

# FLUID: Improving Throughputs in Enterprise WLANs through Flexible Channelization

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University of Wisconsin Madison

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Microsoft Research

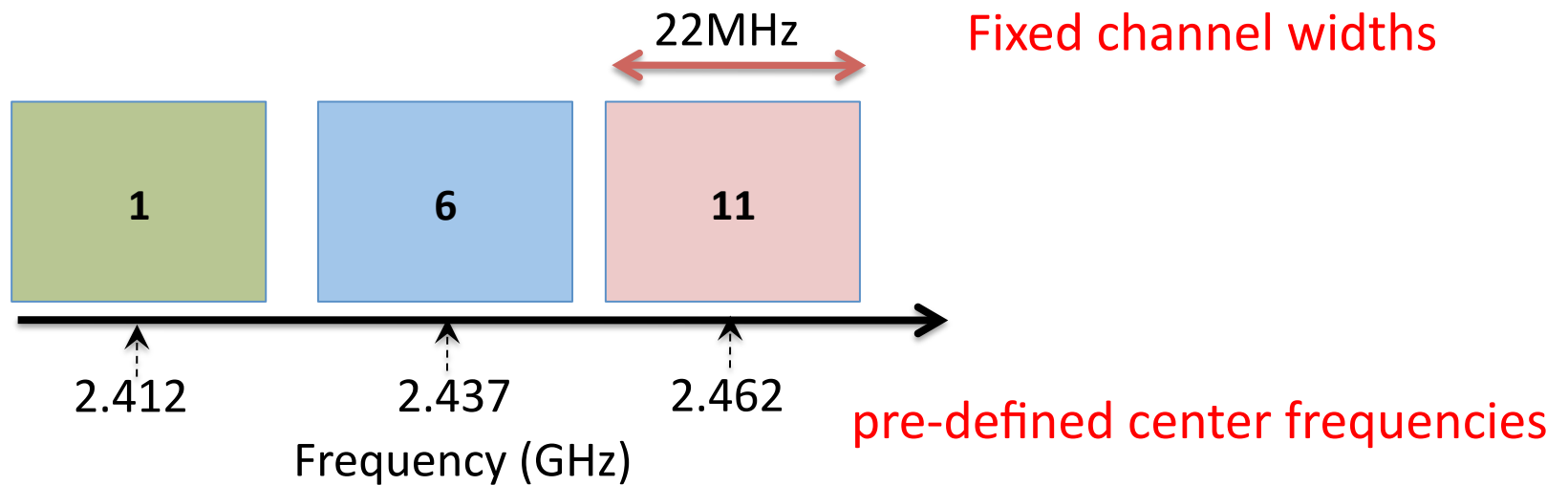


MobiCom 2011

Microsoft®  
**Research**

# Introduction

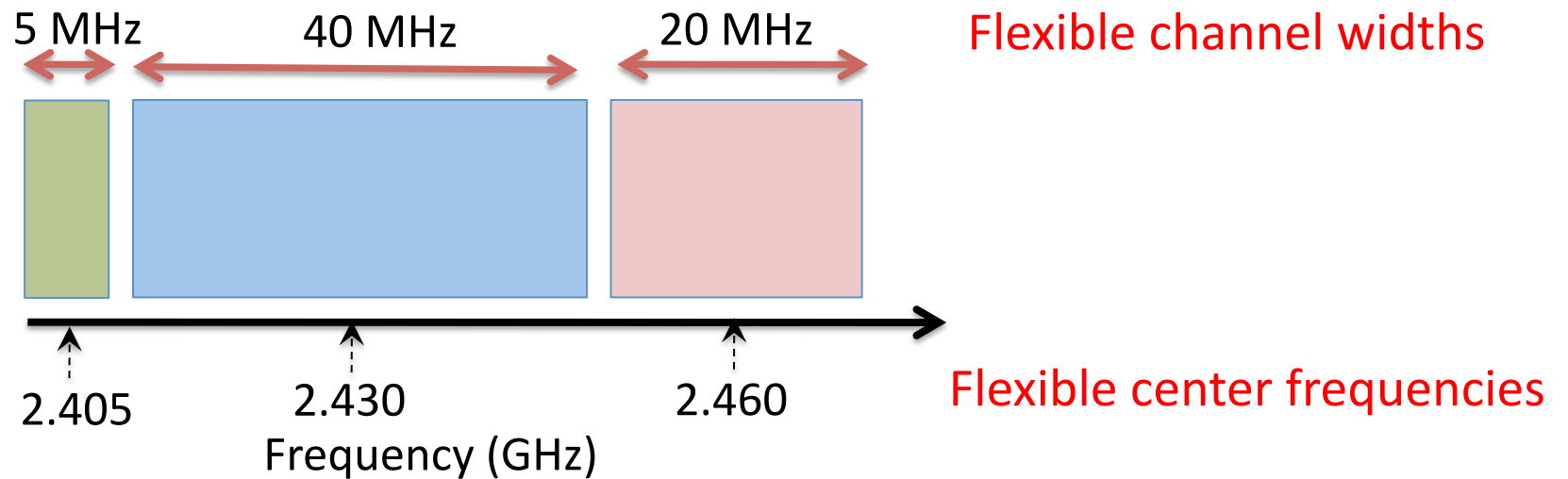
- Channels in traditional 802.11 systems



These constraints are removed for *flexible channels*

# Introduction

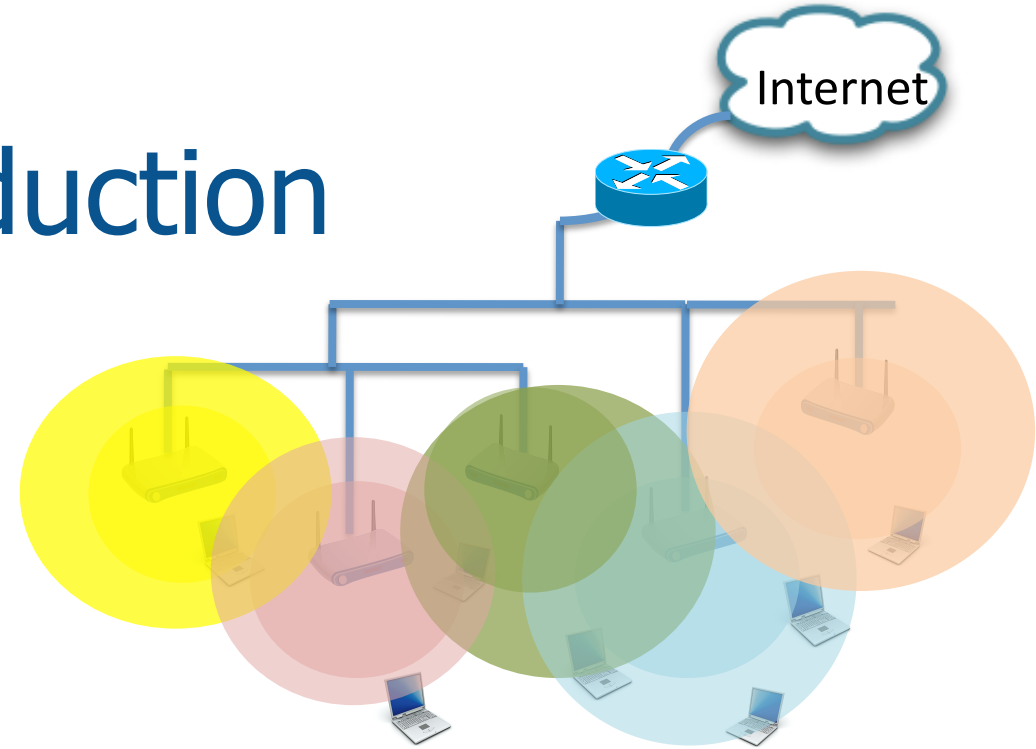
- Flexible channels



**Benefits:** improved spectrum efficiency

**Isolated, good quality link:** wider width → higher throughput

# Introduction



- How do we assign flexible channels?

Assign widths based on demands at each AP

- **Link conflicts *depend* on flexible channels used**
  - Carrier sensing, interference
  - Hidden and exposed terminals

# Introduction



- How do we assign flexible channels?

Assign

How can we systematically model flexible channel conflicts?

- Link conflicts *depend* on flexible channels used
  - Carrier sensing, interference
  - Hidden and exposed terminals

# Outline

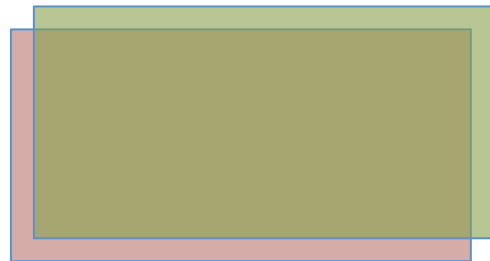
- **Understanding flexible channel conflicts**
- Modeling flexible channel conflicts
- System for enterprise WLAN employing flexible channels
- Evaluation and summary



# Flex Channels for Two Links

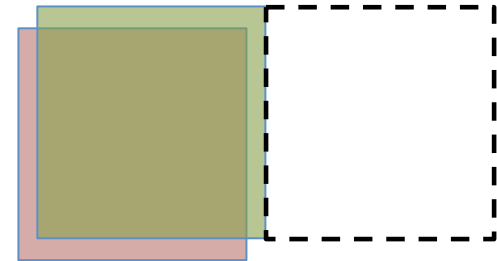
Total available spectrum = 40 MHz

**Choice 1**

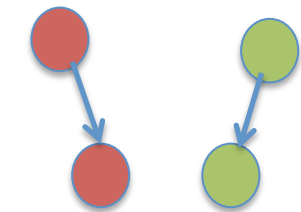


40 / 40

**Choice 2**



20 / 20



802.11 links

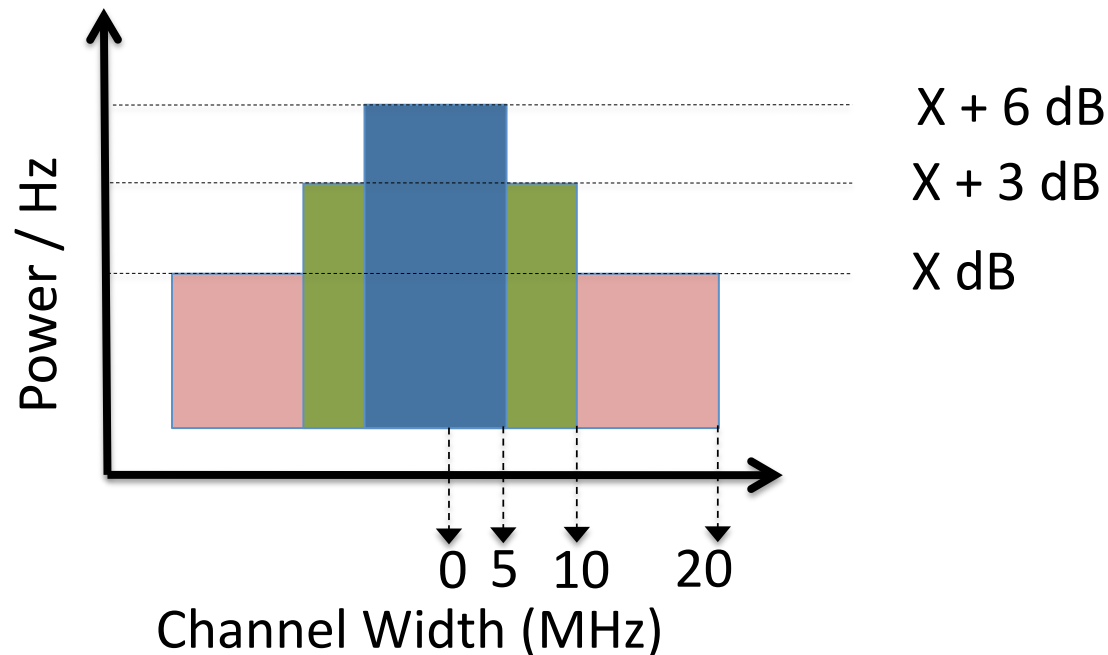
**T = 0.4**

**T = 1**

**Q. Can 20/20 be better than 40/40?**

# Flex Channels for Two Links

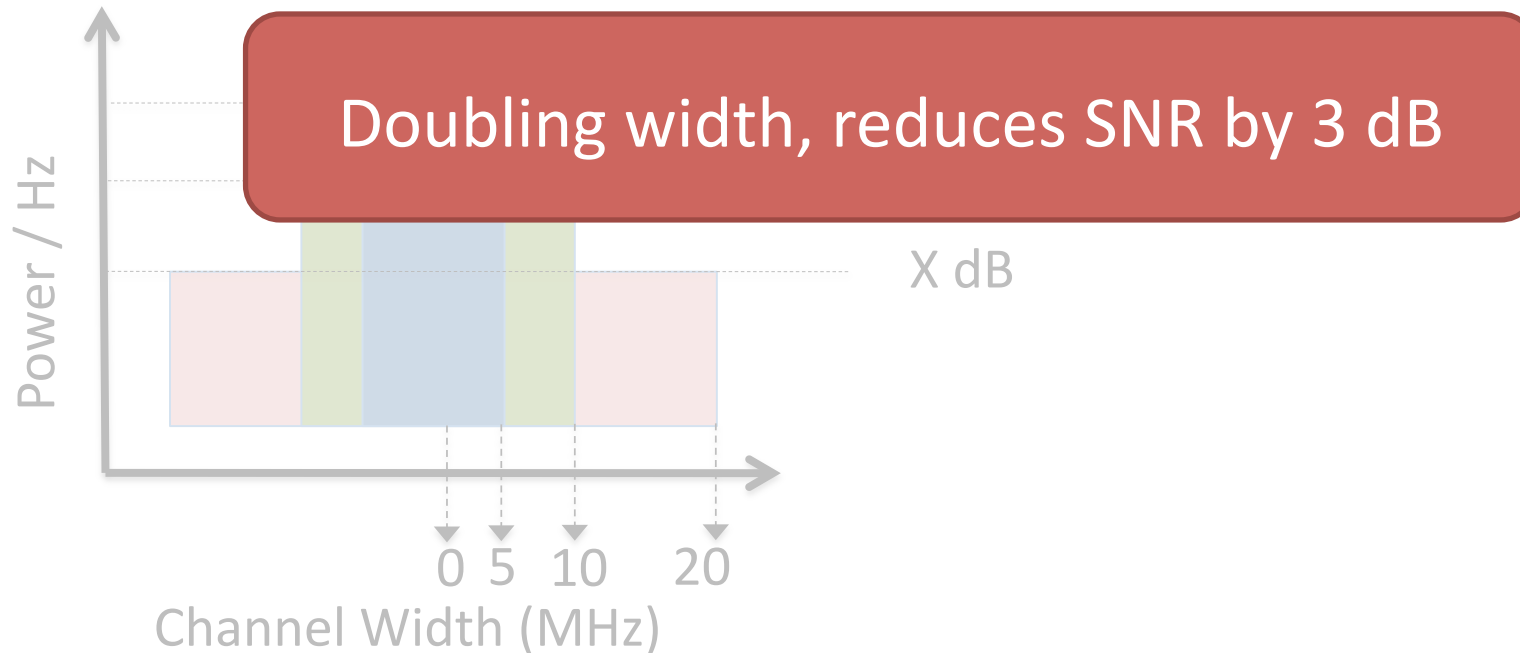
- What happens when we reduce width?



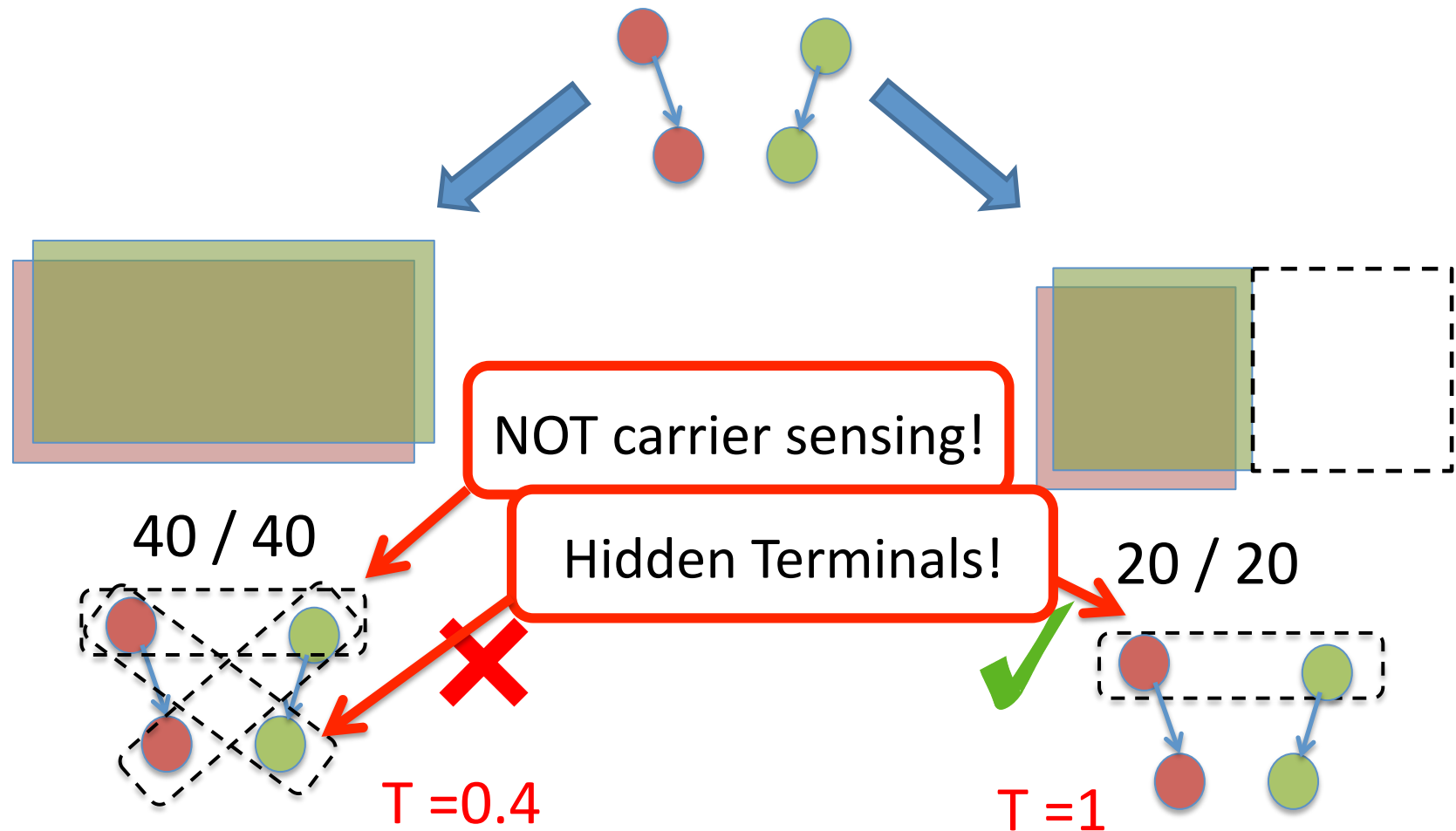


# Flex Channels for Two Links

- What happens when we reduce width?



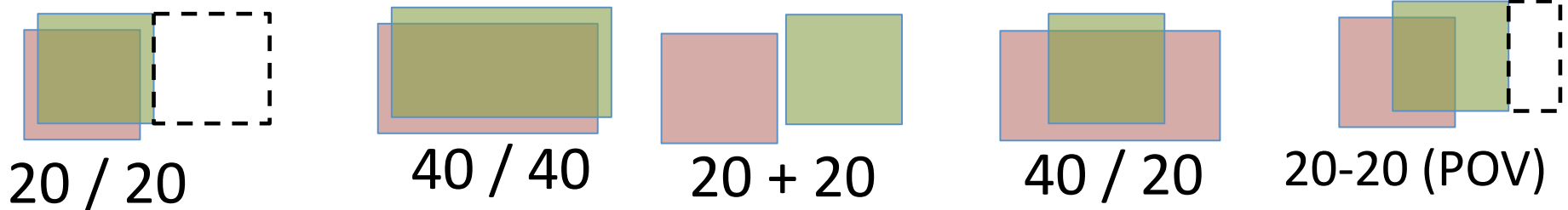
# Flex Channels for Two Links



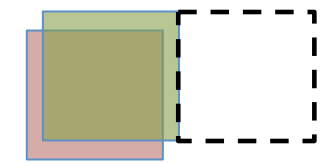


# Flex Channels for Two Links

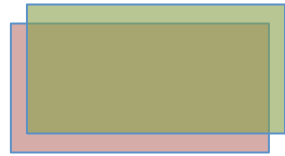
- If a total of 40 MHz is available, how should we assign it to two links?
  - 2 channel widths of 20 MHz and 40 MHz



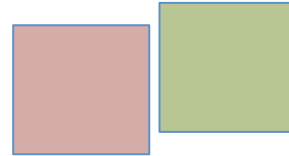
**Each configuration performed the best in some case**



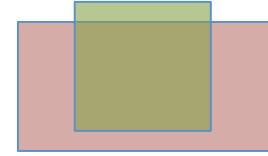
20 / 20



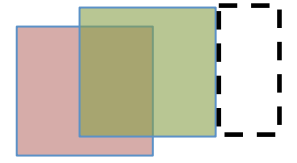
40 / 40



20 + 20

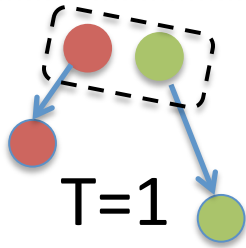


40 / 20

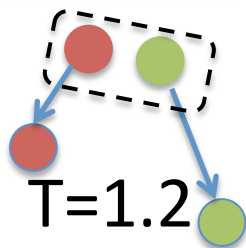


20-20 (POV)

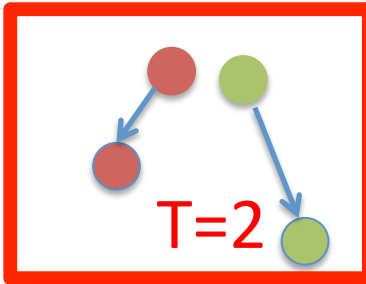
E1



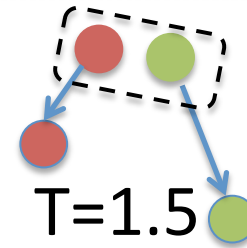
T=1



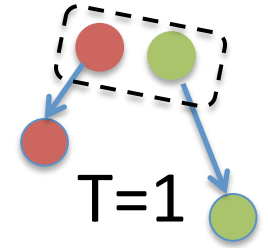
T=1.2



T=2

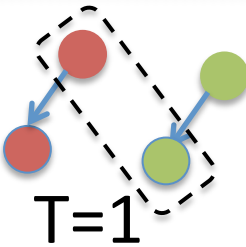


T=1.5

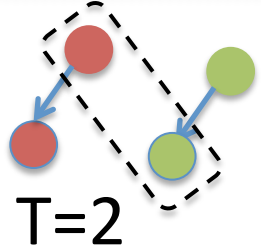


T=1

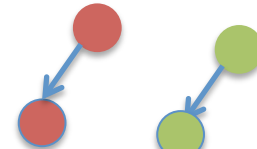
E2



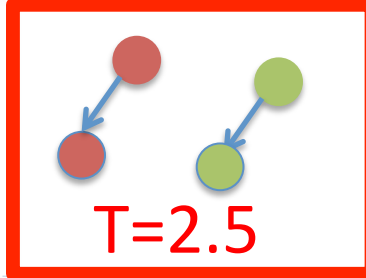
T=1



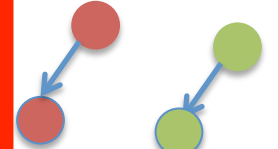
T=2



T=1.7



T=2.5



T=1.7

E3

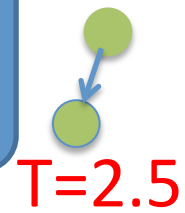
Conflicts (Carrier sensing and Interference) depend on the configuration

T=1.3

T=1

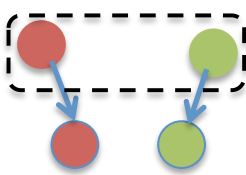
T=2.5

T=1.8

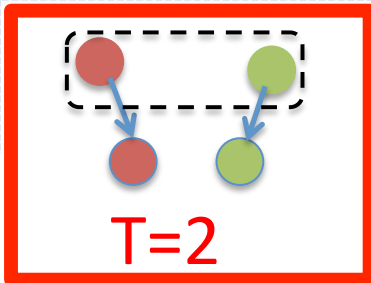


T=2.5

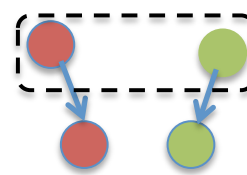
E4



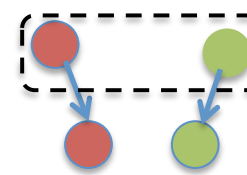
T=1



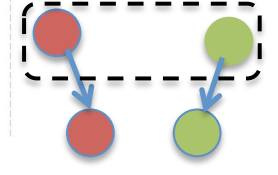
T=2



T=1



T=1.5



T=1

# What about multiple links?

- Difference in power levels effects
  - **Carrier sensing range**

Channel Width	5 MHz	10 MHz	20 MHz	40 MHz
Carrier sense (% links)	28%	24%	19%	13%

Measurement on 600 link pairs, 802.11a

- **Interference range**
- **Hidden and Exposed Terminals**

# What about multiple links?

- Difference in power levels effects
  - Carrier sensing range

Channel Width	5 MHz	10 MHz	20 MHz	40 MHz
Carrier sense	28%	24%	19%	13%

Need for systematically modeling flexible channel conflicts

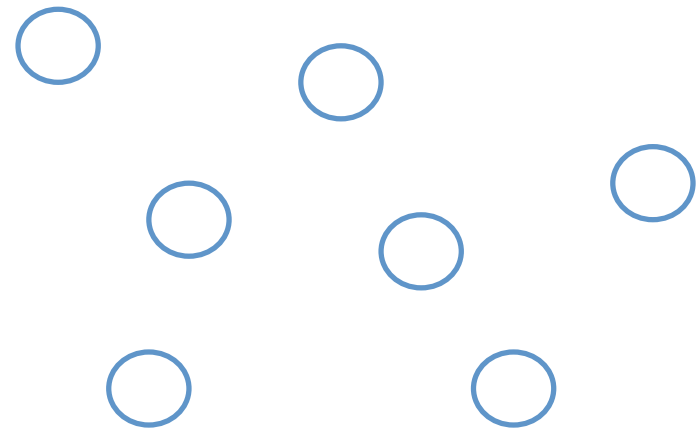
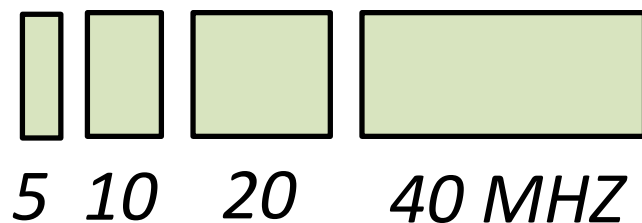
- Interference range
- Hidden and Exposed Terminals

k pairs, 802.11a

# Problem Statement

Given

- Network with  $N$  nodes
- Total Bandwidth  $B$  MHz
- Flexible channels
  - Center frequencies
  - Channel widths



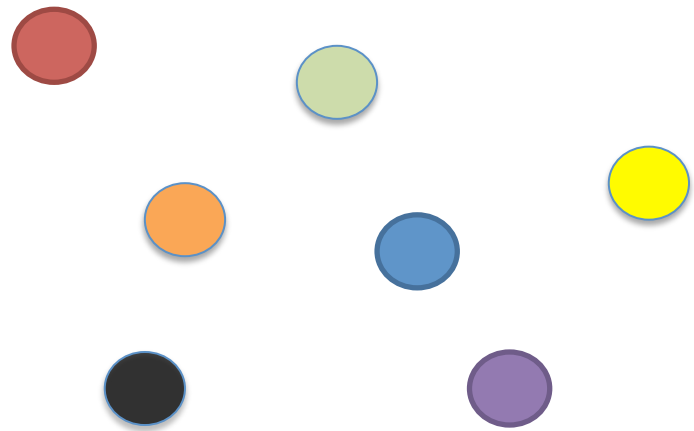
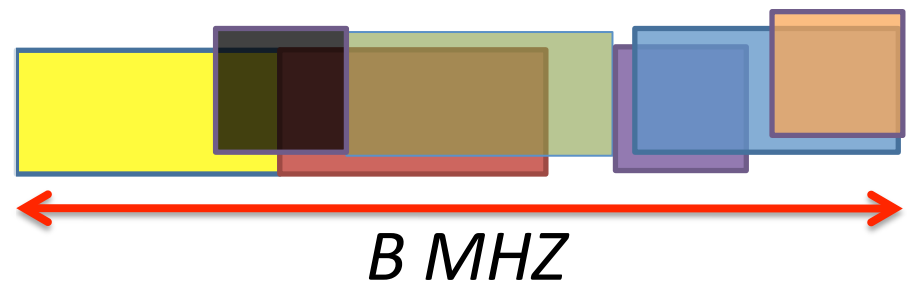
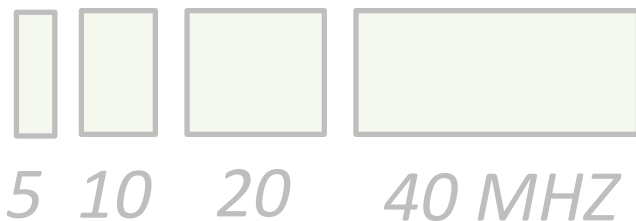
# Problem Statement

Given

- Network with  $N$  nodes
- Total Bandwidth  $B$  MHz

How should we assign flexible channels to nodes?

– Channel widths



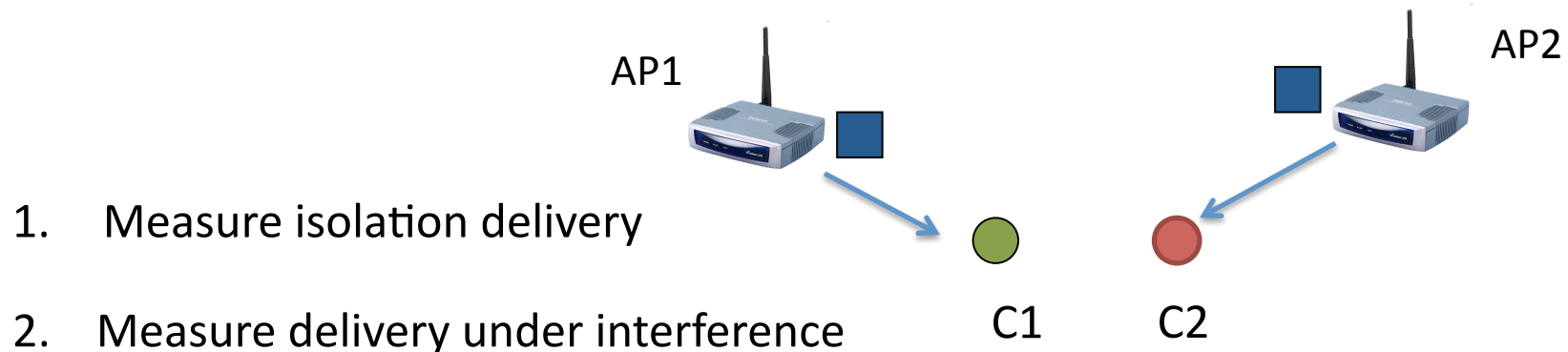


# Outline

- Understanding flexible channel conflicts
- **Modeling flexible channel conflicts**
- System for enterprise WLAN employing flexible channels
- Evaluation and summary

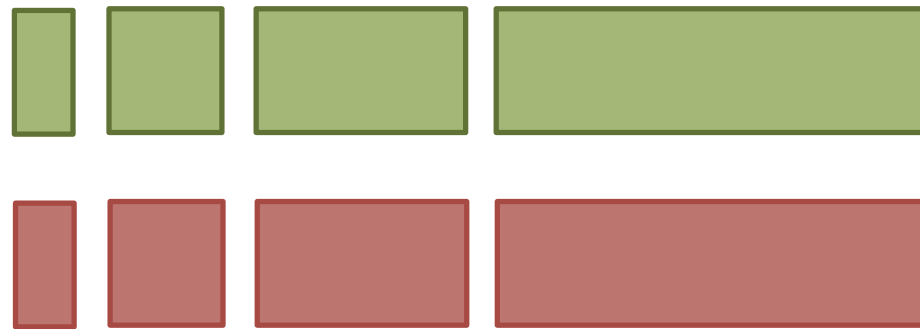
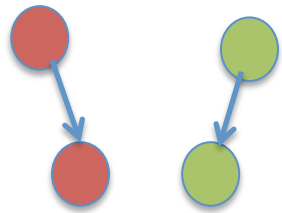
# How to build the conflict graph?

- **Goal:** for any given link and interferer, what is the expected link delivery ratio?
- **Bandwidth tests** (Fixed width channels)



Complexity:  $O(N^2k^2)$  (naive)  
 $O(Nk)$  (SINR modeling)

# How to build the conflict graph?



(flexible channels)

5 MHz 10 MHz 20 MHz 40 MHz

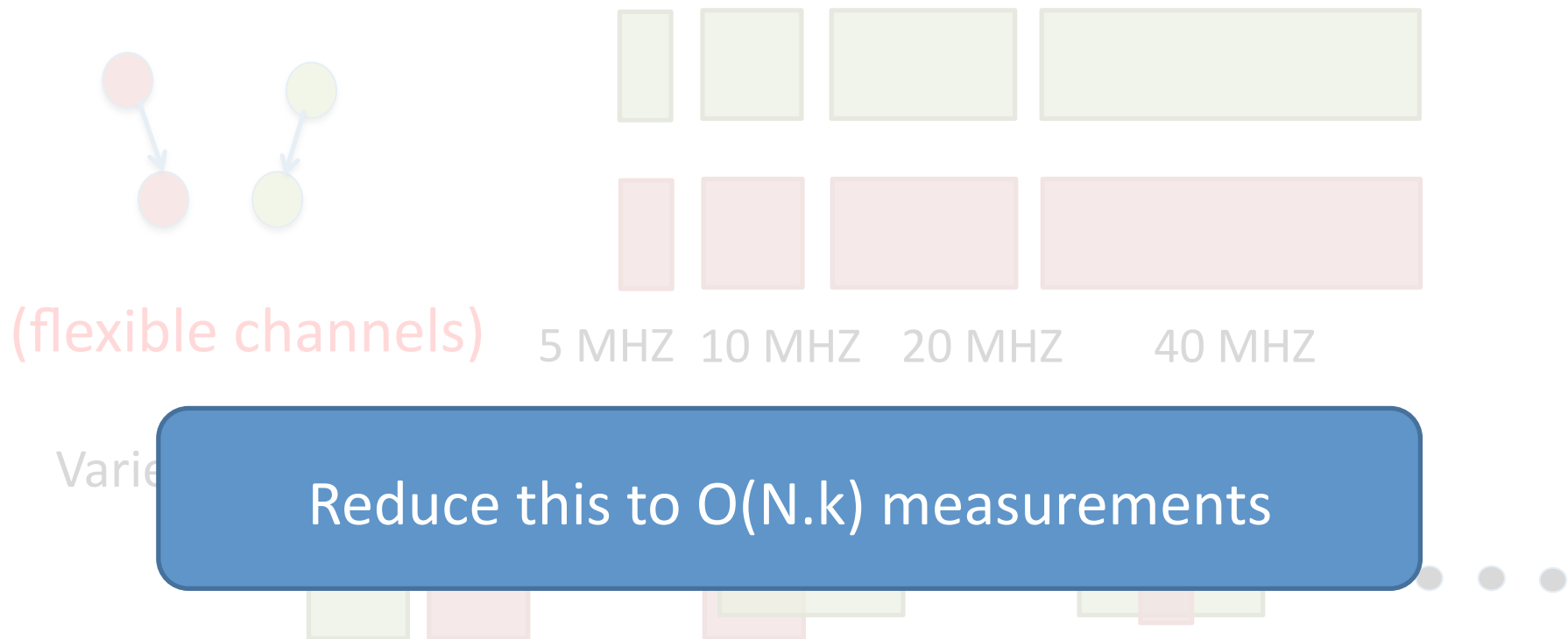
Variety of configurations are possible



**Increased complexity:**

$k$  data rates,  $|w|$  widths  $\longrightarrow O(N^2 k^2 |w| 2^{|w|+1})$

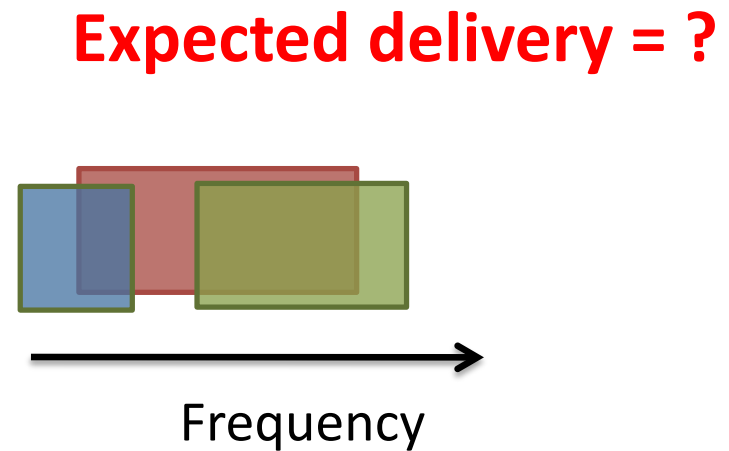
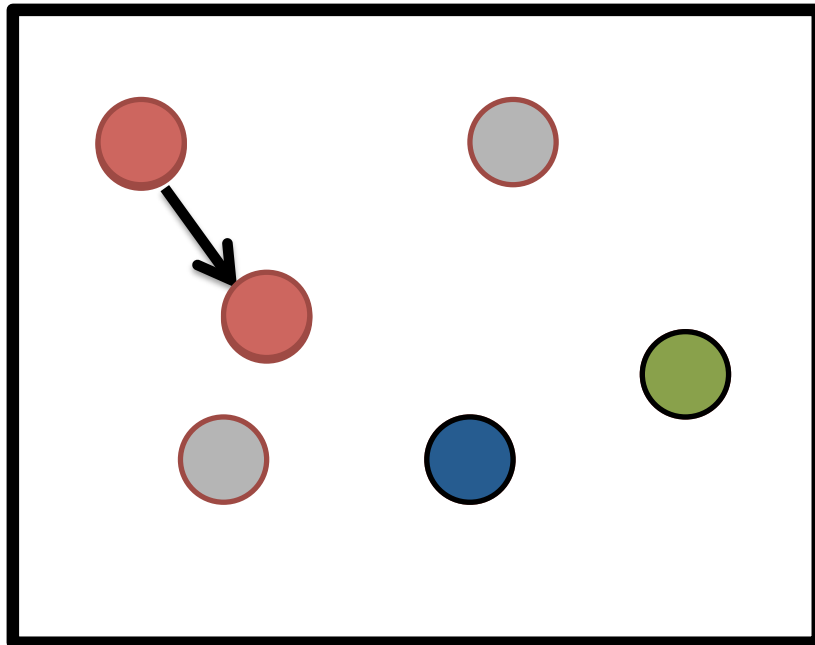
# How to build the conflict graph?



**Increased complexity:**

$k$  data rates,  $|w|$  widths  $\longrightarrow O(N^2 k^2 |w| 2^{|w|+1})$

# Modeling Conflicts



# Modeling Conflicts

$$Delivery = f(SINR)$$

$$SINR = S_t(w_t) - \sum_i (S_i(w_i) + 10 \log I_f) - N$$

Signal strength of the transmitter using width  $W_t$

Signal strength of the interferer using width  $W_i$

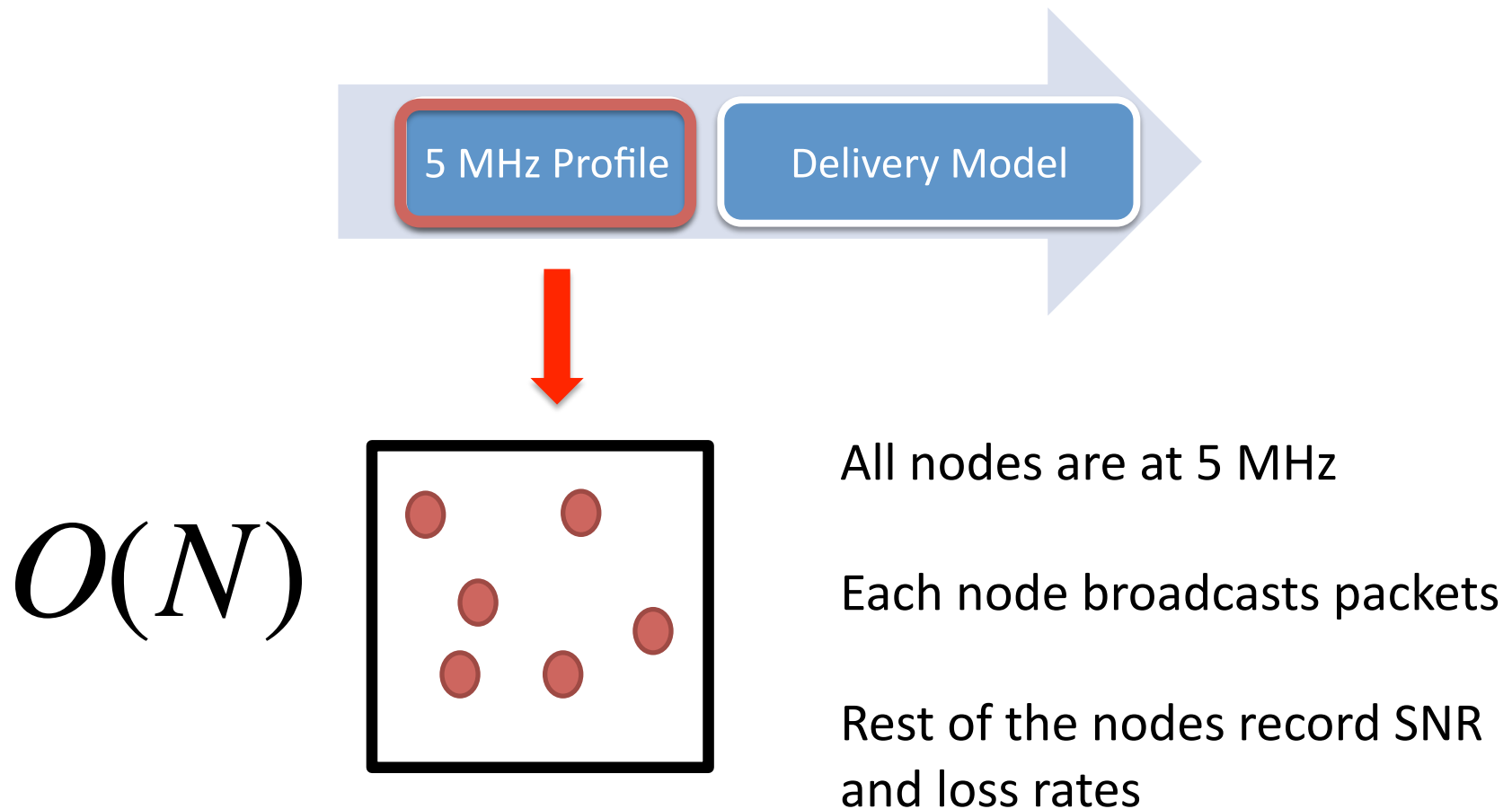
Expected delivery = ?

Accounts for spectral overlaps

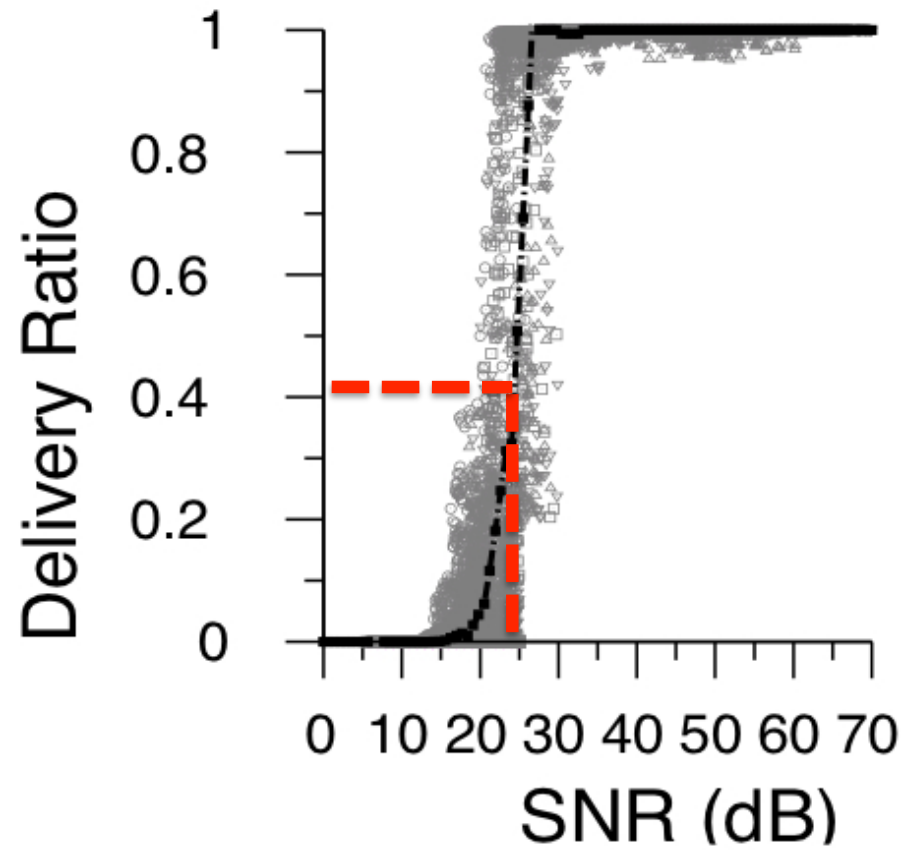
Frequency



# Modeling Conflicts

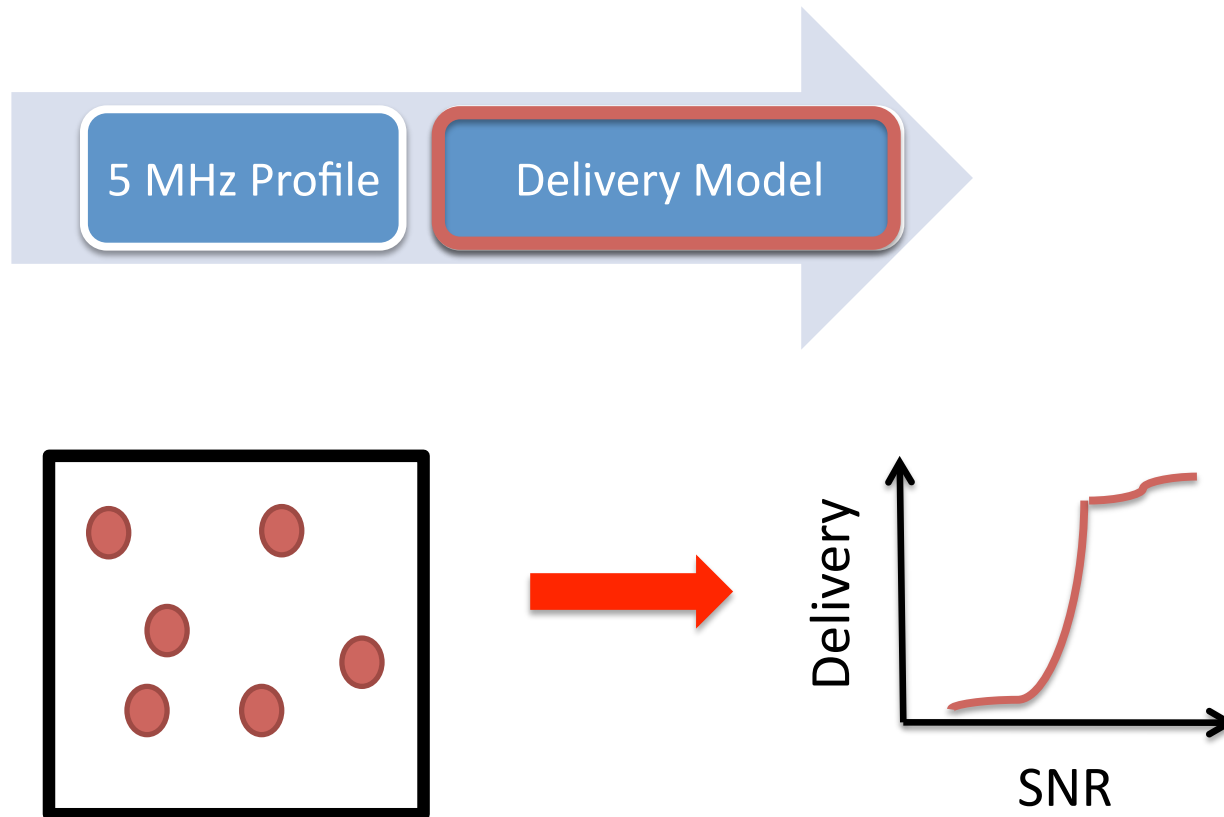


# Modeling Conflicts

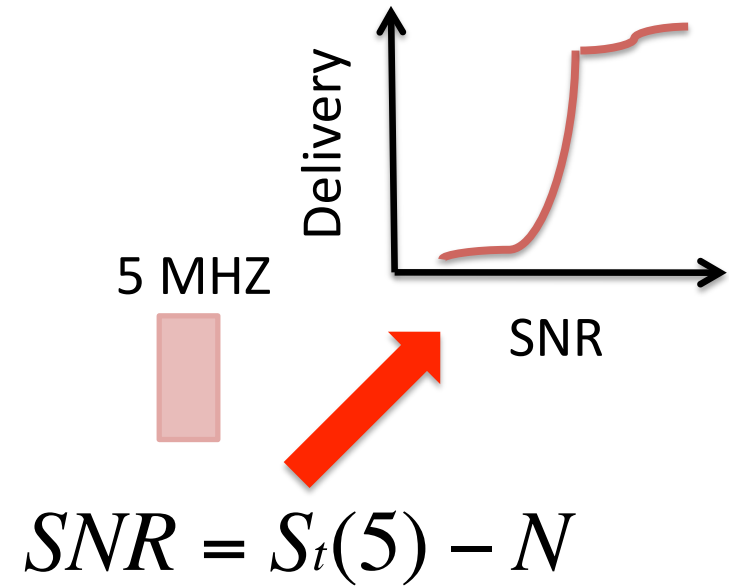
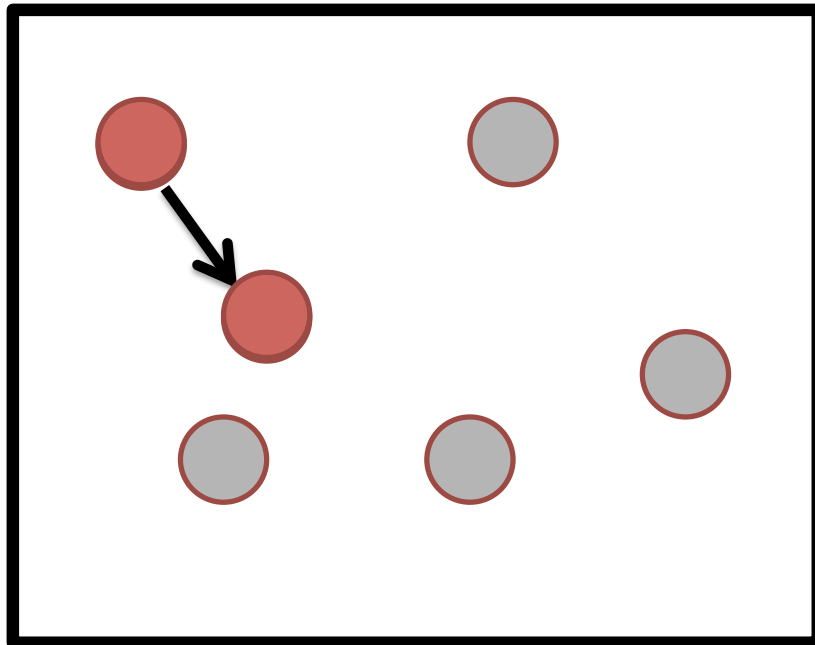




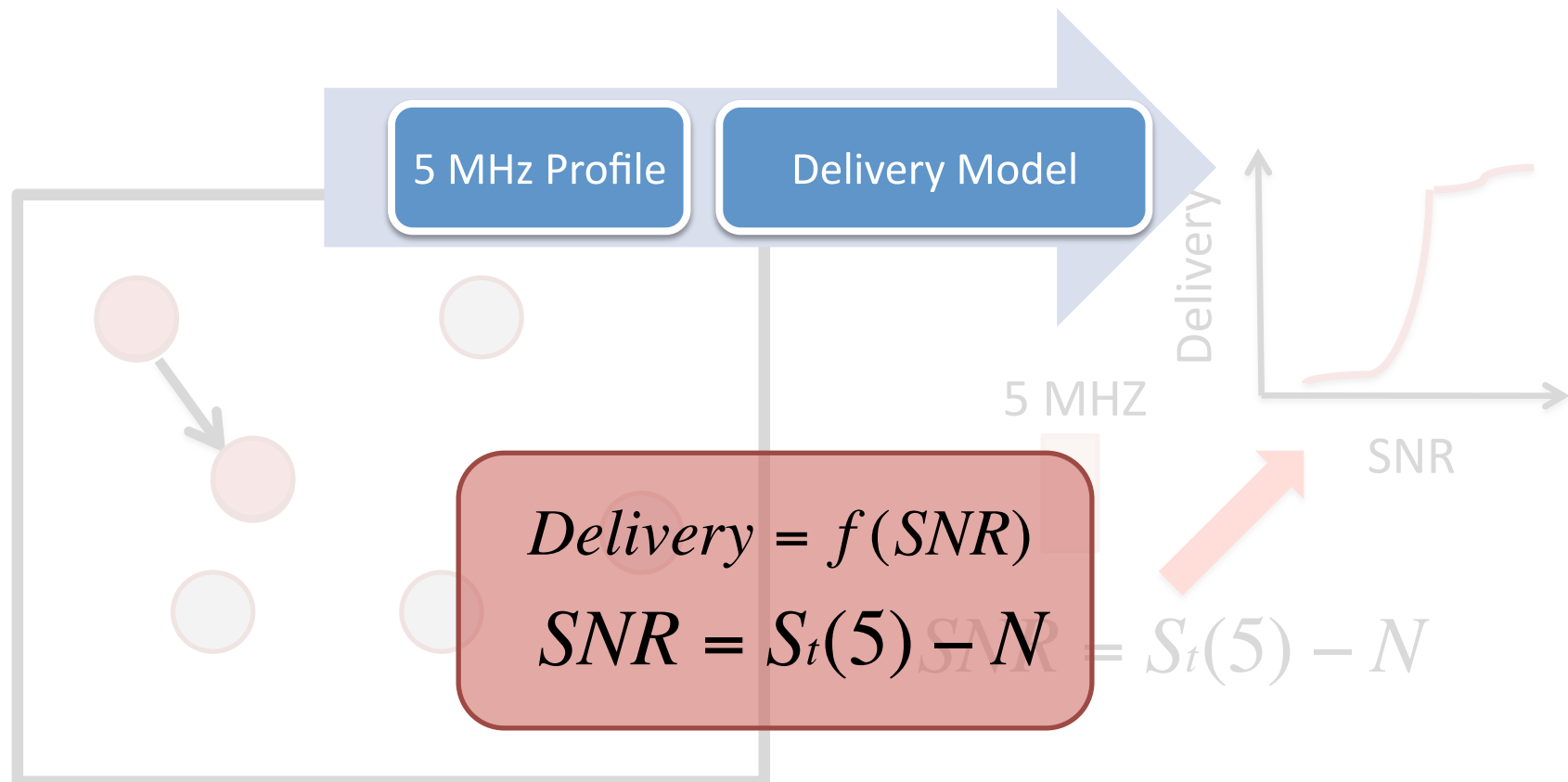
# Modeling Conflicts



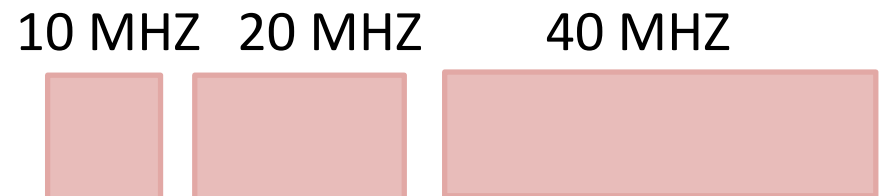
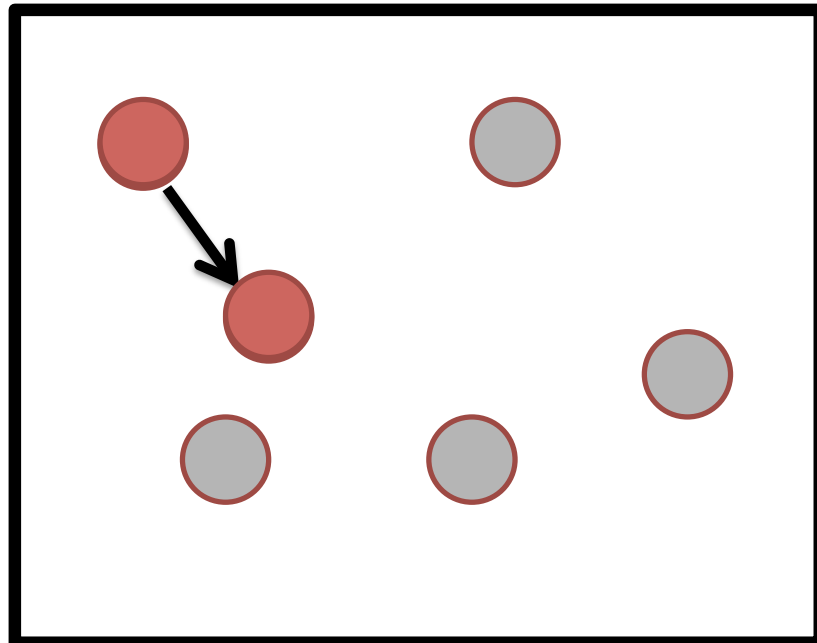
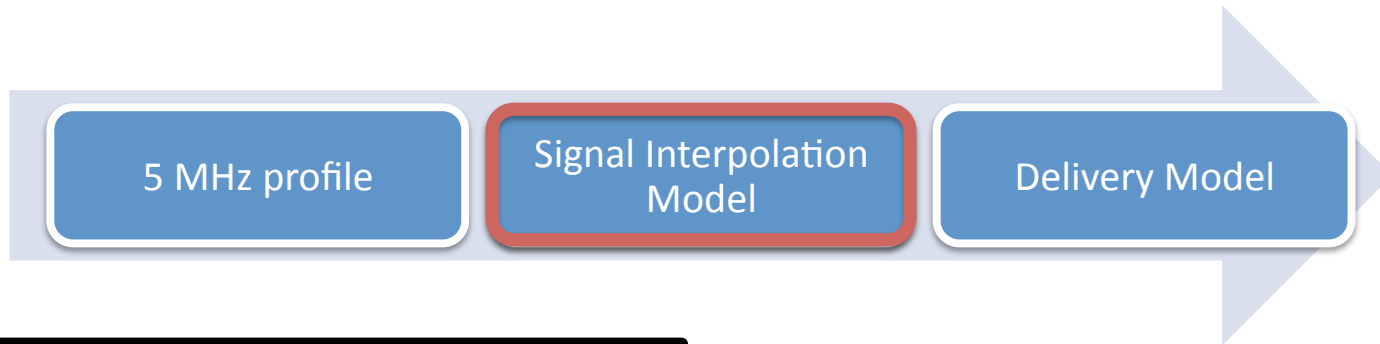
# Modeling Conflicts



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# Modeling Conflicts



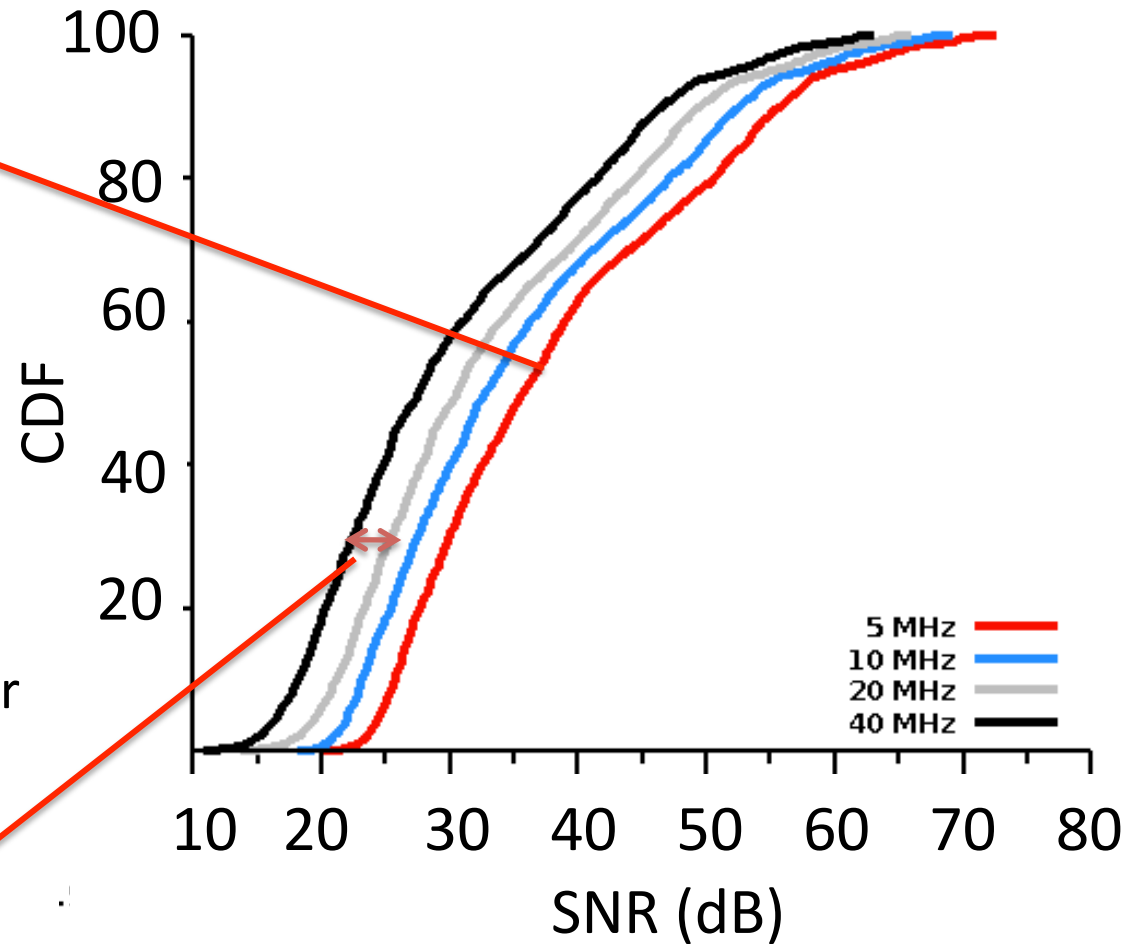
Higher signal strength at 5 MHz

$$S_t(w) = S_t(5) + 10\log(5/w)$$

Signal strength  
at 5 MHz

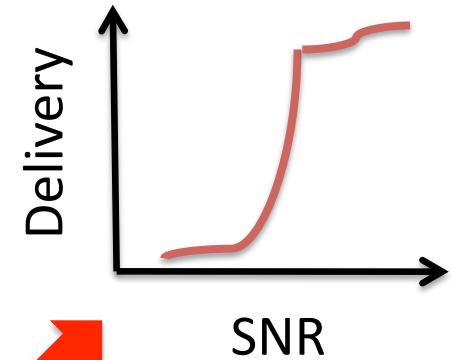
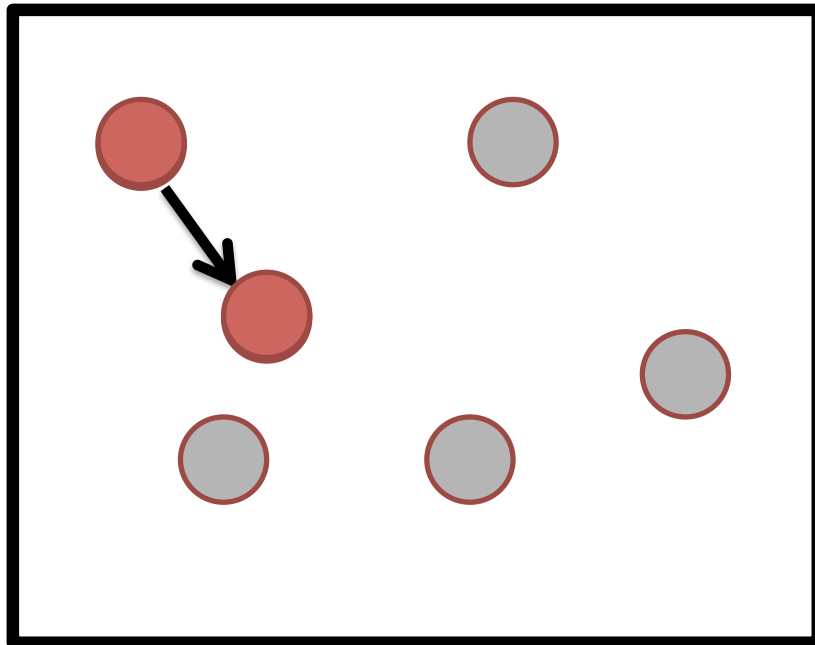
Decrease in power

~3 dB difference



Measurements on 32 nodes, 802.11a

# Modeling Conflicts



$$SNR = S_t(w) - N$$

$$S_t(w) = S_t(5) + 10 \log(5 / w)$$

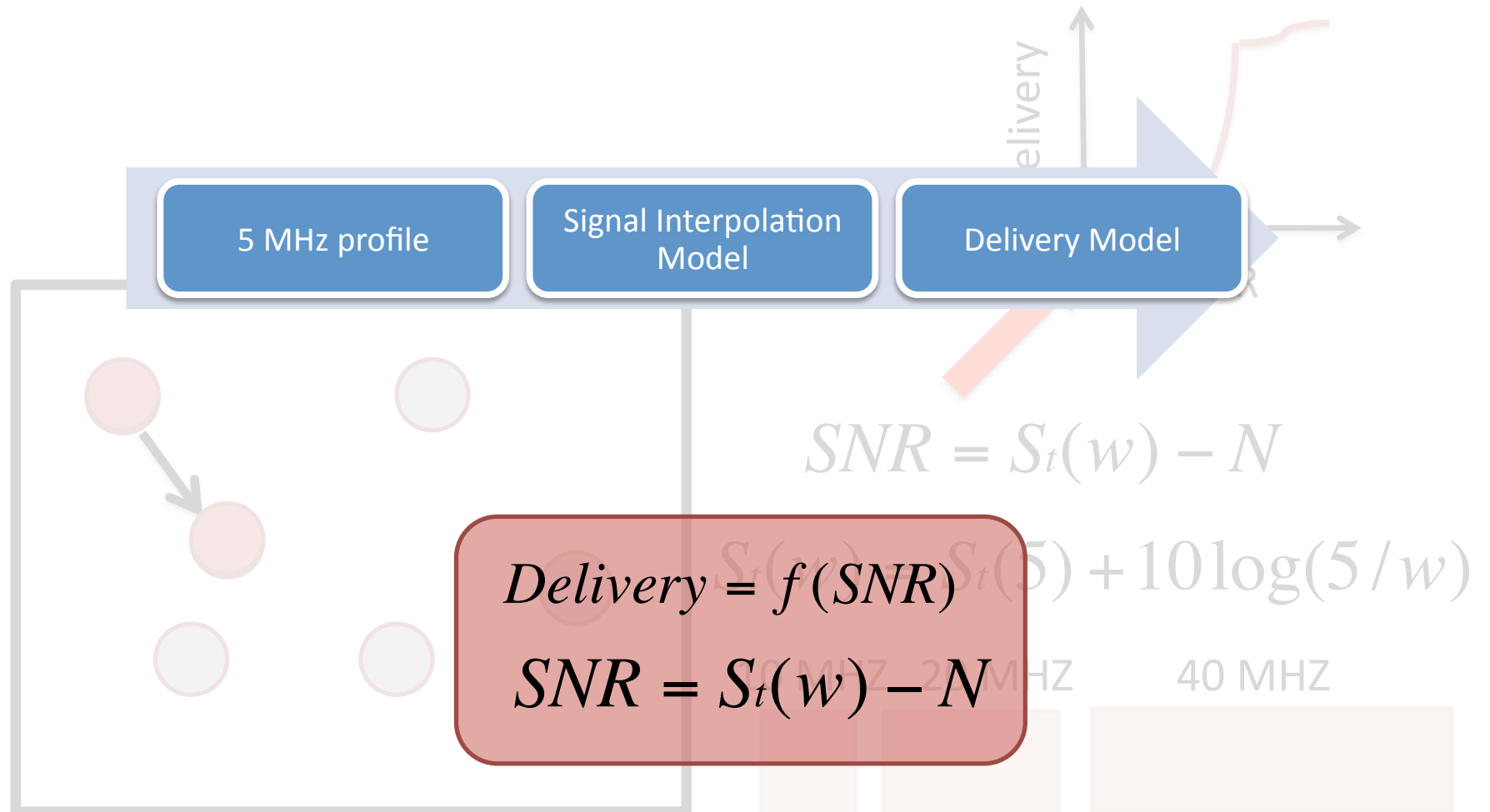
10 MHZ

20 MHZ

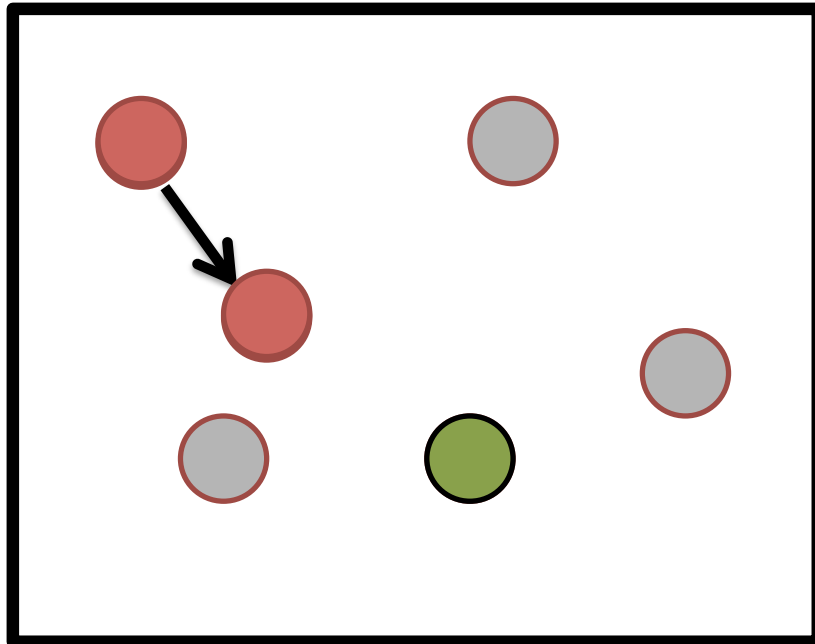
40 MHZ



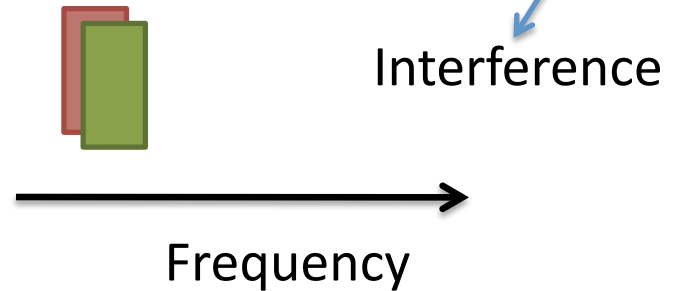
# Modeling Conflicts



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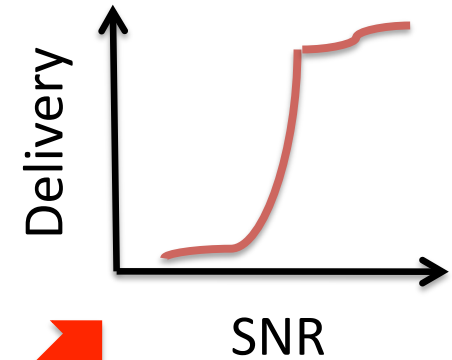
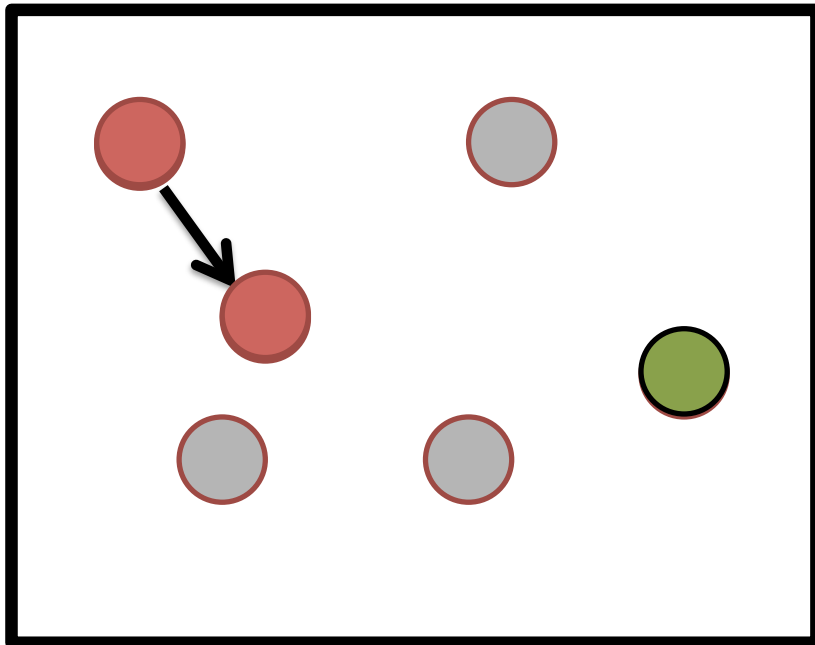


$$SINR = S_t(5) - \underline{S_i(5)} - N$$

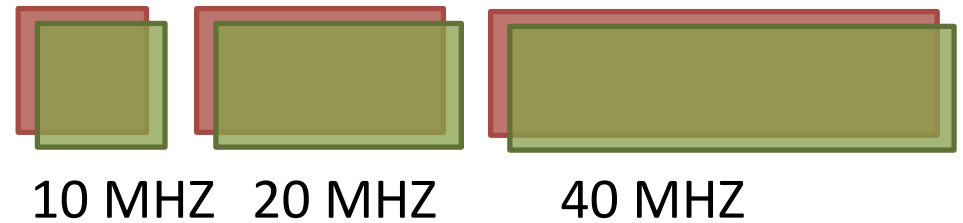




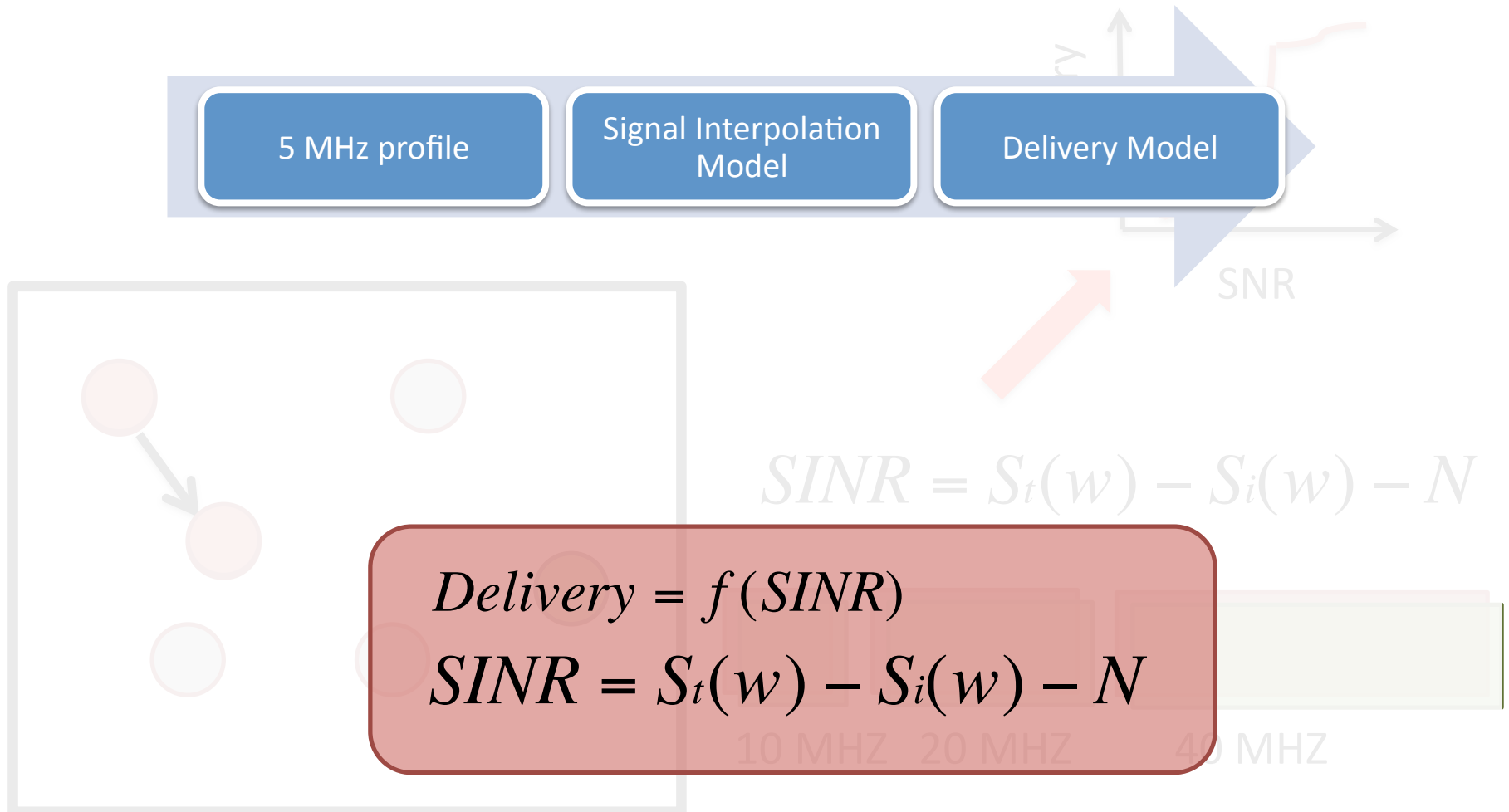
# Modeling Conflicts



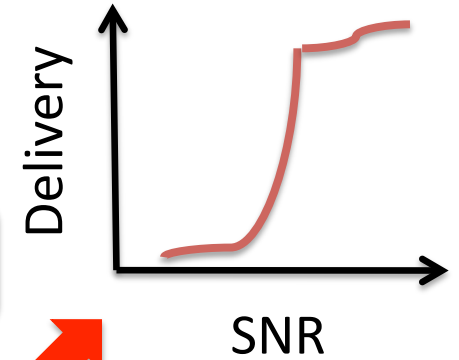
$$SINR = S_t(w) - S_i(w) - N$$



# Modeling Conflicts

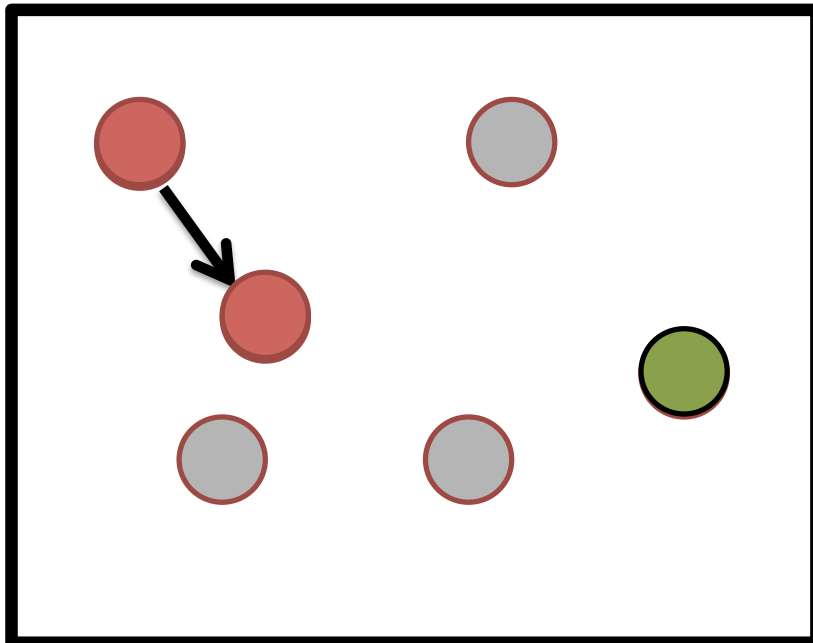


# Modeling Conflicts



$$SINR = S_t(w_t) - \left( S_i(w_i) + \underbrace{10 \log I_f} \right) - N$$

$$I_f \leq 1$$



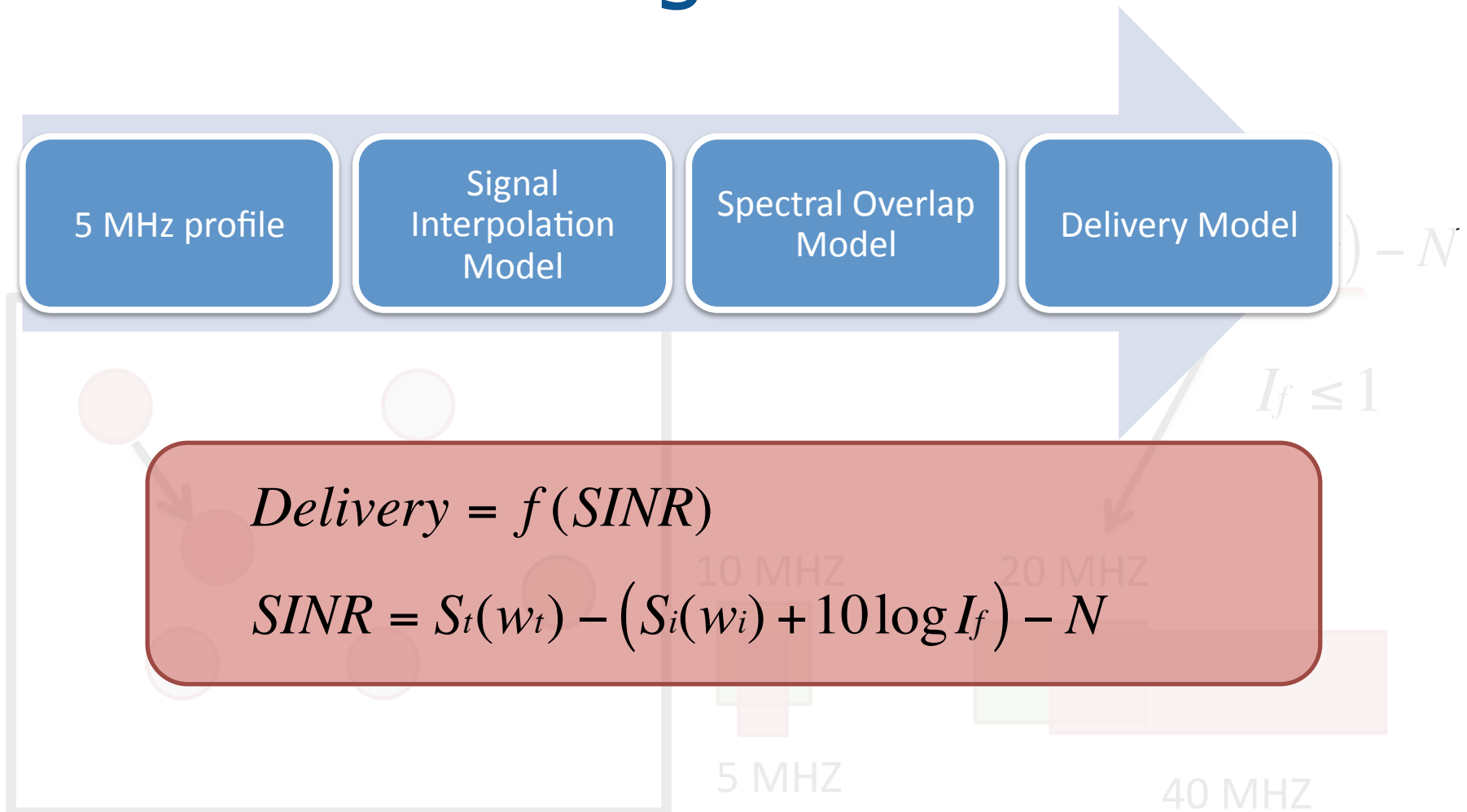
10 MHz

20 MHz

5 MHz

40 MHz

# Modeling Conflicts



# Modeling Conflicts

5 MHz profile

Signal  
Interpolation  
Model

Spectral Overlap  
Model

Delivery Model

$- N$

$I_f \leq 1$

$$Delivery = f(SINR)$$

$$SINR = S_t(w_t) - \sum_i (S_i(w_i) + 10 \log I_f) - N$$

5 MHz

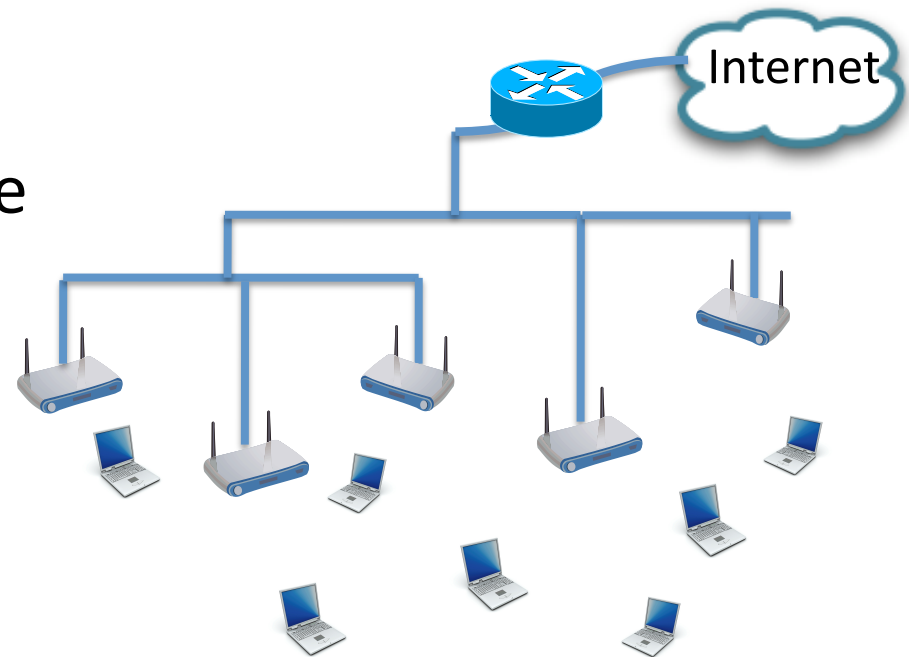
40 MHz

# Outline

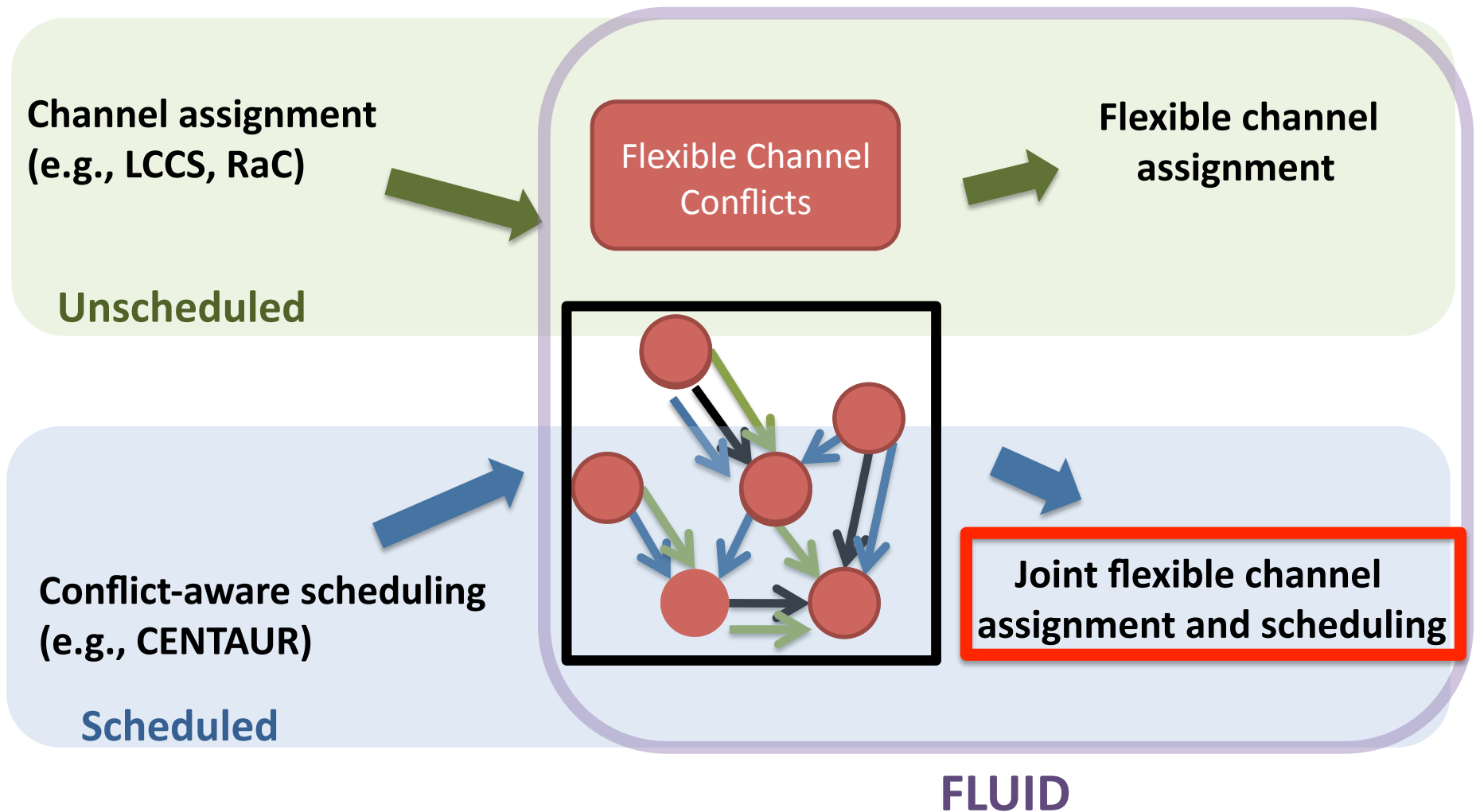
- Understanding flexible channel conflicts
- Modeling flexible channel conflicts
- **System for enterprise WLAN employing flexible channels**
- Evaluation and summary

# FLUID

- A system for enterprise WLANs employing flexible channelization
  - Models the flexible channel conflict graph
  - Uses this conflict graph to mitigate interference



# Flexible channels and FLUID

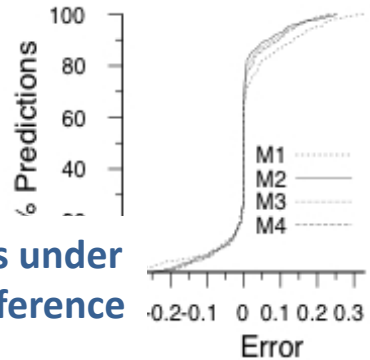
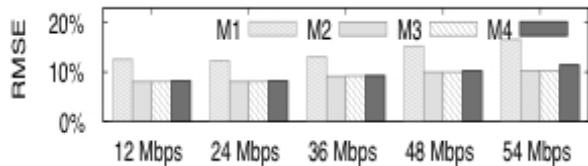




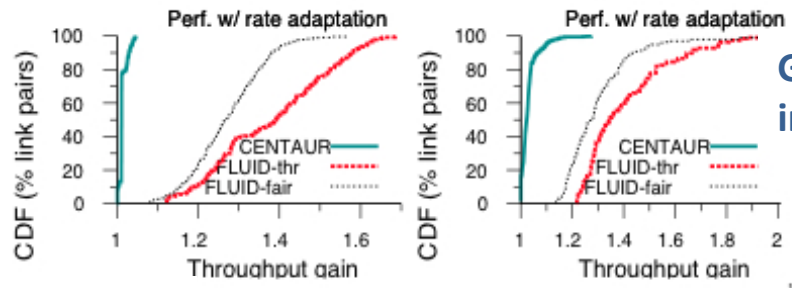
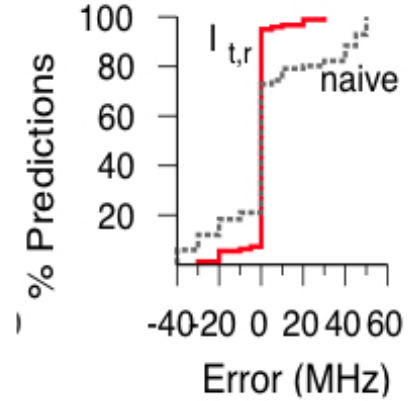
# Outline

- Understanding flexible channel conflicts
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- **Evaluation and summary**

# Evaluation and Results

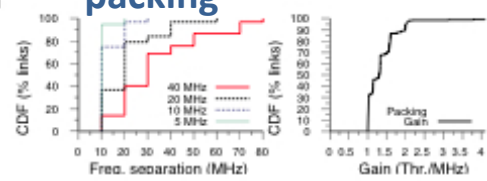


Modeling accuracy

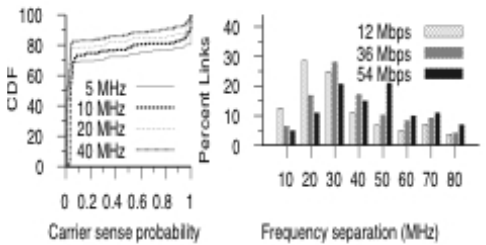


Gains under interference

Gains from conflict-aware packing

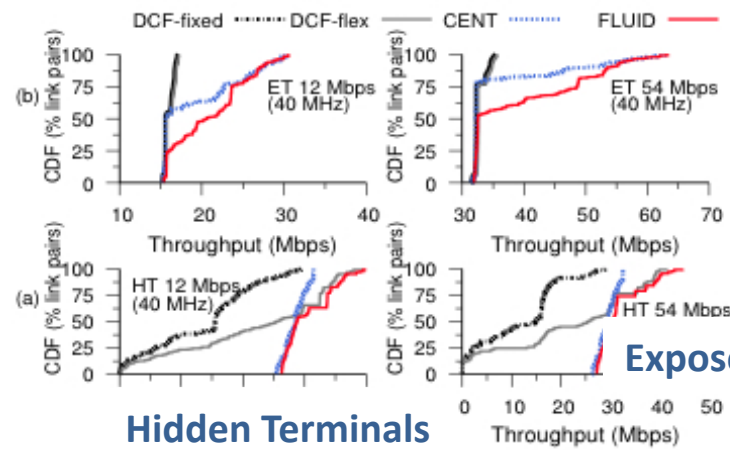
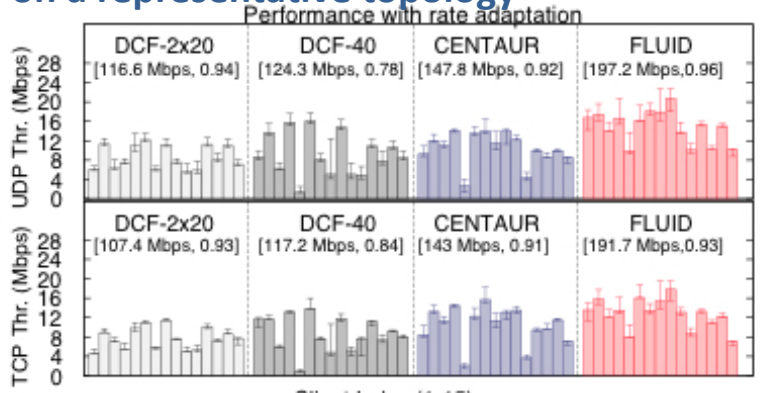


Gains from client-centric widths



Scheduling Vs. Flex channels

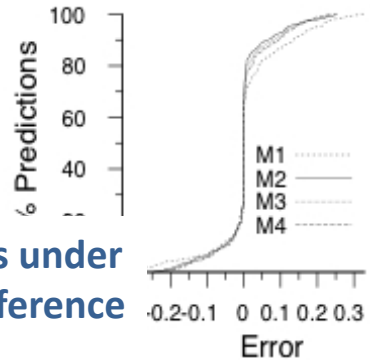
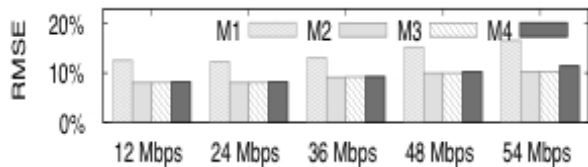
Gains on a representative topology



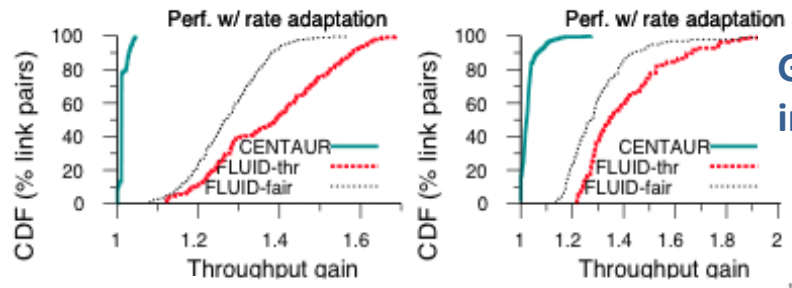
Hidden Terminals

Exposed Terminals

# Evaluation and Results

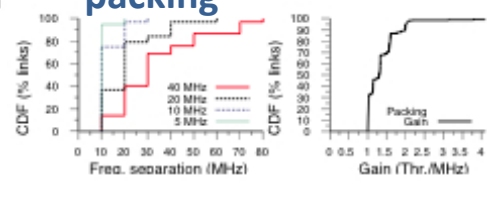


Modeling accuracy

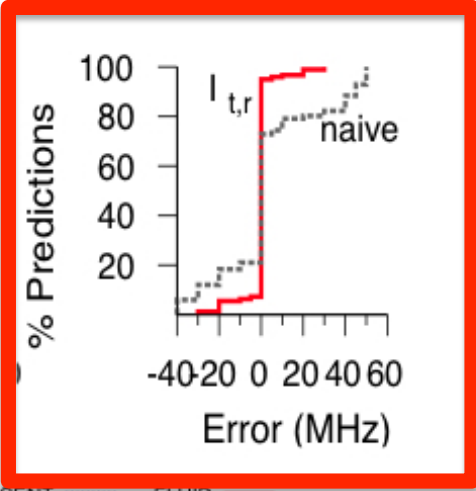


Gains under interference

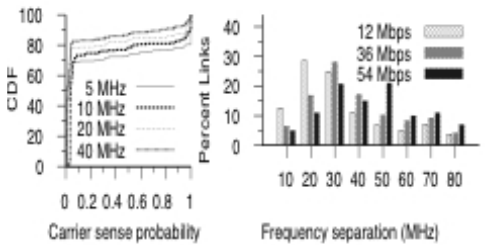
Gains from conflict-aware packing



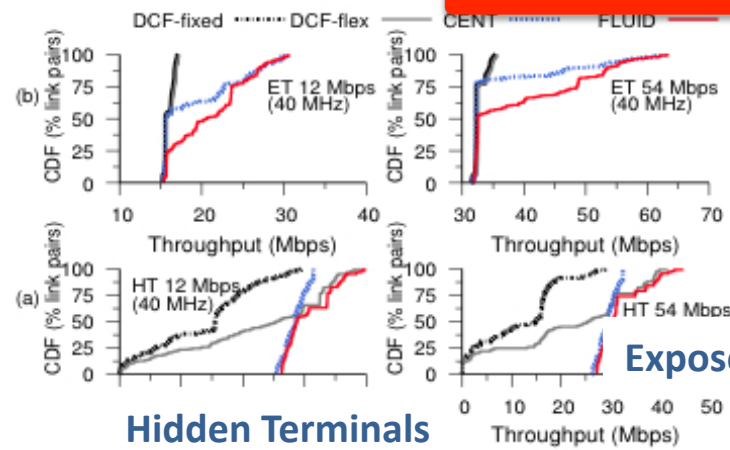
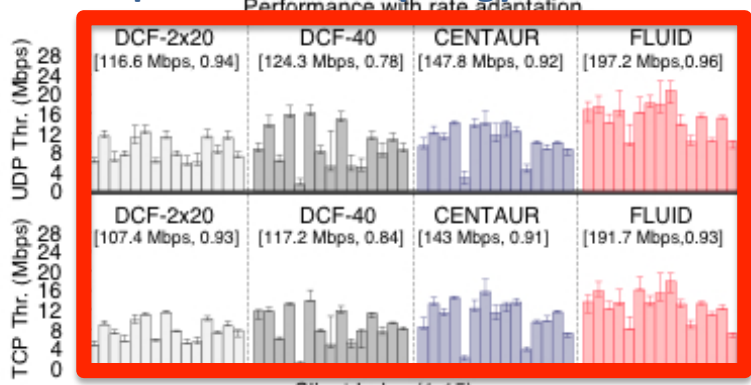
Scheduling Vs. Flex channels



Gains from client-centric widths



Gains on a representative topology



Exposed Terminals

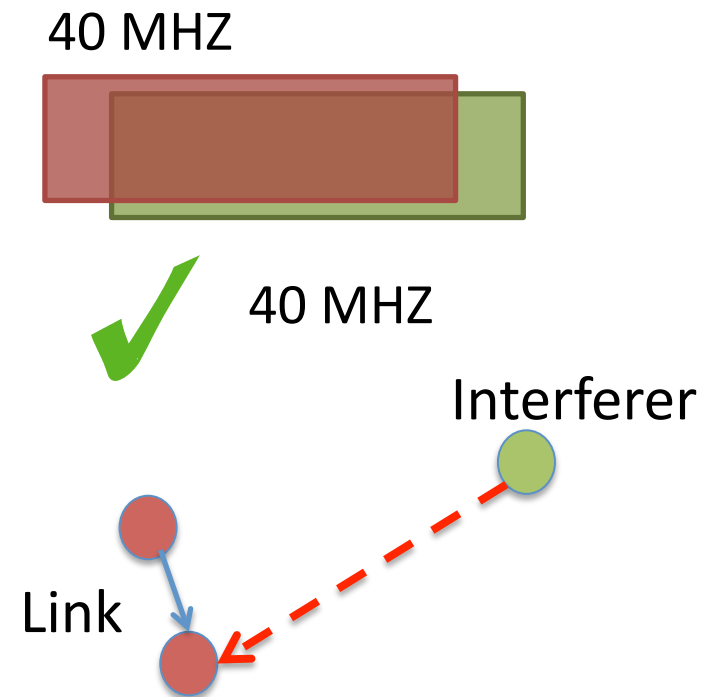
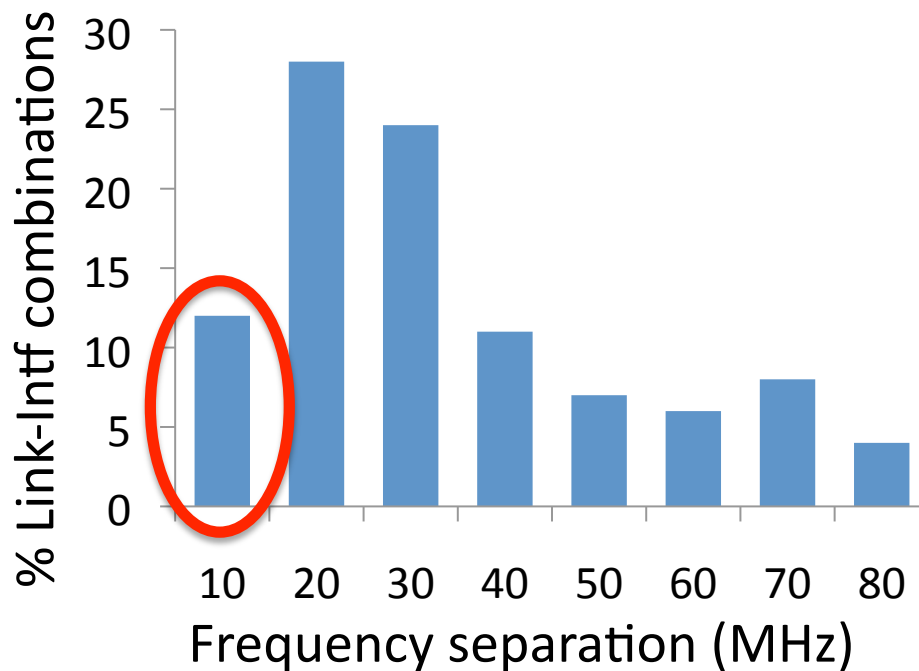
Hidden Terminals

# Evaluation and Results

## 1. How accurate is the model?

500 link – interferer combinations

**Min. freq separation for zero conflict?**

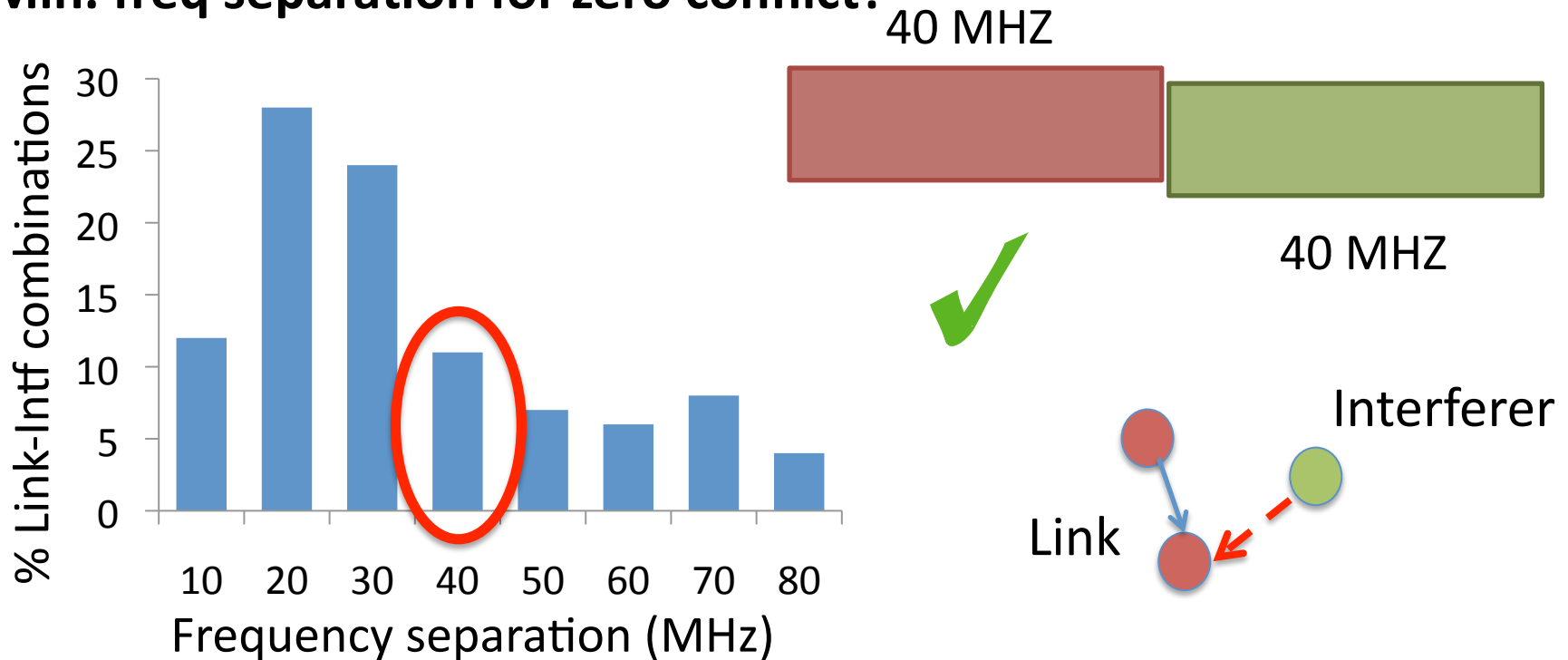


# Evaluation and Results

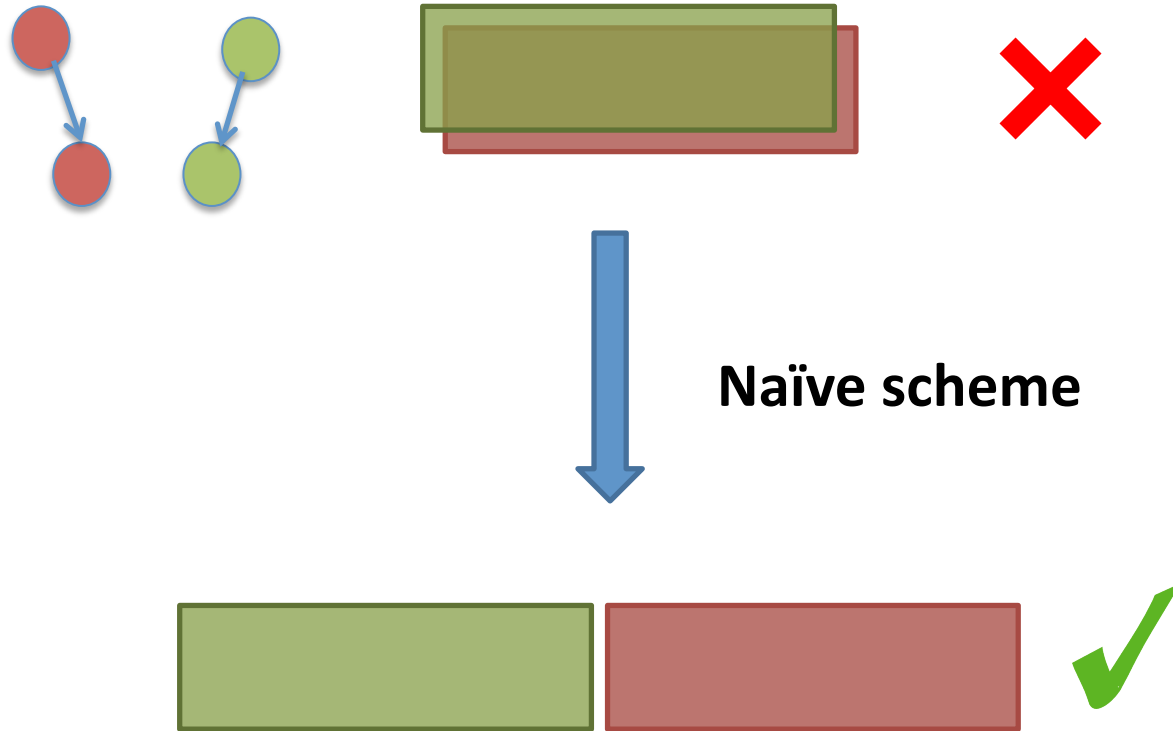
## 1. How accurate is the model?

500 link – interferer combinations

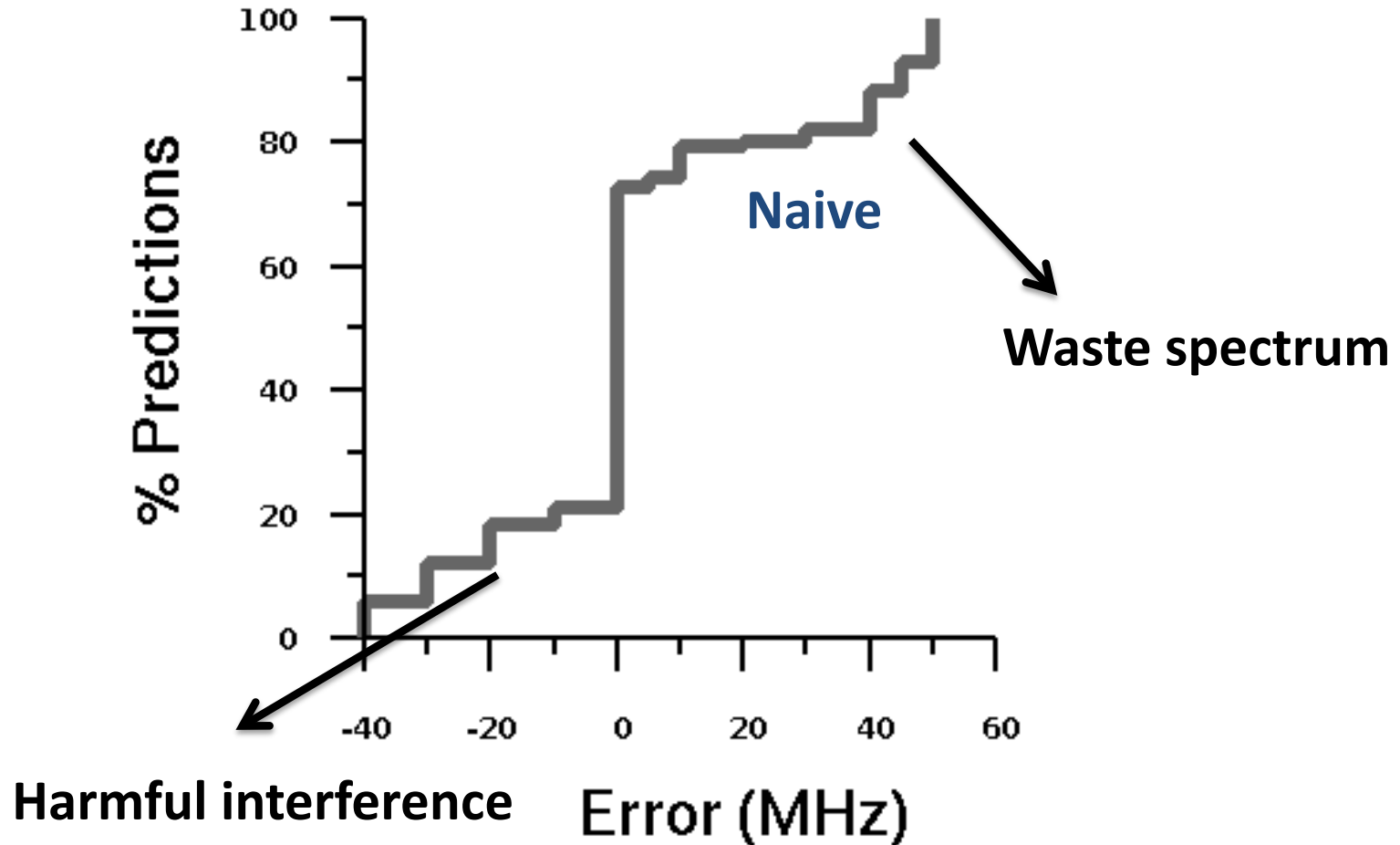
**Min. freq separation for zero conflict?**



# Evaluation and Results

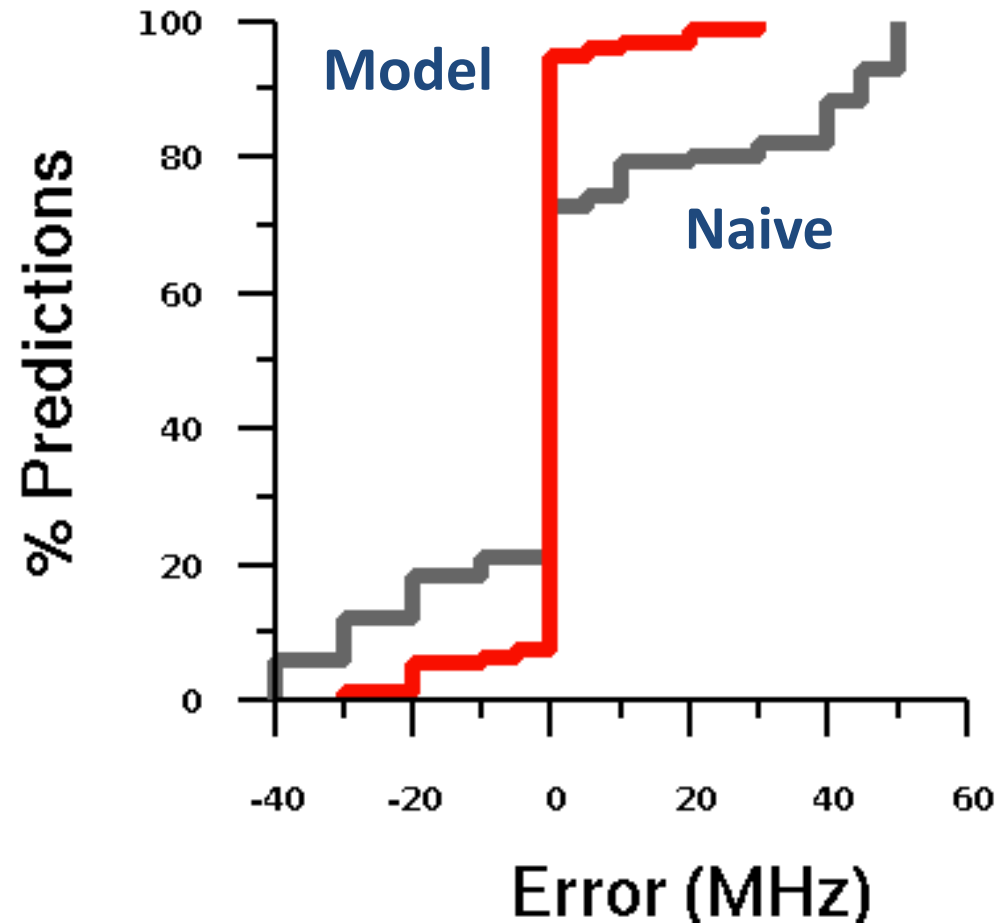


# Evaluation and Results



500 link – interferer combinations

# Evaluation and Results



Accuracy of our model: 87.6%  
Naive model: 52%



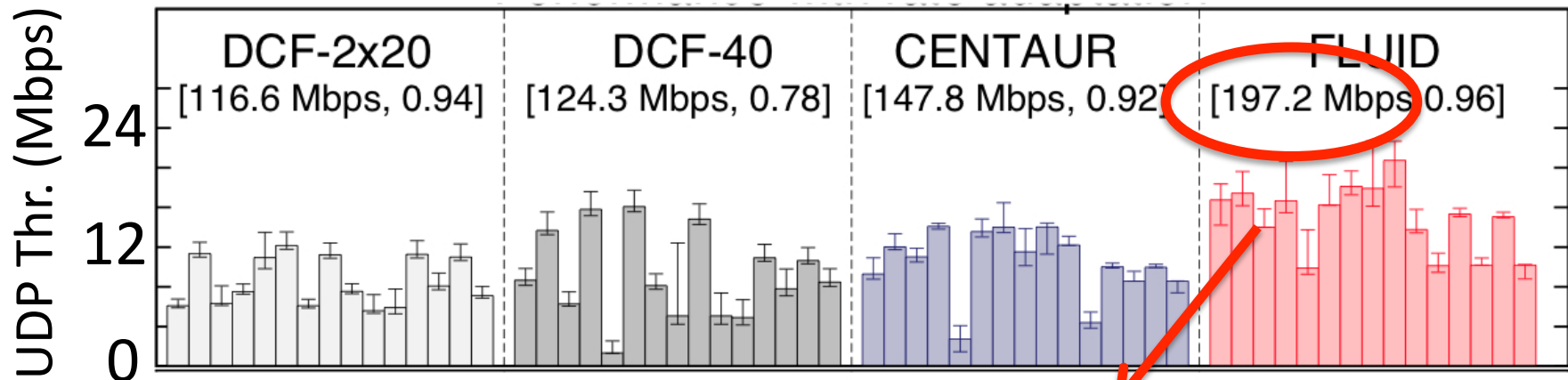
# Evaluation and Results

## 2. What are the overall throughput gains?

- Throughput gains
  - DCF: (Fixed width, Flex-width)
    - 62% gains (average), up to 2.4 X
  - Scheduling/CENTAUR: [MobiCom'09]
    - 30% gains (average)

# Evaluation and Results

Results on a 23 node topology (8 APs, 15 Clients)



FLUID: 59% gain over best DCF  
34% over CENTAUR

# Summary

- Flexible channelization can be a useful tool for managing wireless interference
  - Requires careful consideration of conflicts
- We presented a model that can capture flexible channel conflicts
- We built a system that uses this model to improve the overall throughput in a WLAN

Thanks a lot!  
for your patience