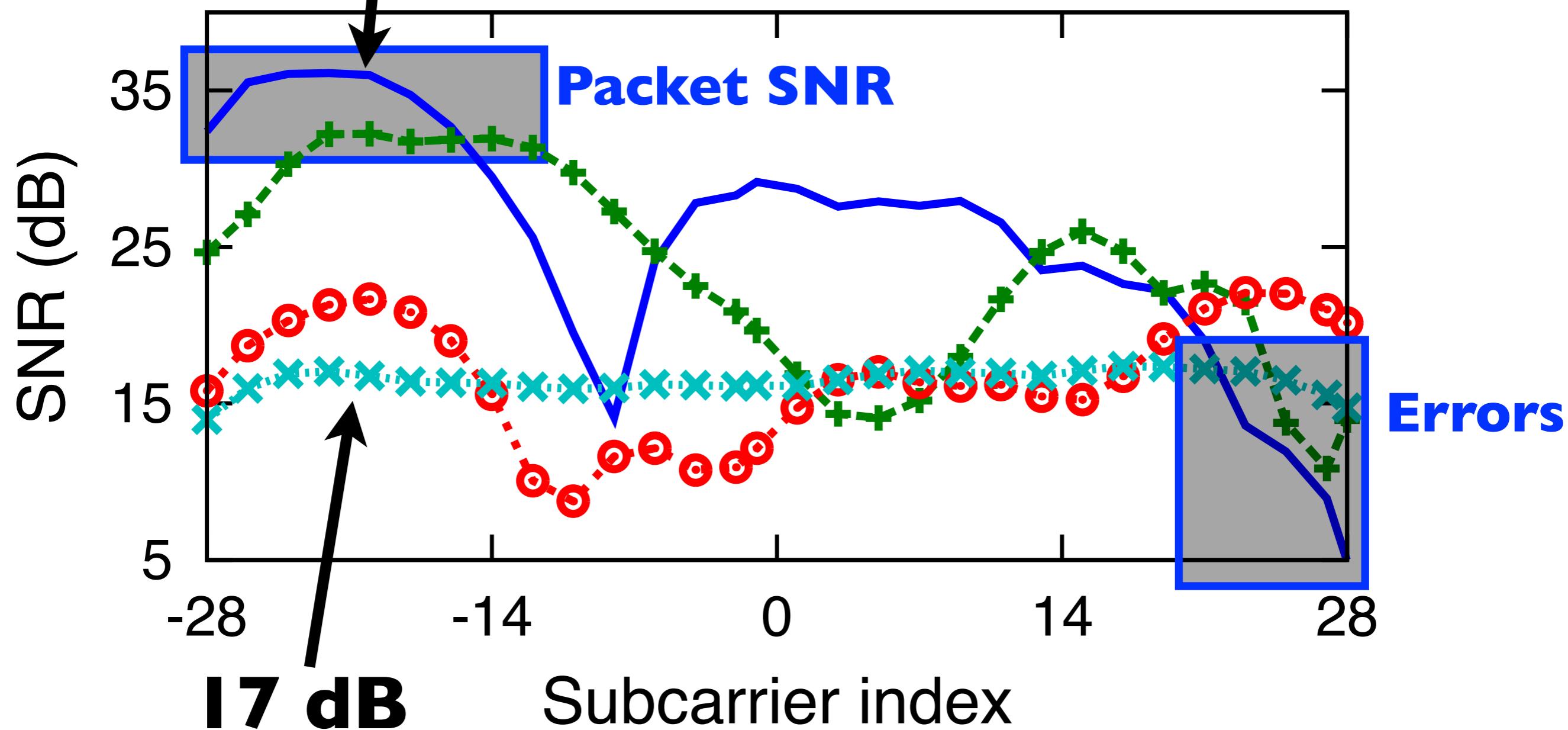


Packet SNR for 4 faded links



Packet SNR for 4 faded links

Fundamental SNR mismatch



An 802.11n opportunity

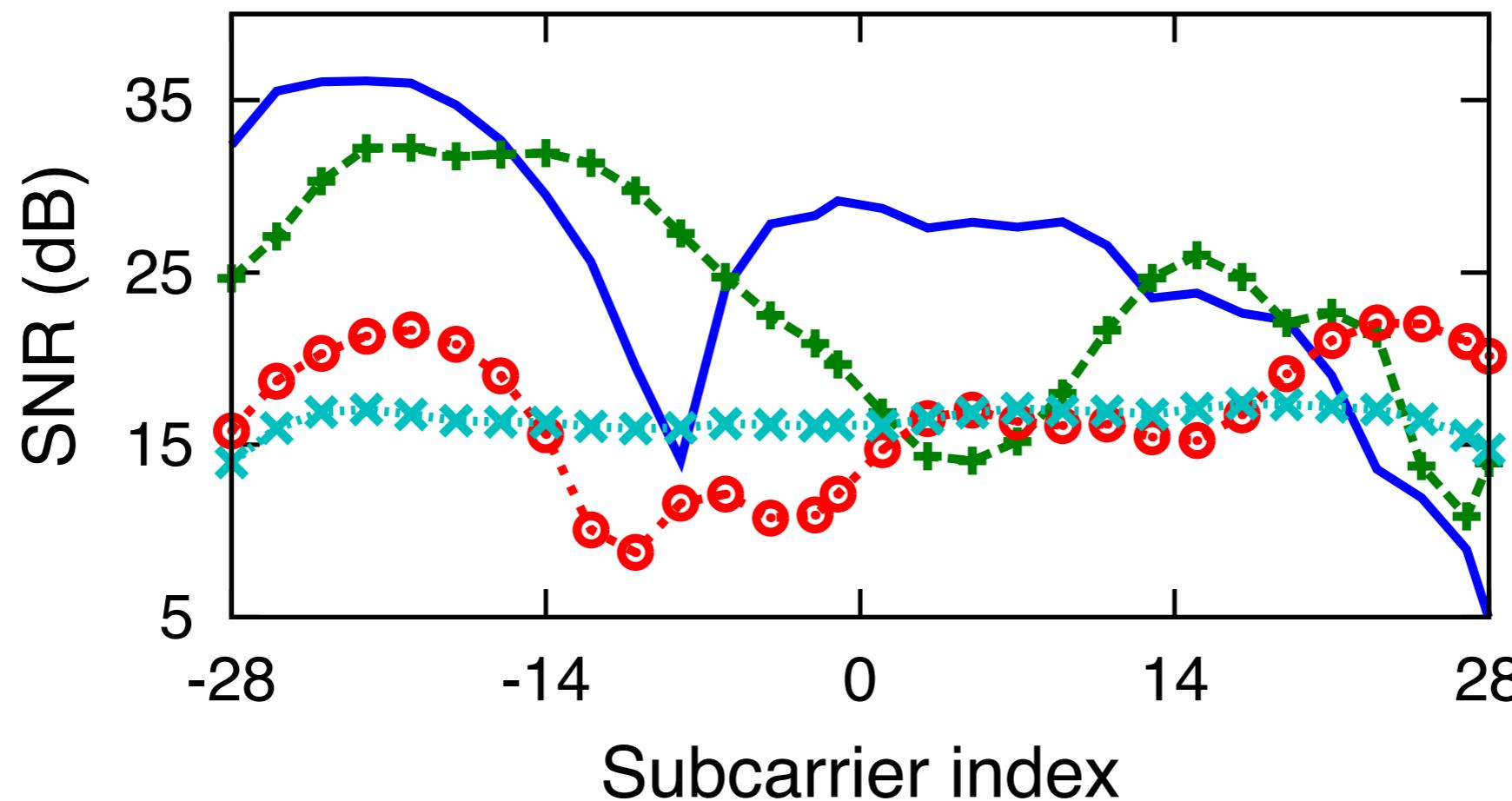
- *802.11n provides detailed channel measurements*
 - Used for advanced MIMO techniques
- ***Channel State Information (CSI) measures MIMO and OFDM!***
 - Matrix captures per-antenna paths
 - One matrix per subcarrier
- *Can we use it to predict packet delivery?*
In theory? In practice?

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

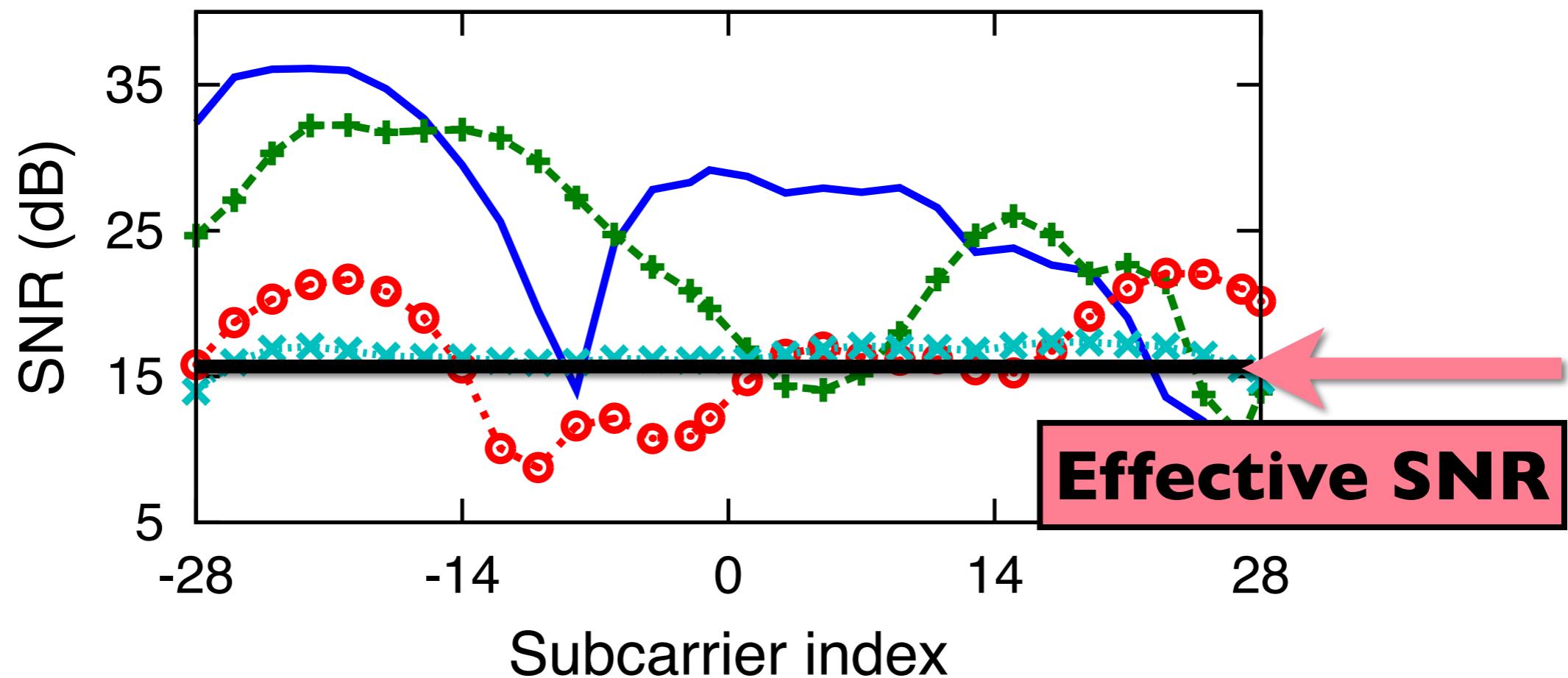
Effective SNR

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

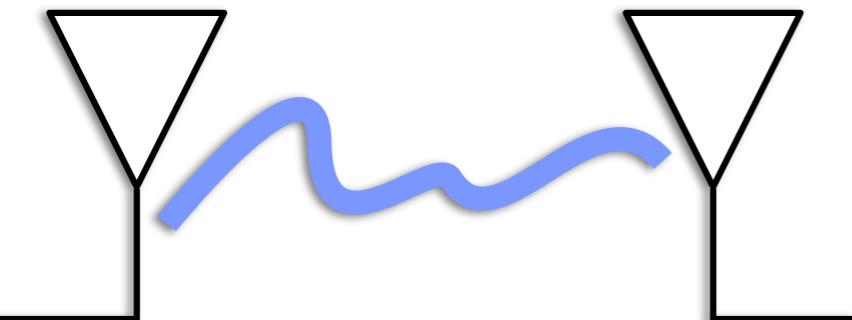


Effective SNR

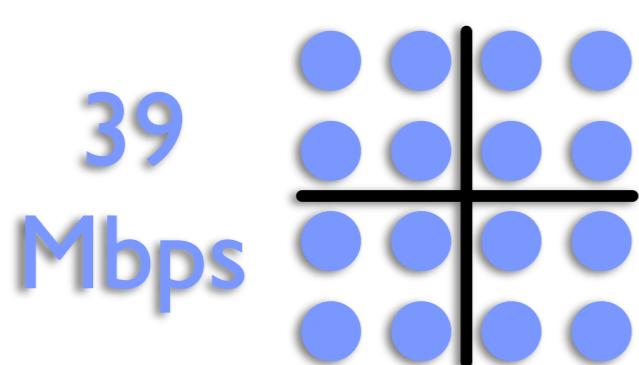
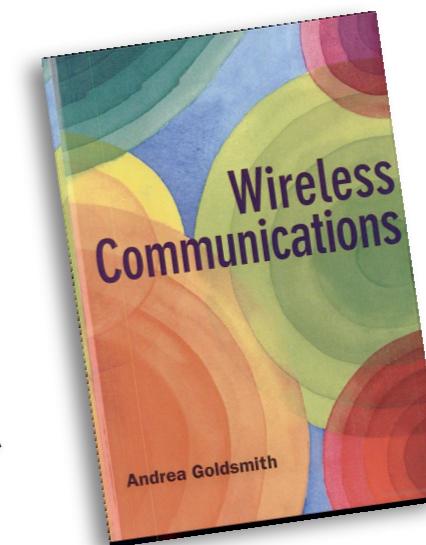
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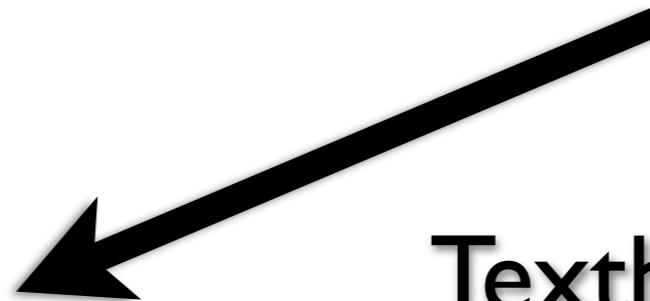
Using Effective SNR



Channel Measurements

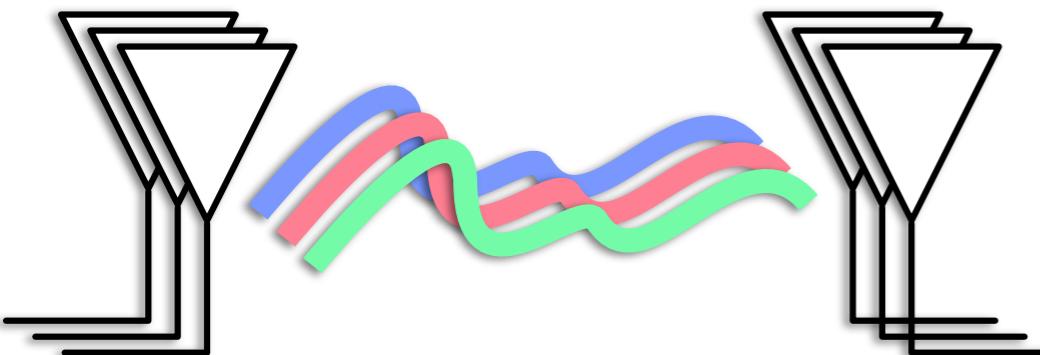


Rate Selection

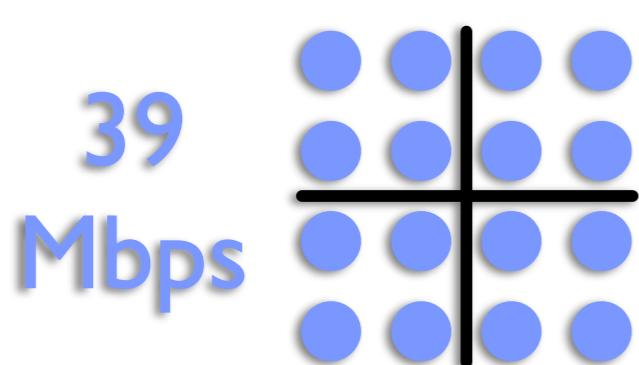
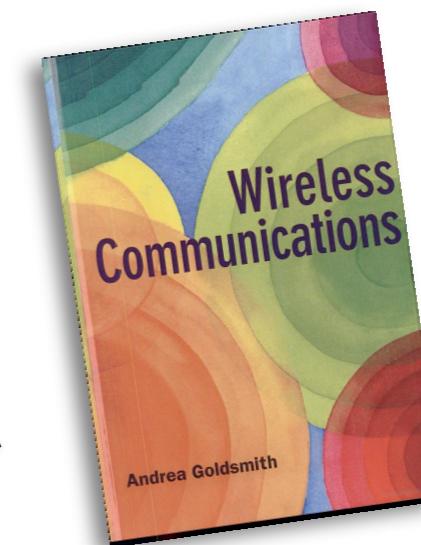


Textbook Algorithms

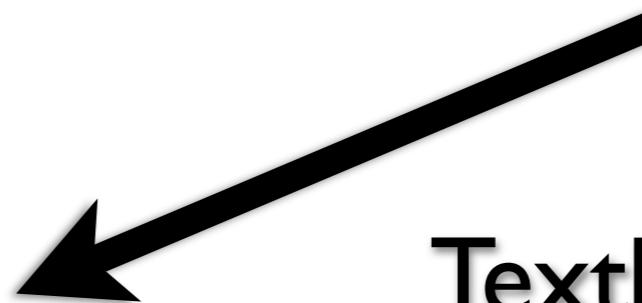
Using Effective SNR



Channel State Information
(MIMO & OFDM)

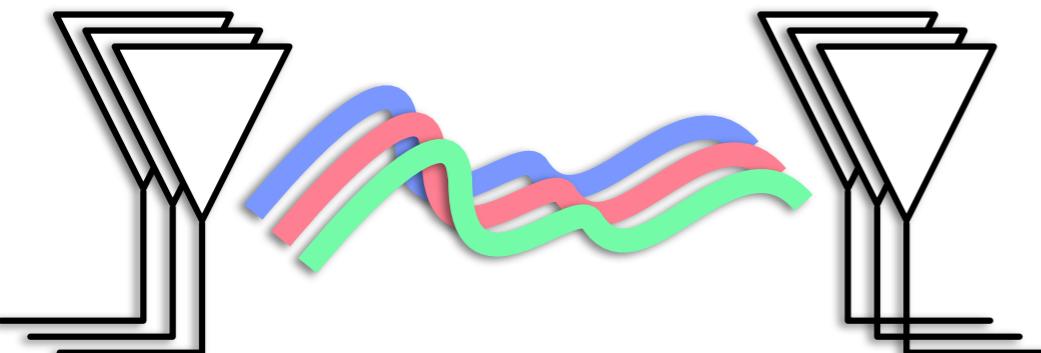


Rate Selection

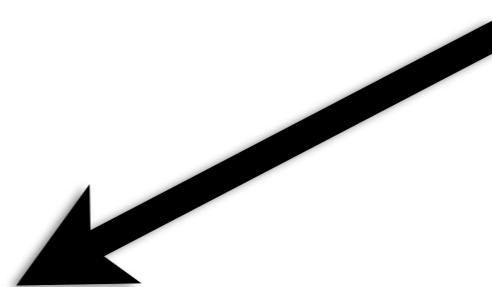
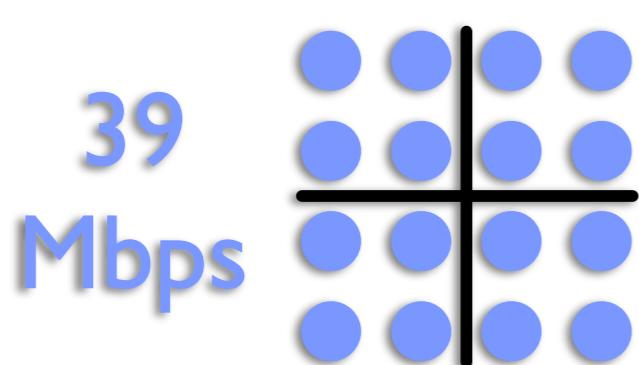
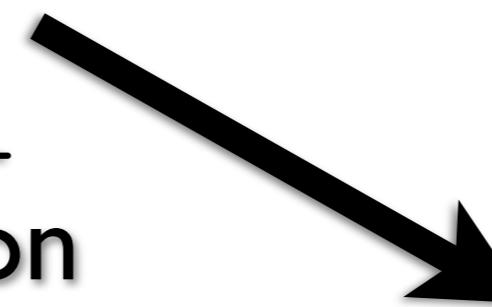


Textbook Algorithms

Using Effective SNR

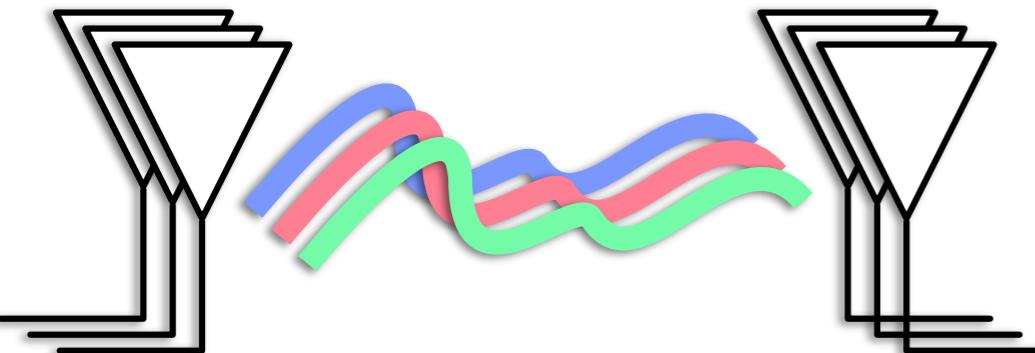


Channel State Information
(MIMO & OFDM)



Rate Selection

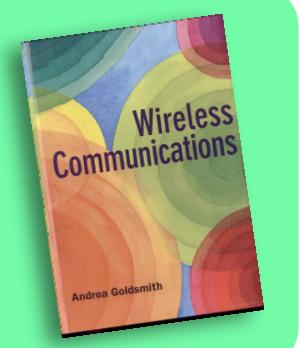
Using Effective SNR



Channel State Information
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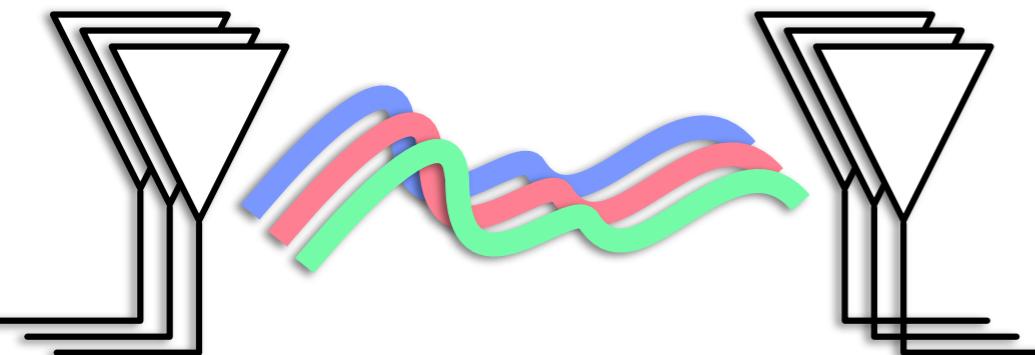
- 1x65 X
- 1x52 X
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- 3x13 ✓

**Effective
SNR Model**



Working Configurations;
Application Decision

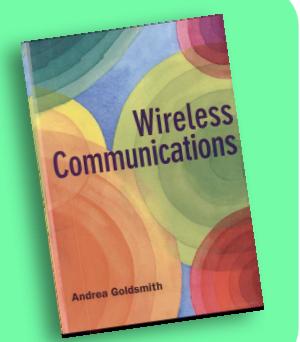
Using Effective SNR



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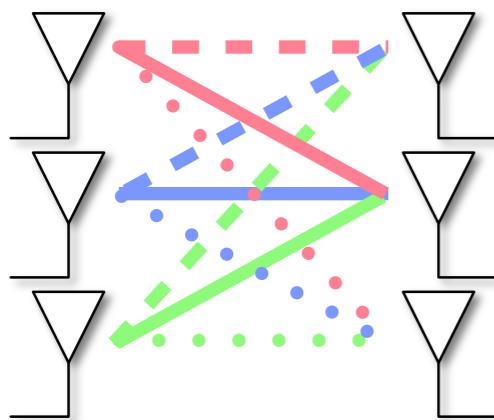
Effective
SNR Model



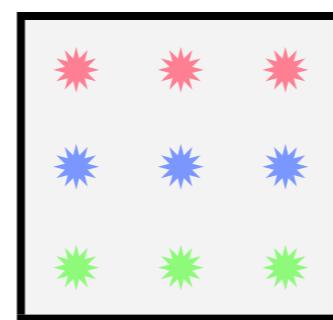
Working Configurations;
Application Decision

Obtaining CSI

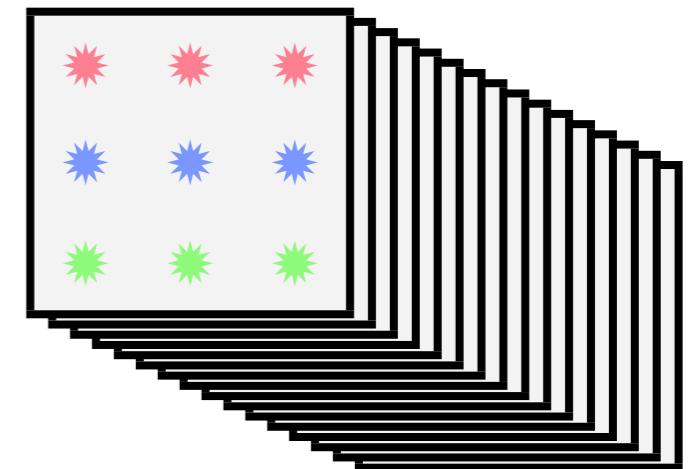
- *RX measures CSI* from packet preamble
NICs do this for MIMO/OFDM operation
- *For every received frame*
Measures ***all antennas + subcarriers*** used



3-antenna Link

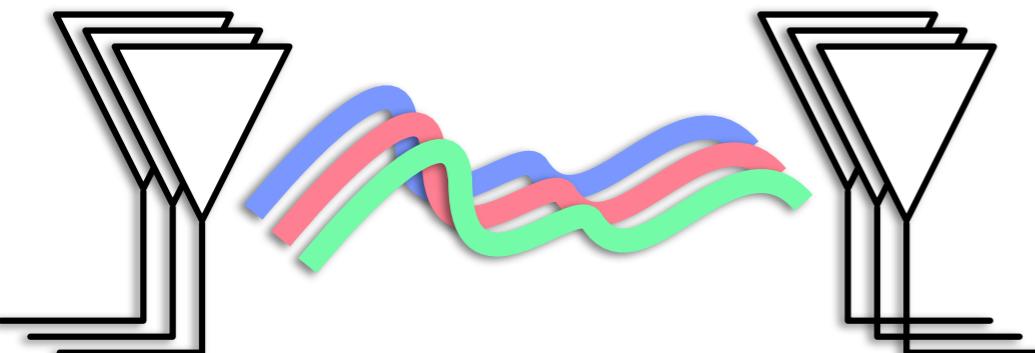


3x3 Matrix



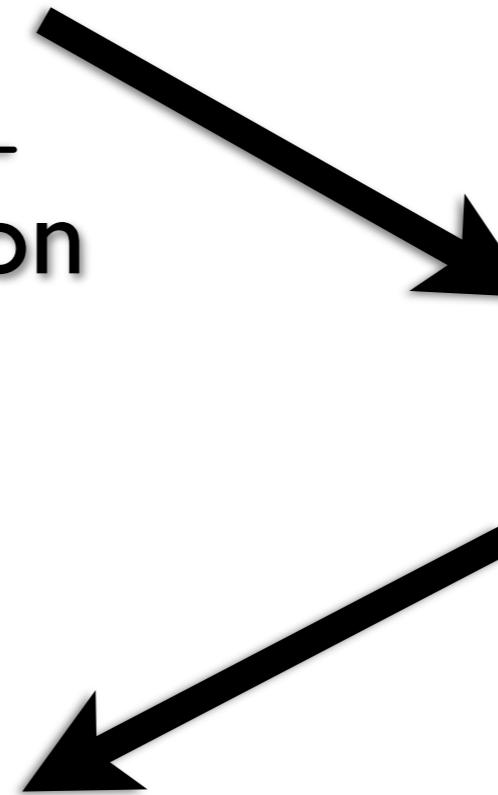
One matrix
per Subcarrier

Using Effective SNR

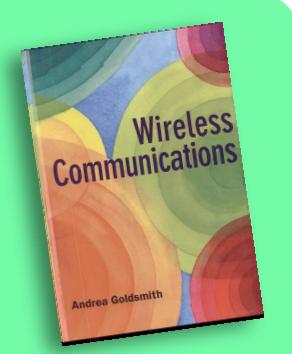


Channel State Information
(MIMO & OFDM)

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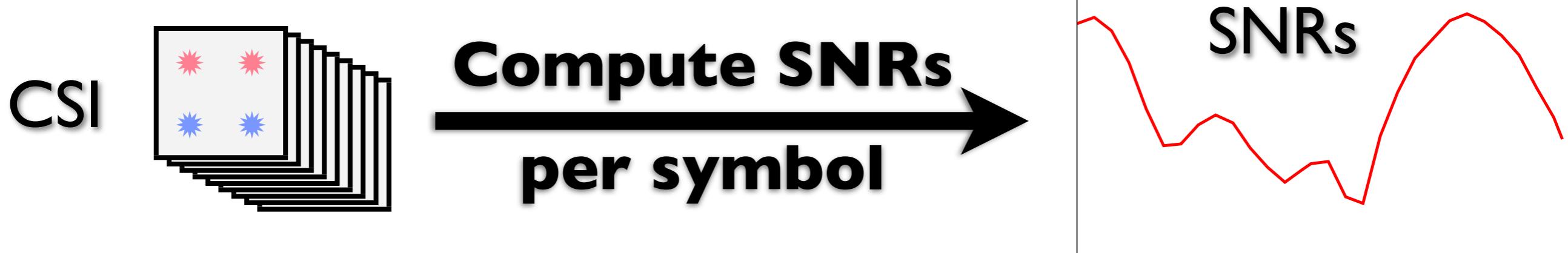


**Effective
SNR Model**



Working Configurations;
Application Decision

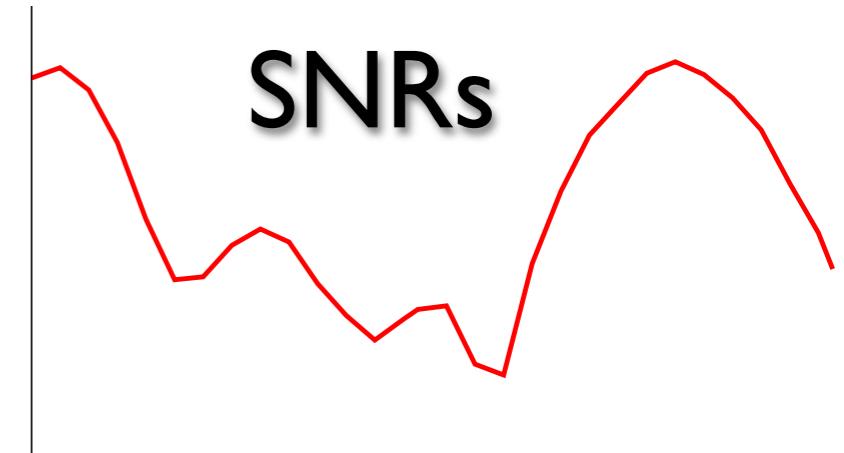
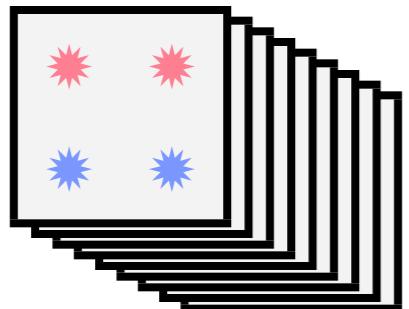
Computing Effective SNR



- *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

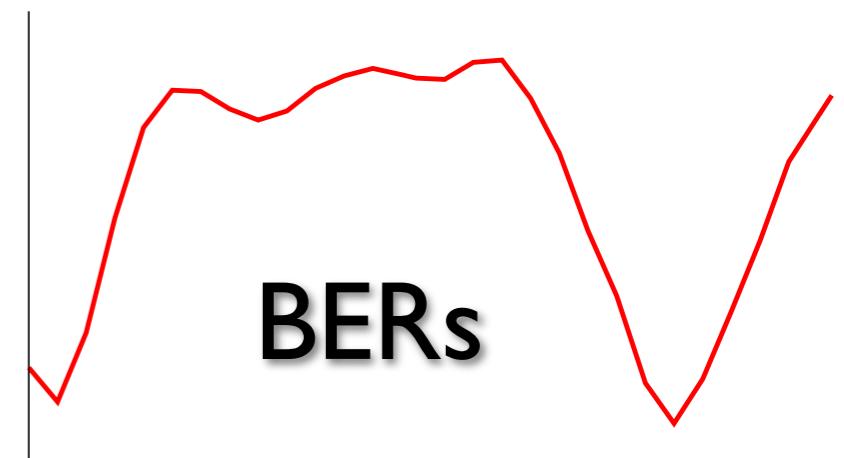
CSI



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

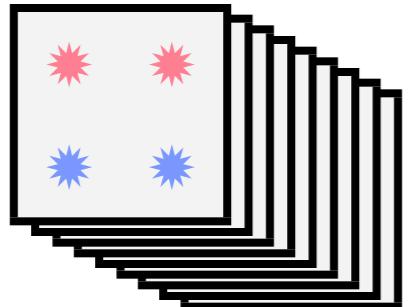
**Textbook
formulas**

**Compute
BERs
per symbol**

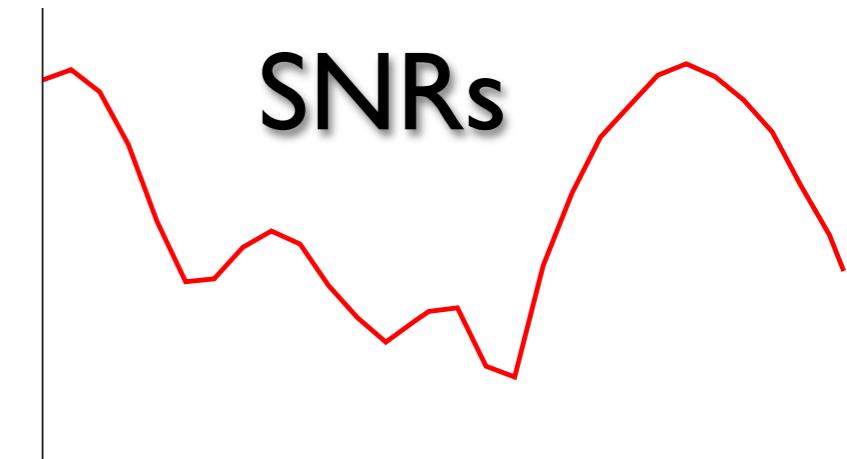


Computing Effective SNR

CSI



SNRs

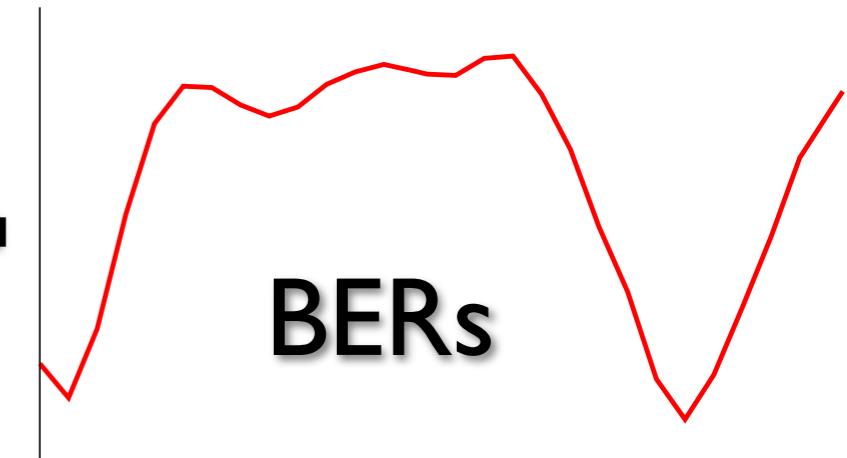


BER_{eff}

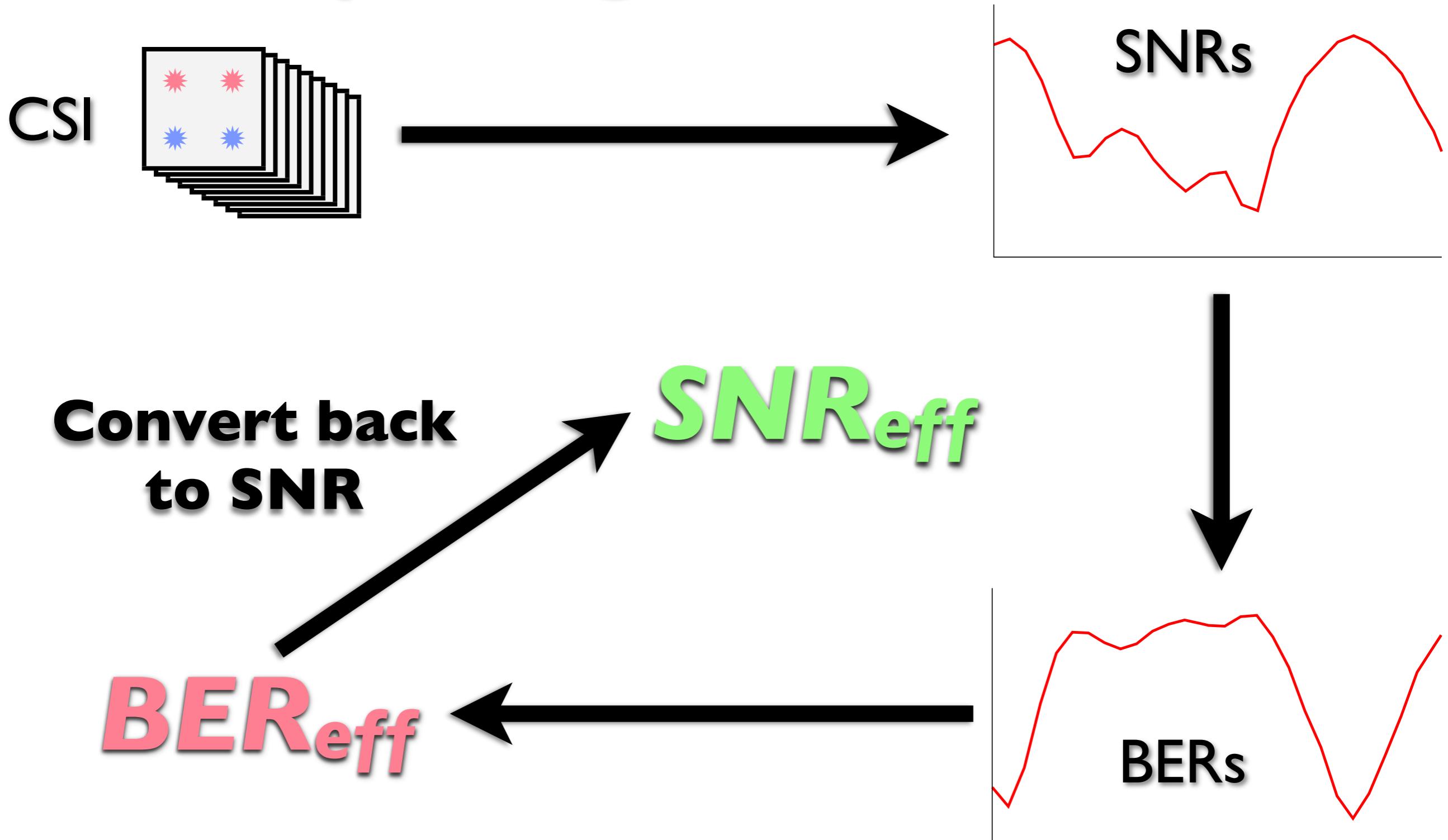
**Average:
Effective BER**



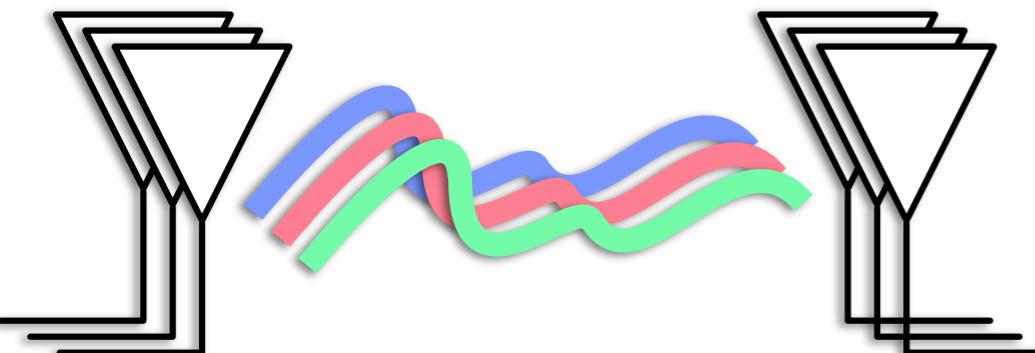
BERs



Computing Effective SNR

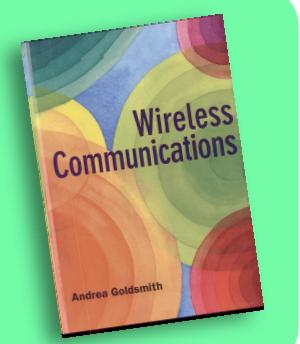


Using Effective SNR



Channel State Information
(MIMO & OFDM)

Effective
SNR Model



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Working Configurations;
Application Decision

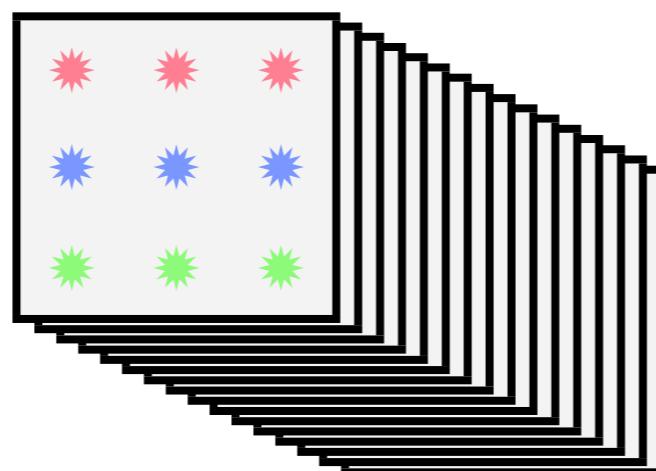


Predicting Packet Delivery

- **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

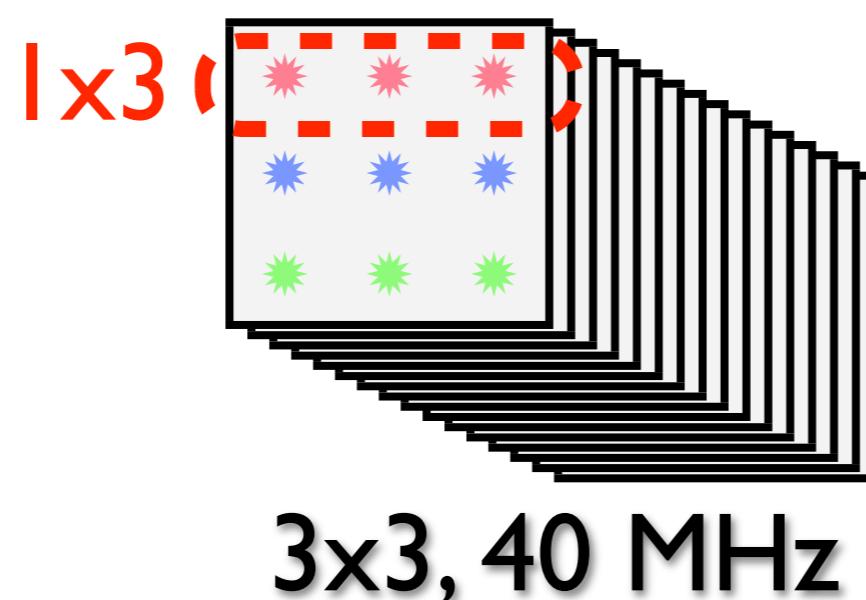
- **Rate/MIMO/Channel width selection:**
What is the fastest configuration for this link?



3x3, 40 MHz

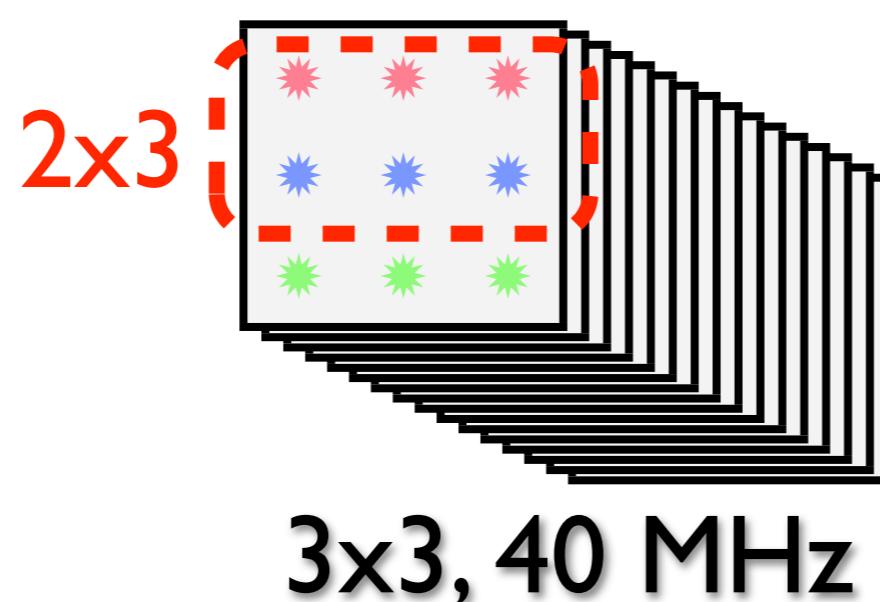
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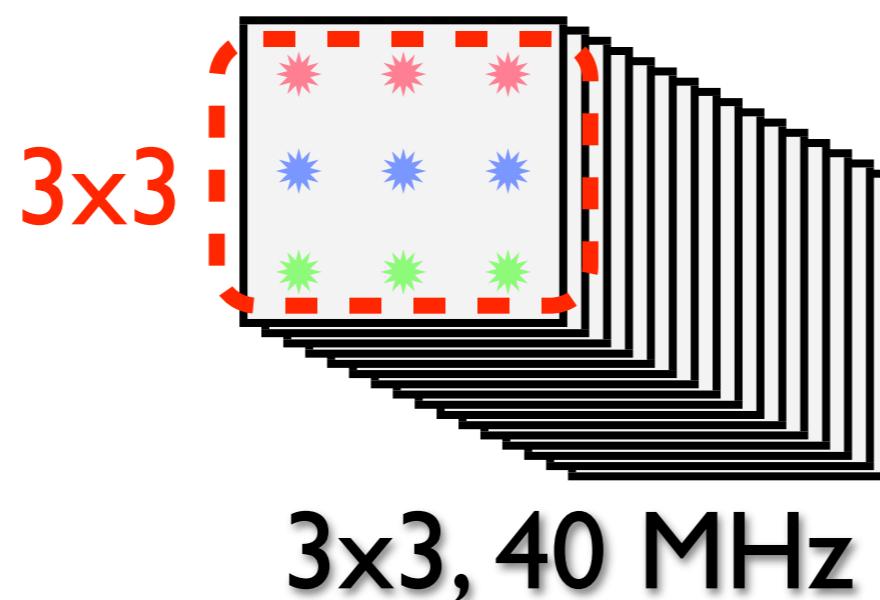
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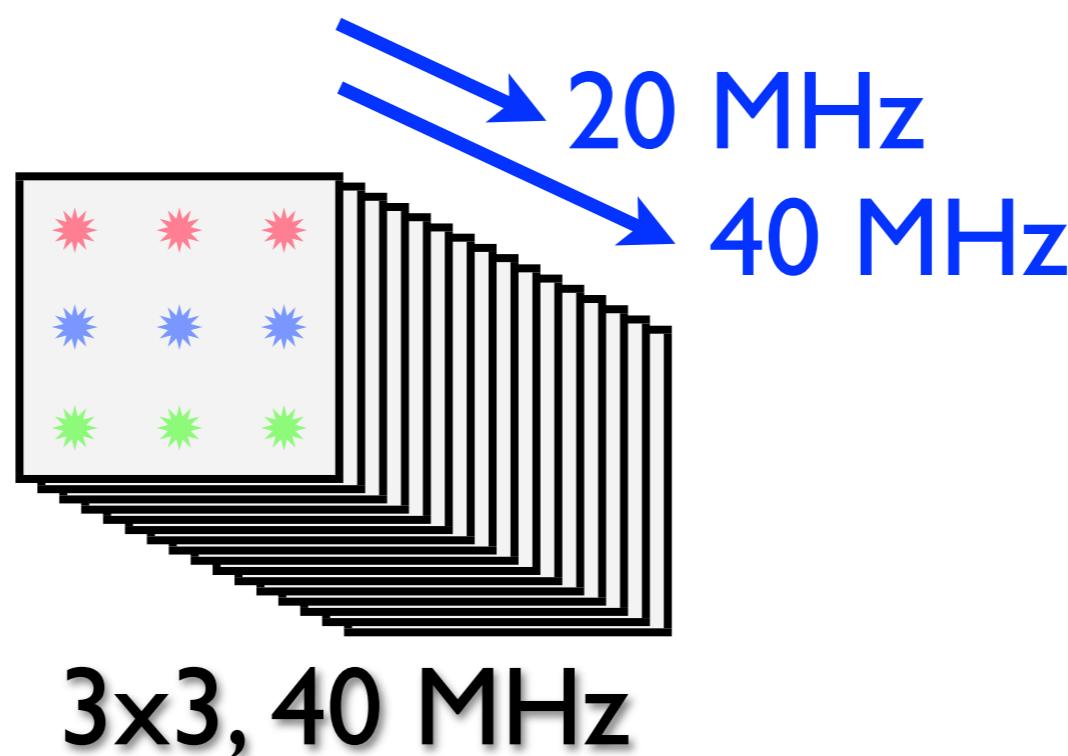
Example Applications

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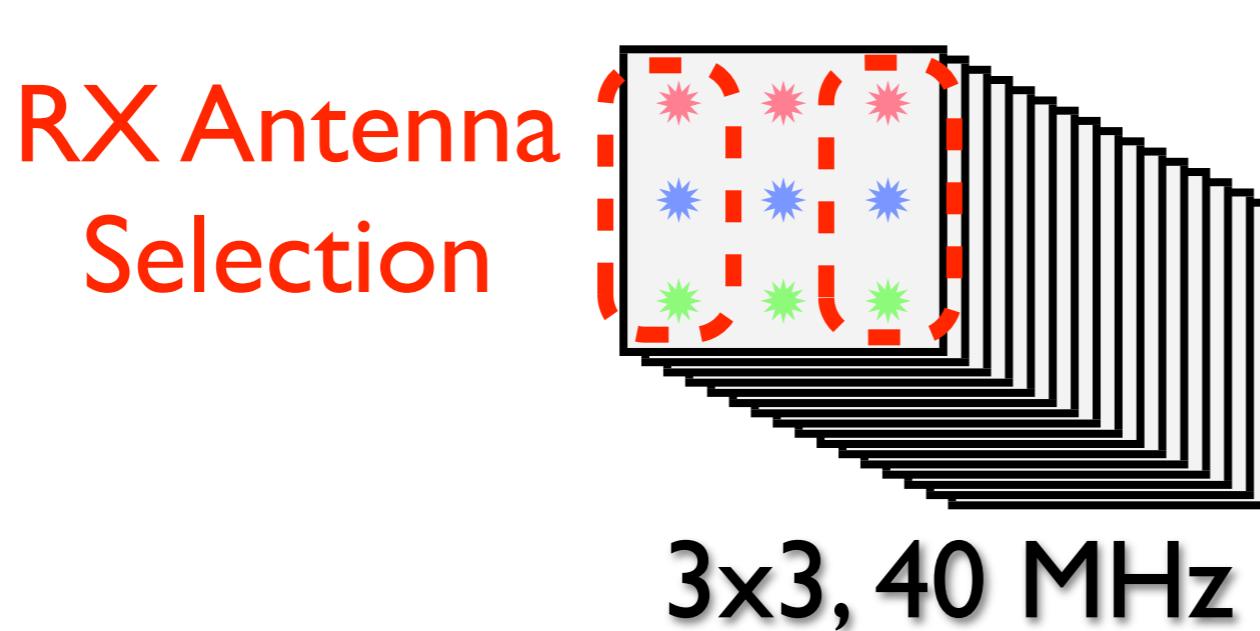
Example Applications

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



Example Applications

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

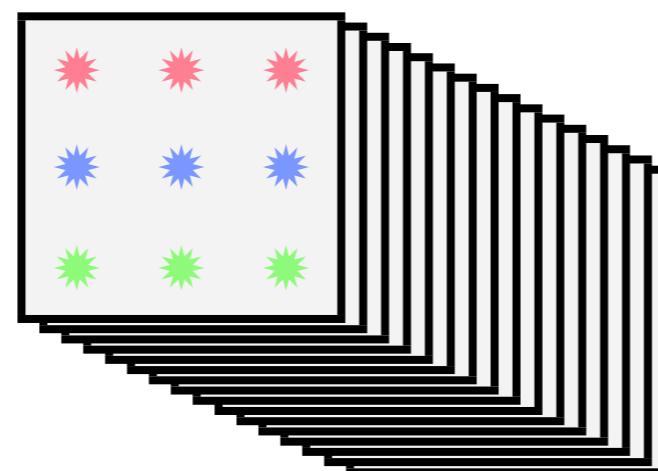


Example Applications

- **Spatial Reuse:**

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

Power ×

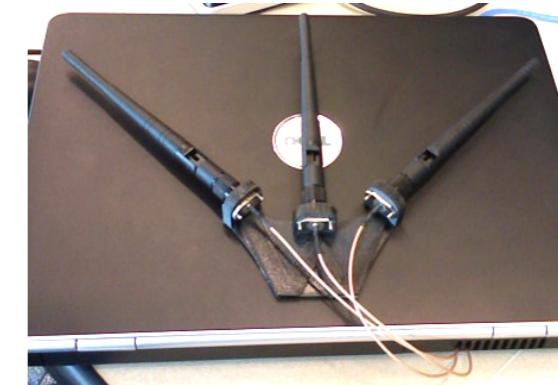
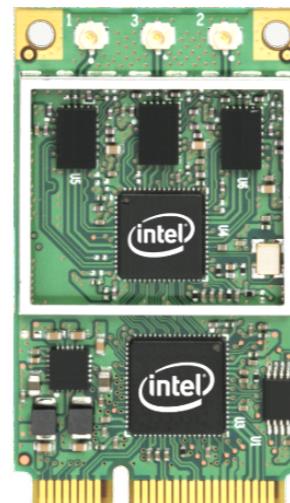


3x3, 40 MHz

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



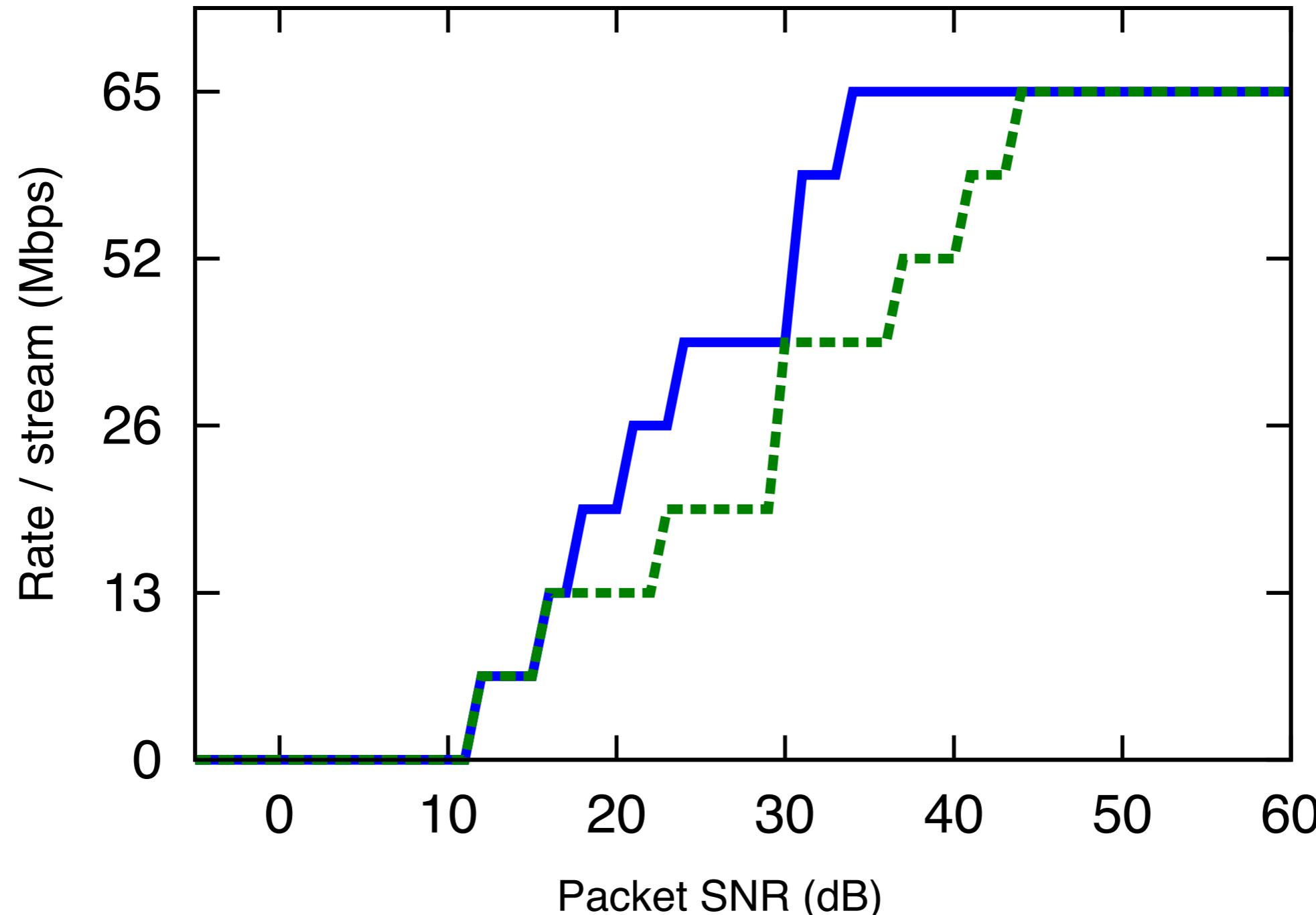
- Intel Wi-Fi Link 5300 NIC (3x3, 450 Mbps)
- Two testbeds with > 200 widely varying links
- Linux (2.6.35-rc3) open source *iwlwifi* driver
- Firmware **debug mode**: send CSI to RX host
- Real-time computation: **~4 μ s** per 3x3 CSI

Evaluation Questions

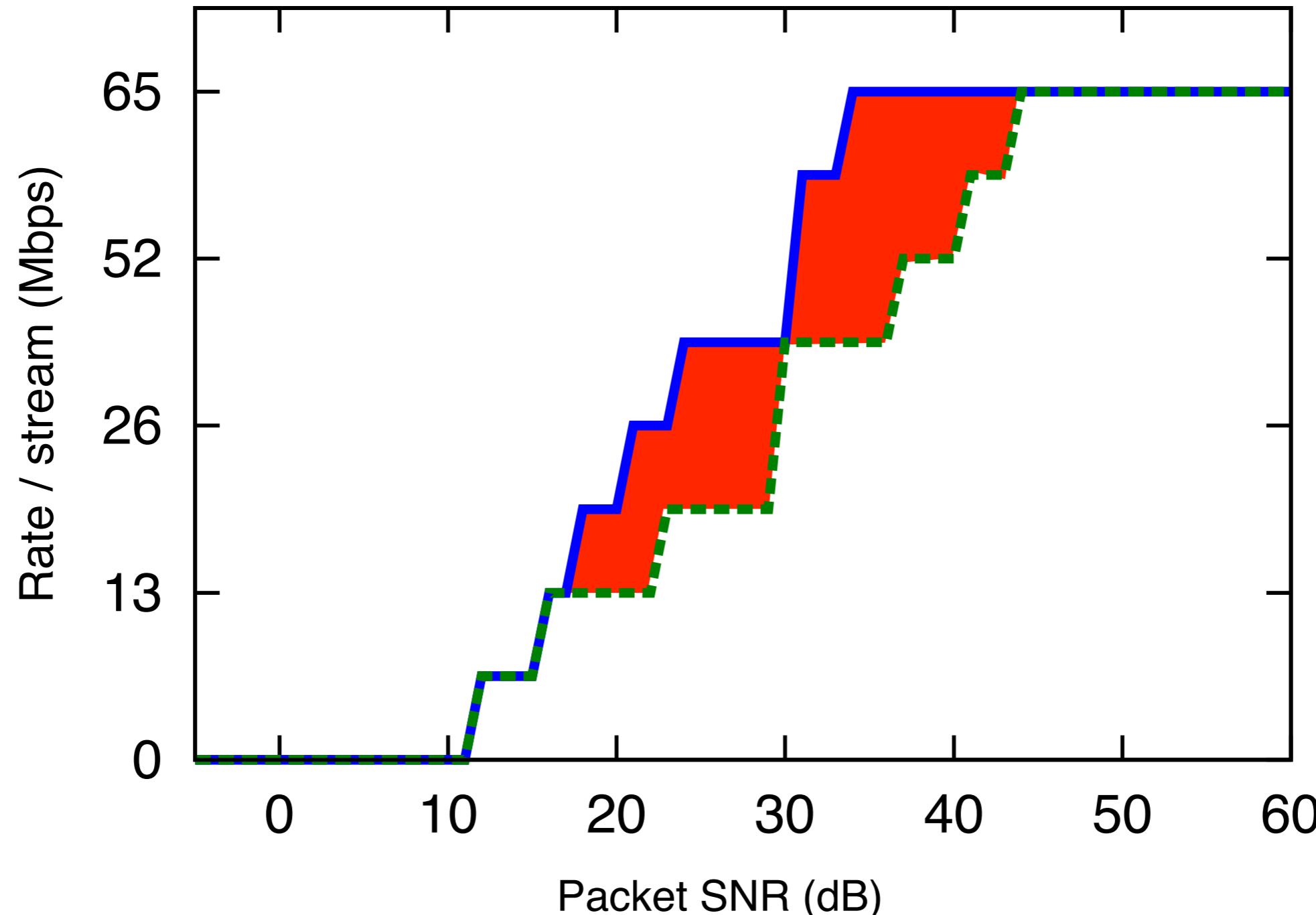
- Does Effective SNR accurately predict packet delivery?
- Does an Effective SNR rate selection algorithm perform well?
- More results in the paper
 - *Wireless link transition region*
 - *Transmit power control*
 - *Collisions*

Predicting Optimal 3x3 Rate

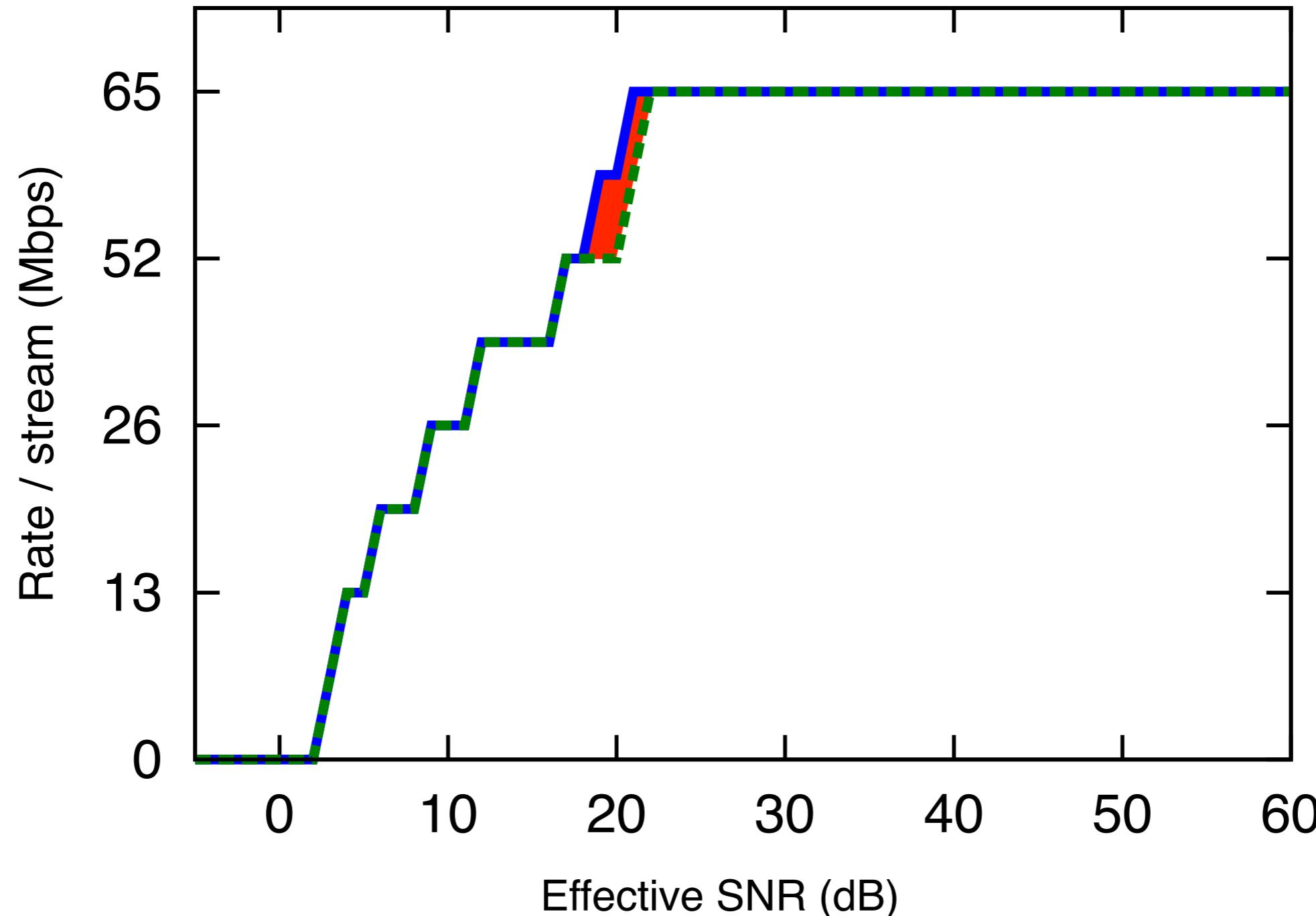
Predicting Optimal 3x3 Rate



Predicting Optimal 3x3 Rate



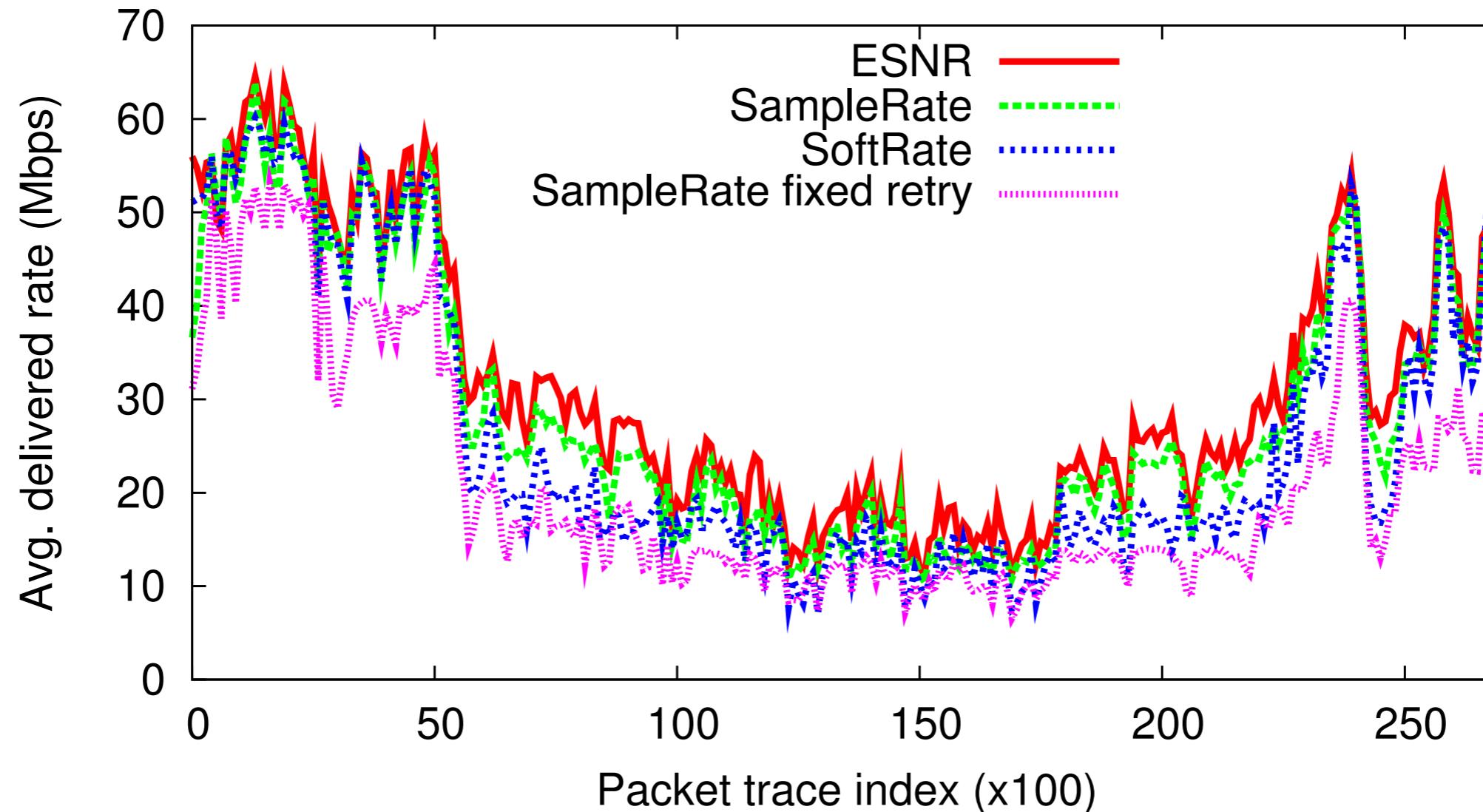
Predicting Optimal 3x3 Rate



Rate control evaluation

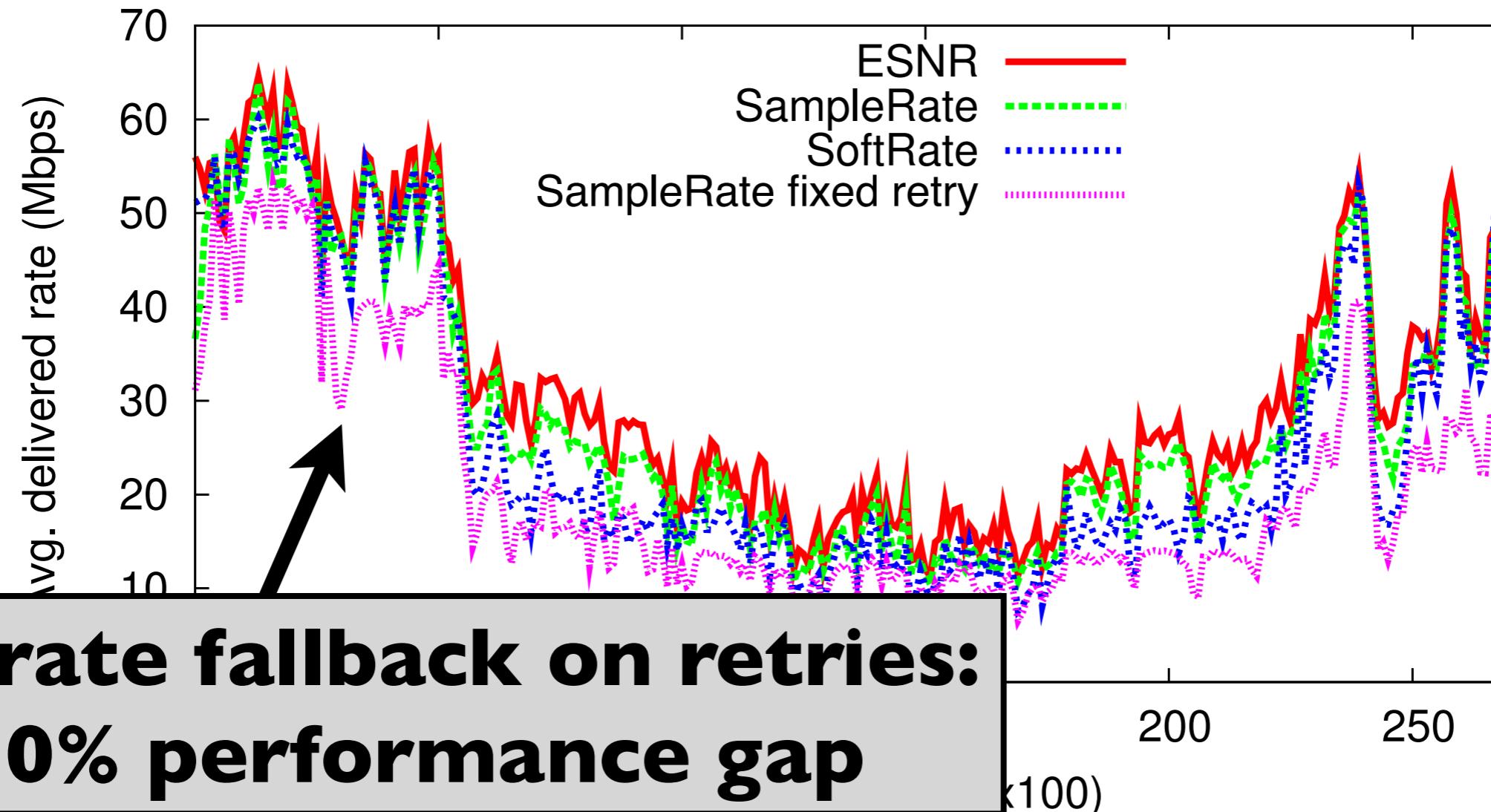
- **802.11a:** Does Effective SNR match related work?
ESNR versus SampleRate, SoftRate, OPT
- **802.11n:** Does Effective SNR extend to 802.11n?
ESNR versus OPT
- **Channel simulation over mobile trace**
to compare against related work & vary speed
 - MATLAB simulation + SoftRate GNU Radio
 - Effective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

Effective SNR for 802.11a



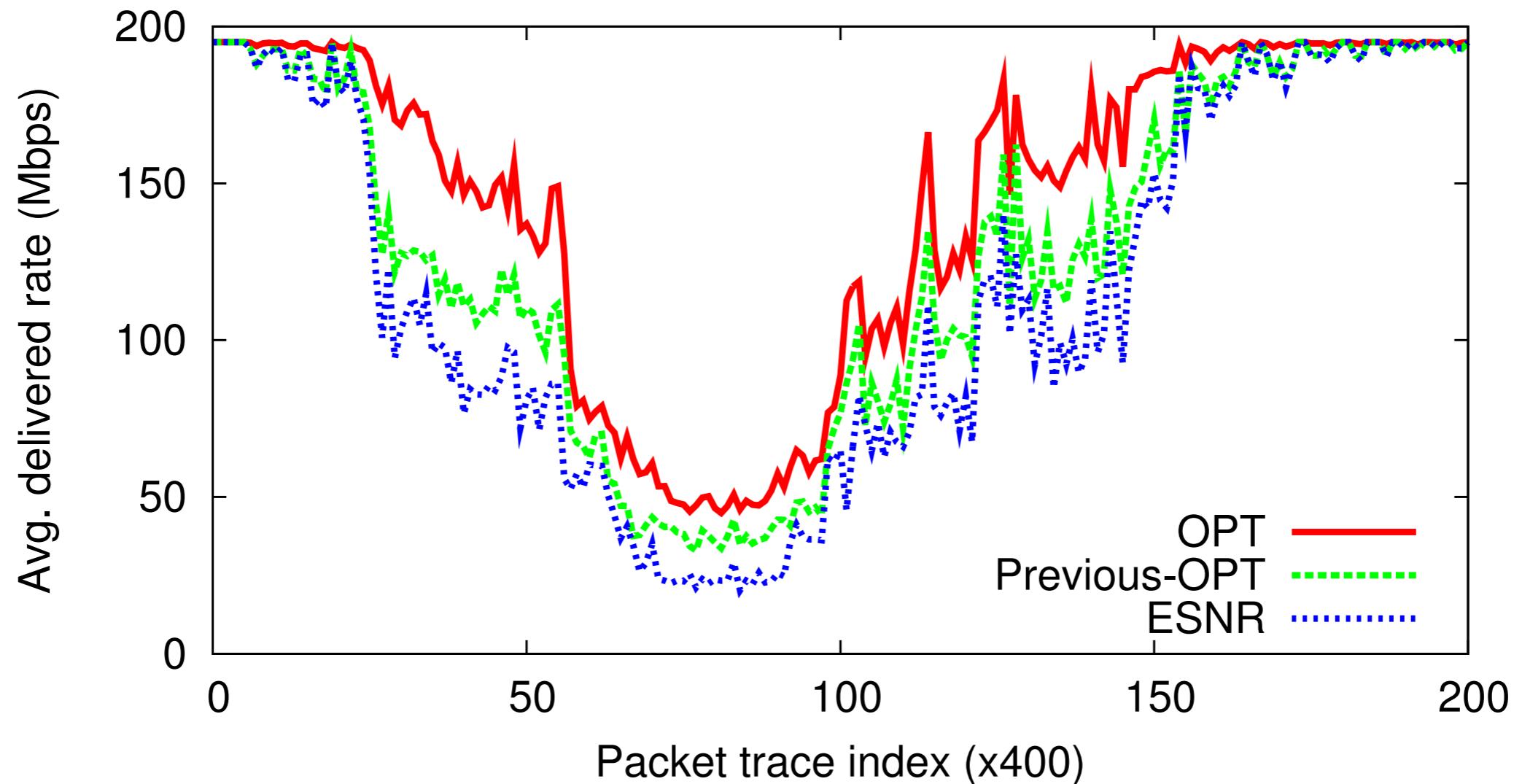
- ***Matches or beats 802.11a algorithms***
- All within 15% of OPT

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