# To Fragment or Not To Fragment: Viability of NC-OFDMA in Multihop Networks

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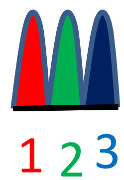
# Availability of Non-Contiguous Spectrum

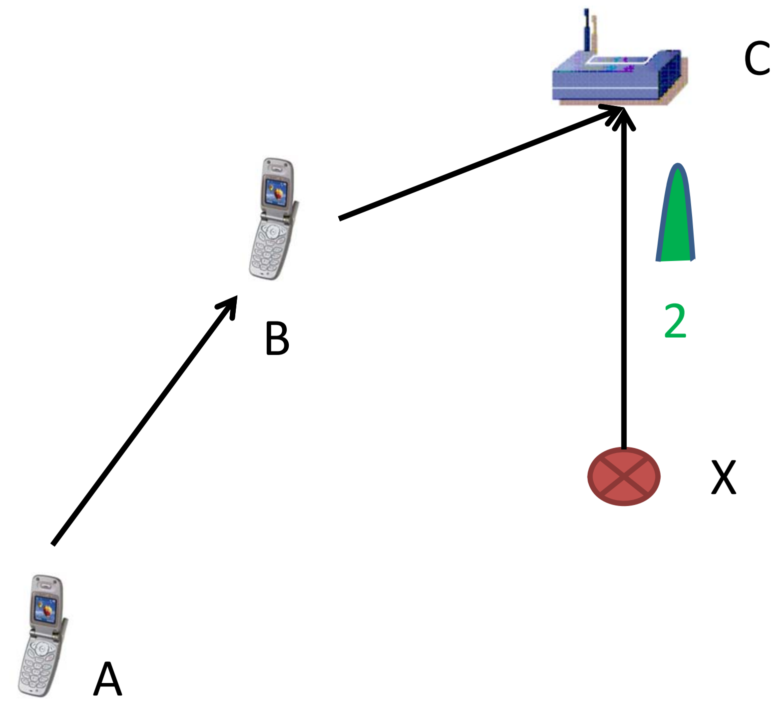
- Demand for wireless services is increasing rapidly
  - Qualcomm predicts a 1000x increase by 2020
- FCC has opened up 300 MHz in TV bands
  - Plans to open up additional 500 MHz “license-by-rule” bands by 2020
- Any radio can use these bands if it abides by FCC rules
- If uncoordinated networks use these bands, they will adjust spectrum usage according to traffic demands
  - Available bands will become non-contiguous
- TV white space is itself non-contiguous in nature

# Case for Noncontiguous OFDMA - I

- Three available channels



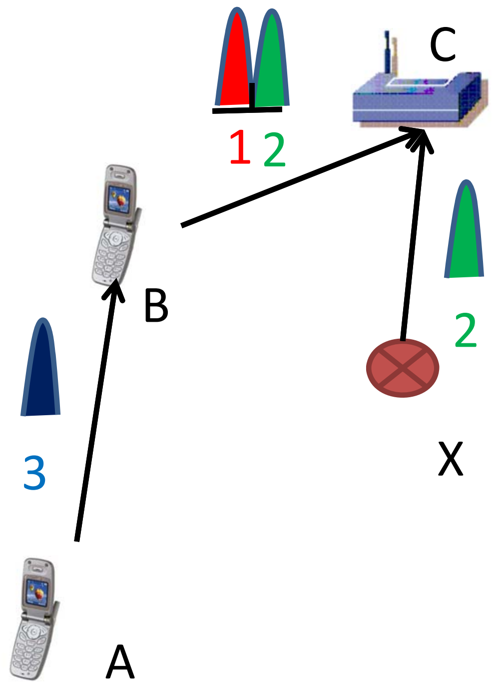

- Node A transmits to node C via node B.
- Node B relays node A's data and transmits its own data to node C.
- Node X, an external and uncontrollable interferer, transmits in channel 2.




- ❑ If we use max-min rate objective and allocate channels, node B requires two channels; node A requires one channel
- ❑ **Scheduling options for Node A and Node B?**

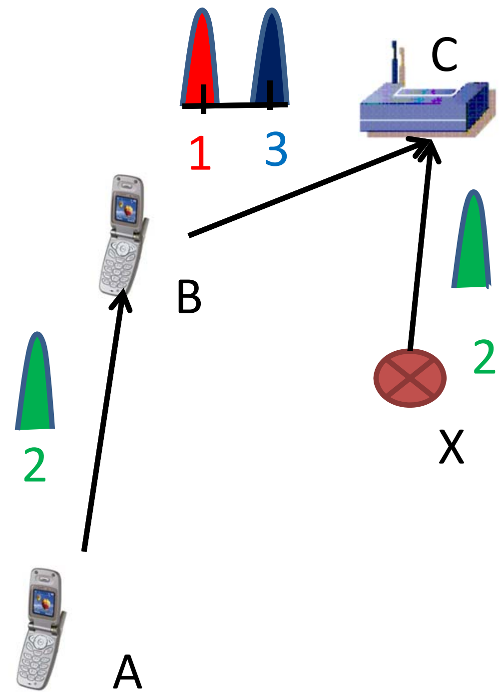
# Case for Noncontiguous OFDMA - II

#1: Contiguous OFDM



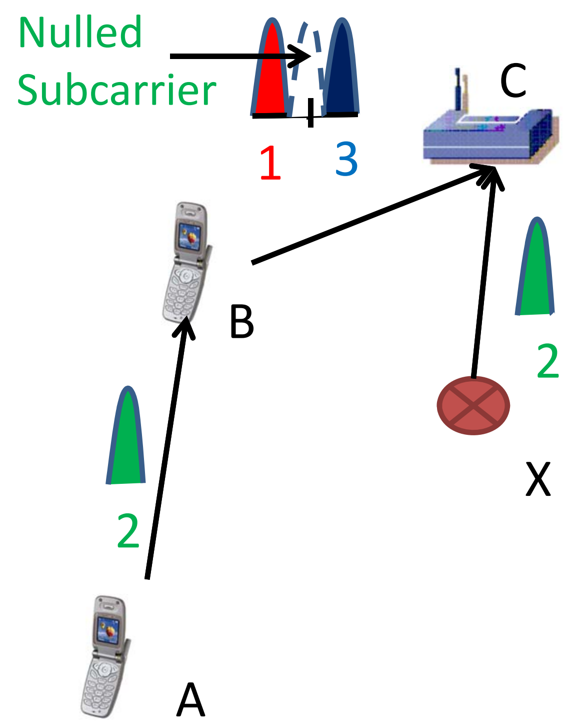

- Transmission in link BC suffers interference in channel 2

#2: Multiple RF front ends




- Spectrum fragmentation limited by number of radio front ends

#3: Non-Contiguous OFDM (NC-OFDMA)




NC-OFDM accesses multiple fragmented spectrum chunks with single radio front end

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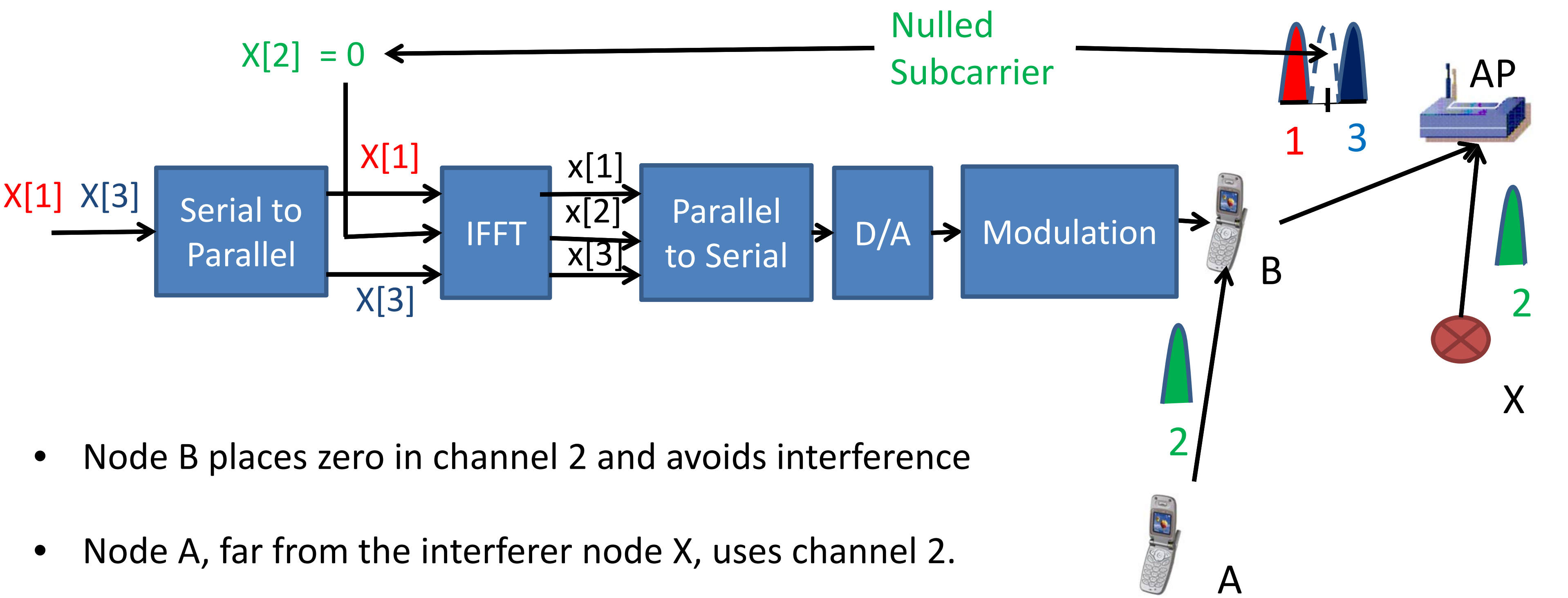
# NC-OFDM Operation

<u>#3:</u> Non-Contiguous OFDM




- Node B places zero in channel 2 and avoids interference
- Node A, far from the interferer node X, uses channel 2.
- Both nodes use better channels.
- Node B spans three channels, *instead of two.*
  - *Sampling rate increases.*

NC-OFDM accesses multiple fragmented spectrum chunks with single radio front end

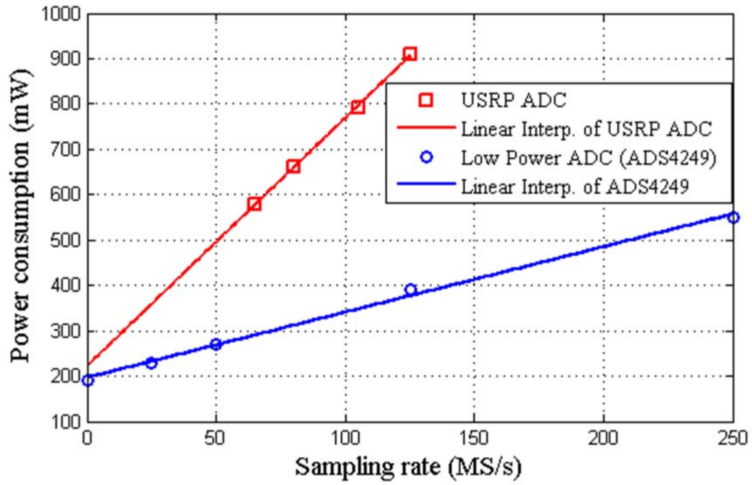
# Benefits and Challenges of NC-OFDMA

## Benefits:

- Avoids interference, incumbent users.
- Uses better channels

## Challenges:

- Increases sampling rate
  - Increases ADC & DAC power
  - Increases amplifier power

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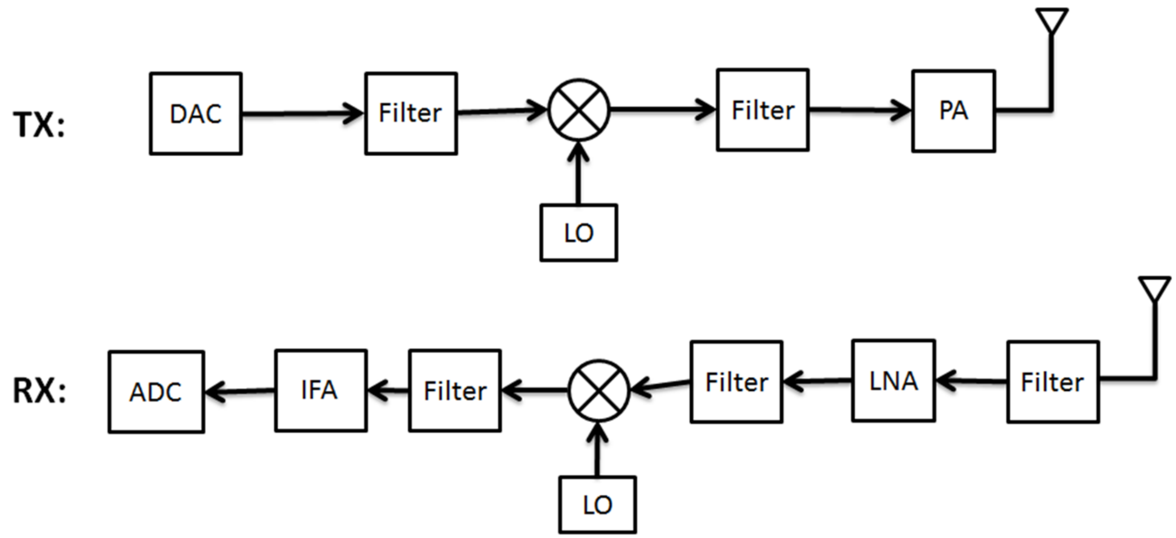
# Power Consumption Model




- ADC and DAC power depend on the sampling rate
- Other blocks deal with analog signals – power consumption does not depend on sampling rate
  - We ignore programmable amplifier's power consumption here.

Tx Power, $p_t = \alpha_1 + \alpha_2 f_s + \sum_{m \in M} p_m$ Rx Power, $p_r = \beta_1 + \beta_2 f_s$.

$\alpha_1, \alpha_2, \beta_1, \beta_2$ – constants $f_s$ - Sampling rate $p_m$ - Allotted power in channel m.

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# Optimization Formulation – Our Approach

## Formulation

$$\min \sum_{i\in N} P_{sys,i}$$

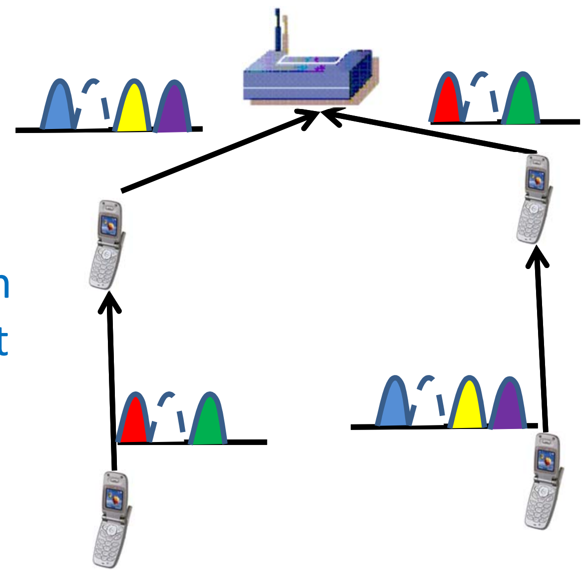
Total System Power Minimization

$$(P_{TxCkt,i} + P_{RxCkt,i} + \sum_{j\in N} P_{ij}) <= P_{sys,i} \quad \forall \mathrm{i} \in \mathrm{N}$$

Individual System Power Constraint

$$W * \log_2 (1 + \frac{g_{ij} P_{ij}}{N_0 W}) >= f_{ij} \qquad \forall (i,j) \in (N,N)$$

Capacity Constraint



Interference, flow conservation, half duplex constraints

## Notation

$N$ – Set of nodes. $P_{sys,i}$ – System power of node i.

$P_{TxCkt,i}$ – Ckt power of node i's Tx path, $P_{ij}$ – Emitted power at link ij

$W$ – Bandwidth, $N_0$ – Noise Spectral Density, $g_{ij}$ – Link gain of ij, $f_{ij}$ – Flow at ij.

# Transmit Power Minimization - Waterfilling

## Formulation

$$\min \sum_{i \in N} P_{Tx,i}$$

Total Trasnmit Power Minimization

$$\sum_{j \in N} P_{ij} <= P_{Tx,i} \quad \forall \mathrm{i} \in \mathrm{N}$$

Individual Transmit Power Constraint

$$W * \log_2 \left(1 + \frac{g_{ij} P_{ij}}{N_0 W}\right) >= f_{ij} \qquad \forall (i,j) \in (N,N)$$

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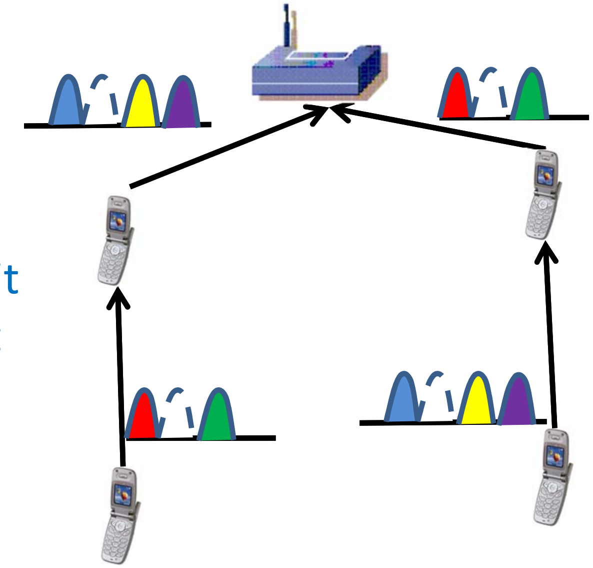

Interference, flow conservation, half duplex constraints

## Notation

$N$ – Set of nodes. $P_{Tx,i}$ – Transmit power of node i.

$P_{ij}$ – Emitted power at link ij

$W$ – Bandwidth, $N_0$ – Noise Spectral Density, $g_{ij}$ – Link gain of ij, $f_{ij}$ – Flow at ij.

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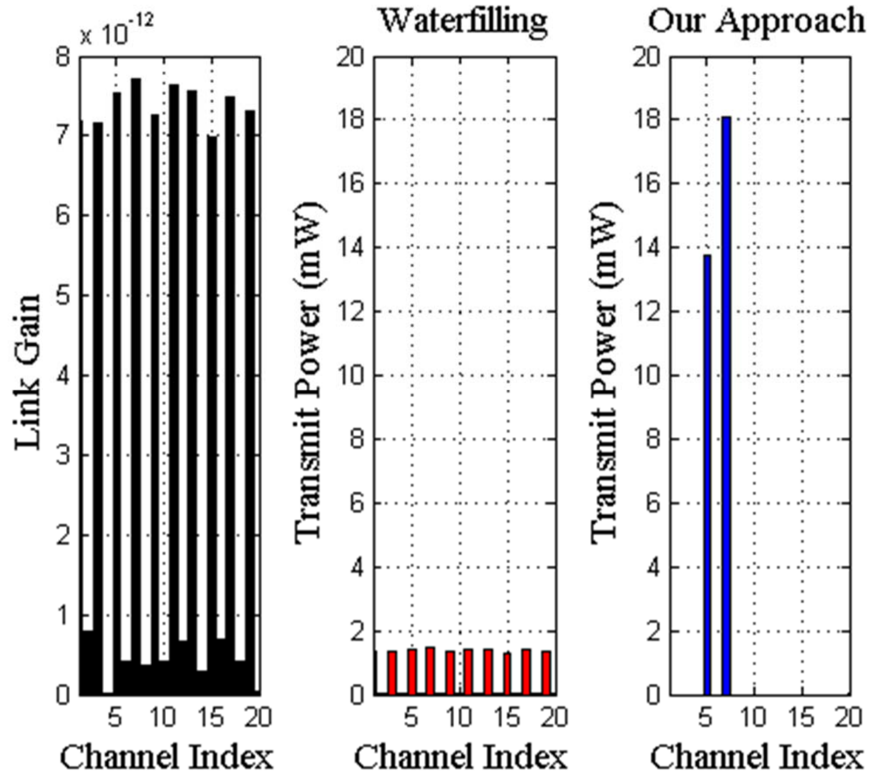
# Comparison with Waterfilling - I

Point-to-Point Link




- Channel width – 3 MHz. Minimum required rate – 18 Mbps.
- Waterfilling selects good channels across the whole list.
- Our approach selects two non-contiguous good neighbors.

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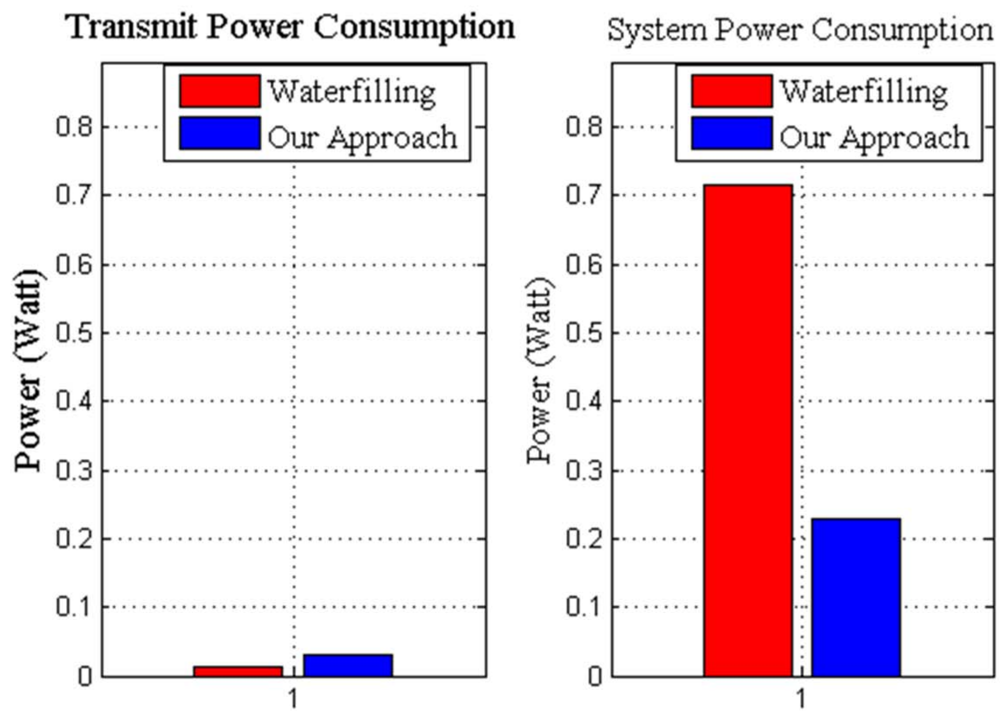
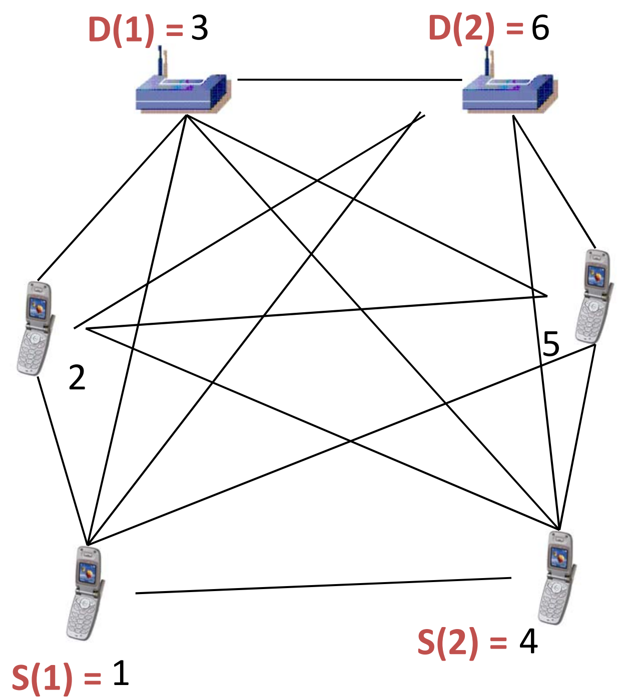
# Comparison with Waterfilling - II

Point-to-Point Link

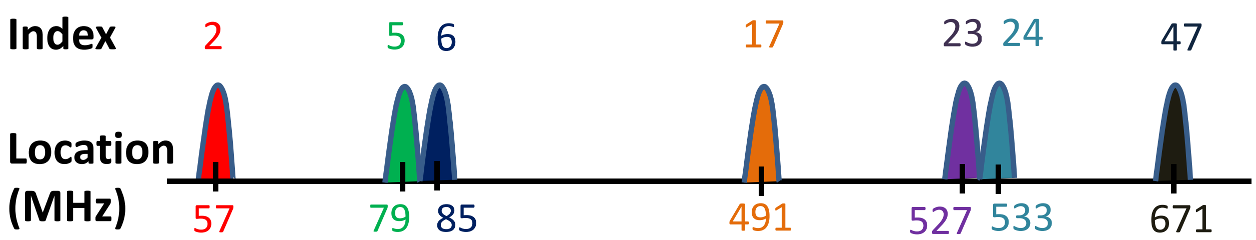



- Waterfilling consumes less transmit power.
- Our approach consumes less system power.

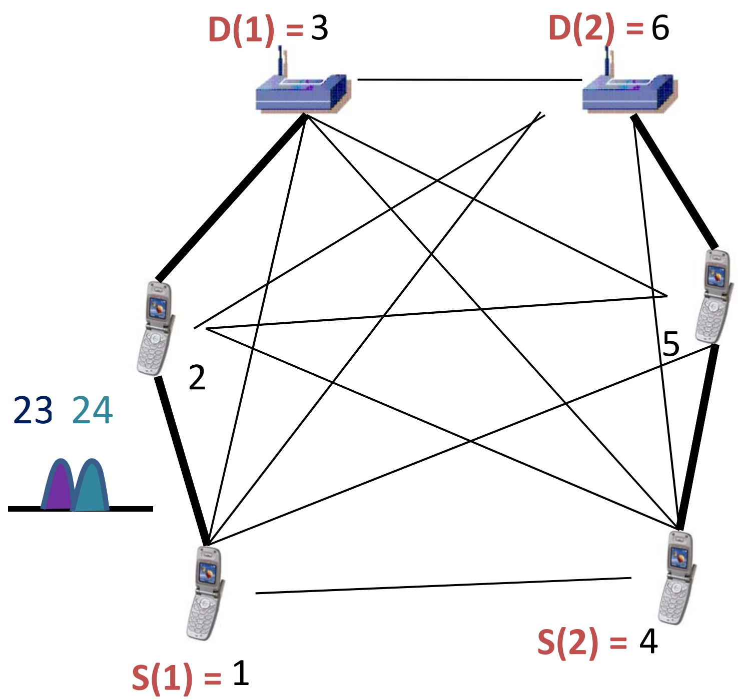
# Multi-hop Scenario (TV Bands in Wichita, KS)

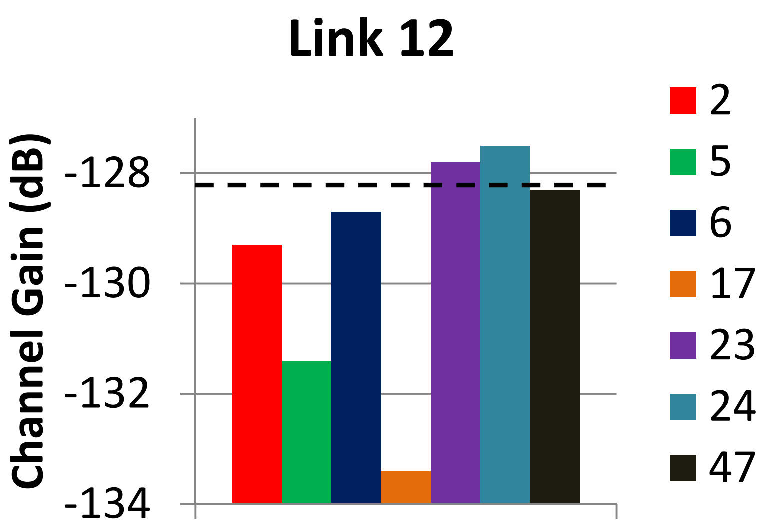


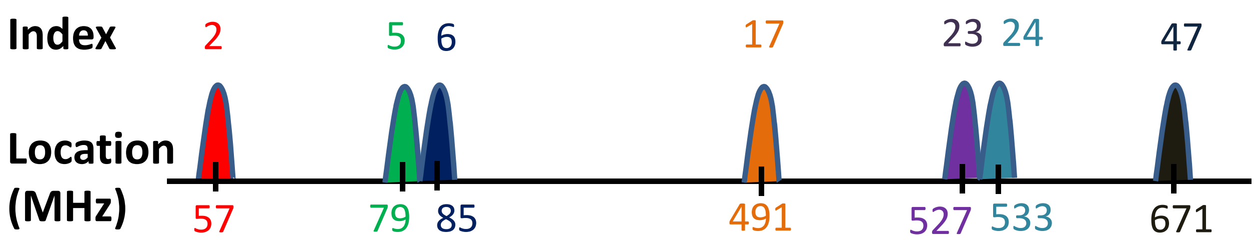

- Channel width – 6 MHz.
- Two sessions.
- Required rate – 10 Mbps.
- Node 1 transmits to 3.
- Node 2 transmits to 4.



# Waterfilling Approach



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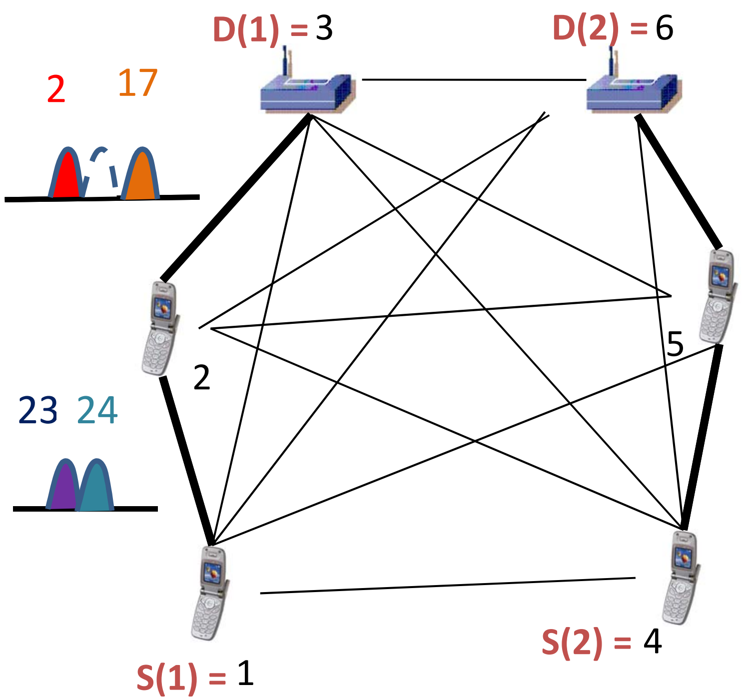


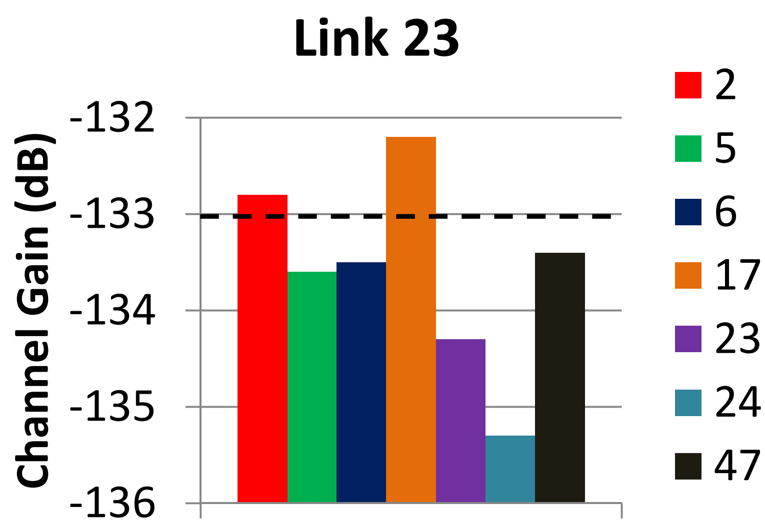


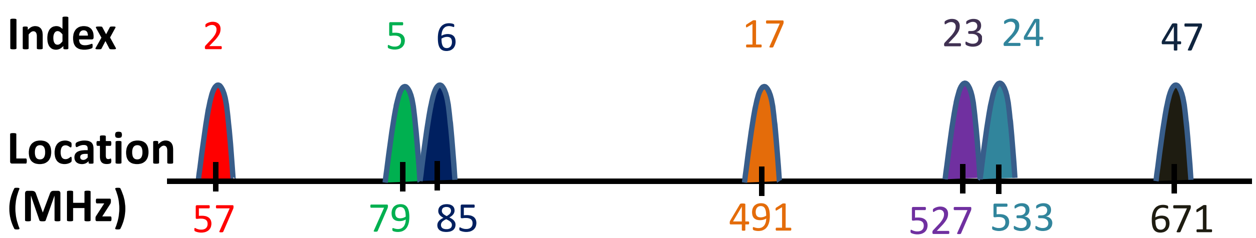

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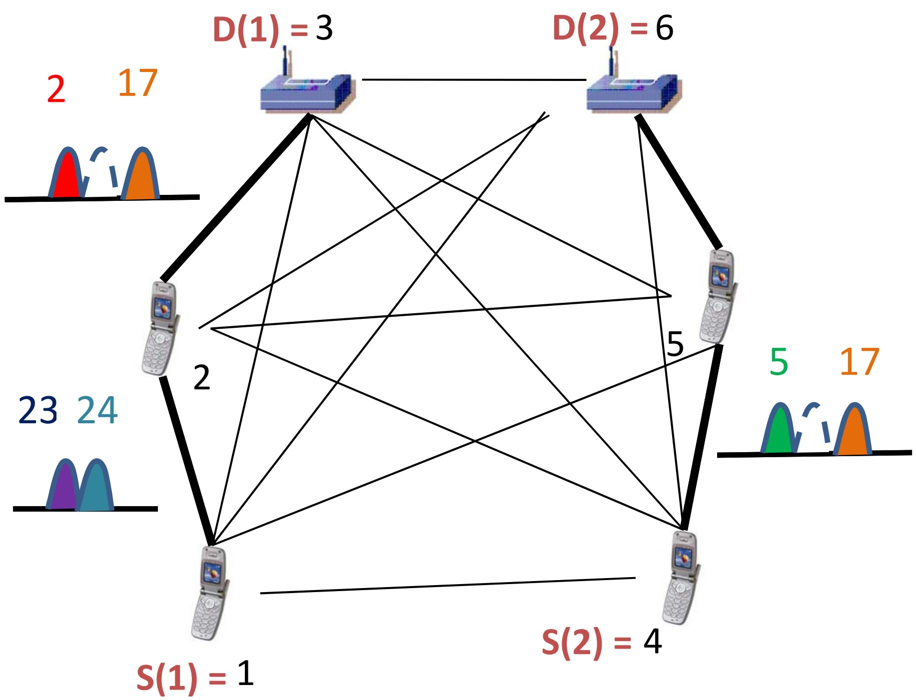


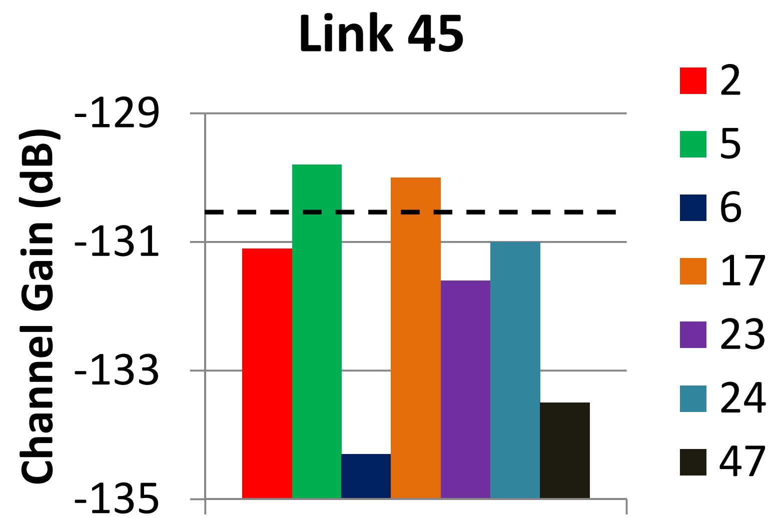


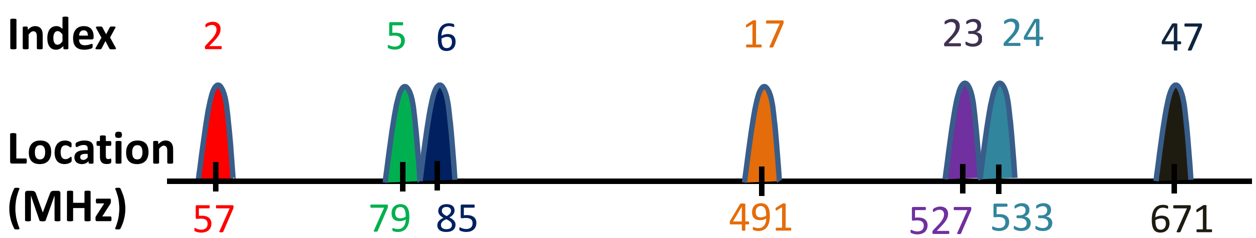

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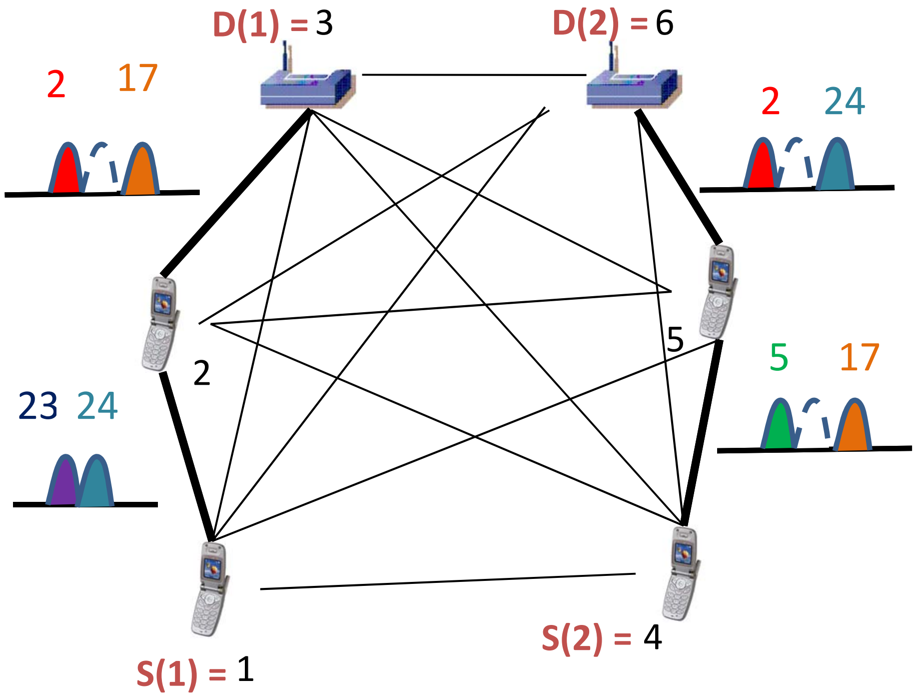


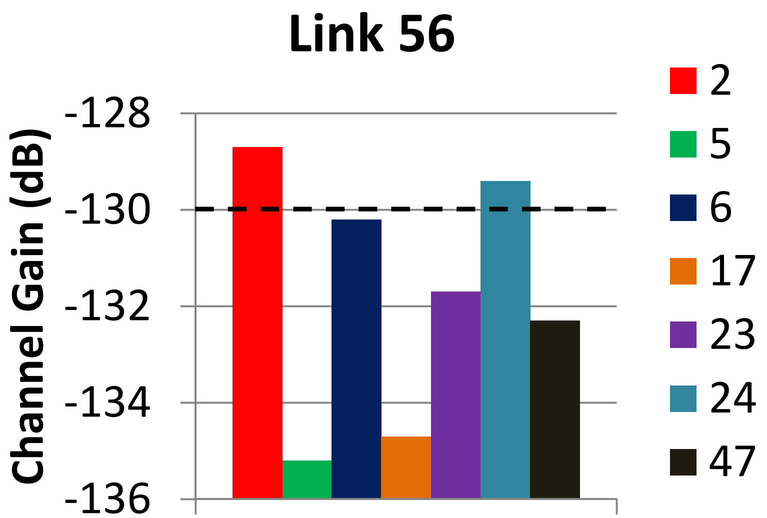


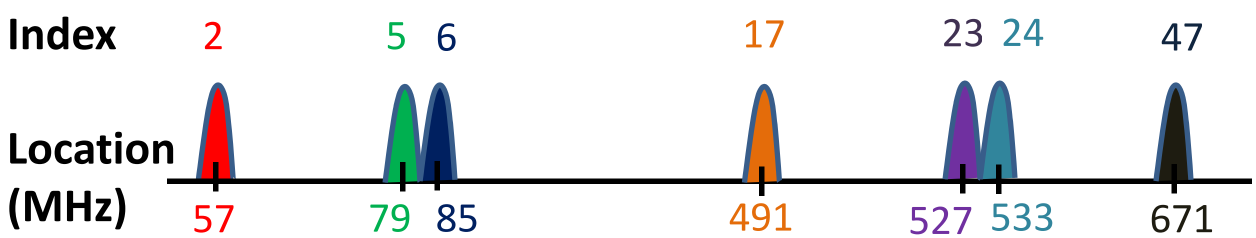


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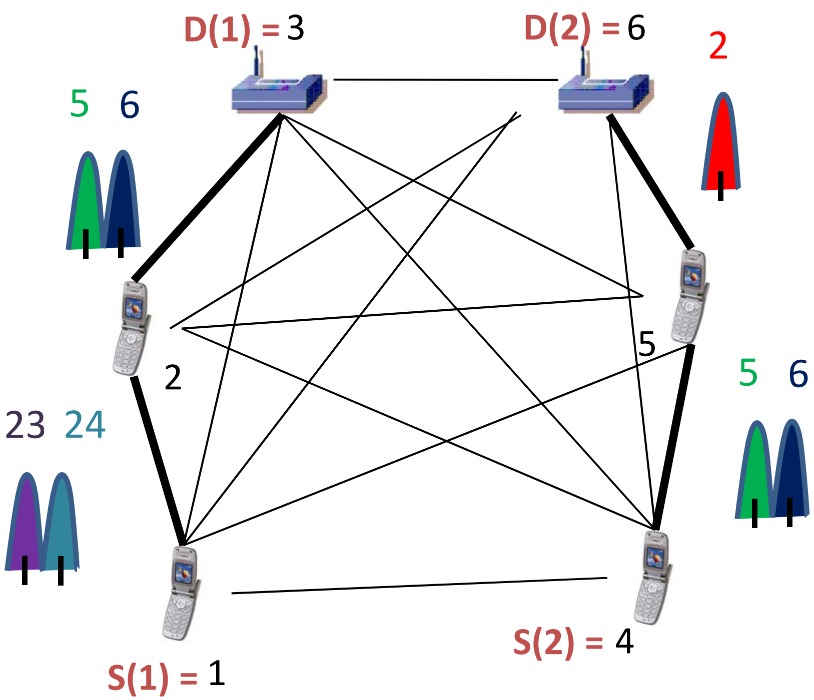
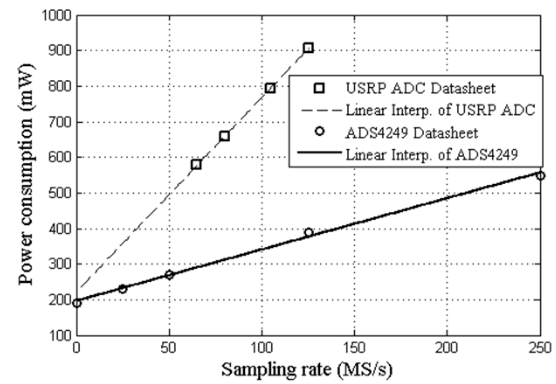
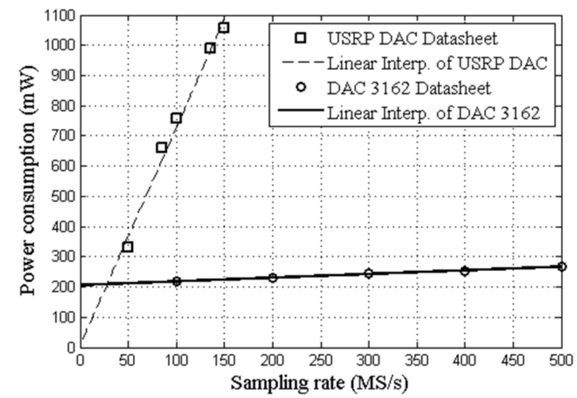
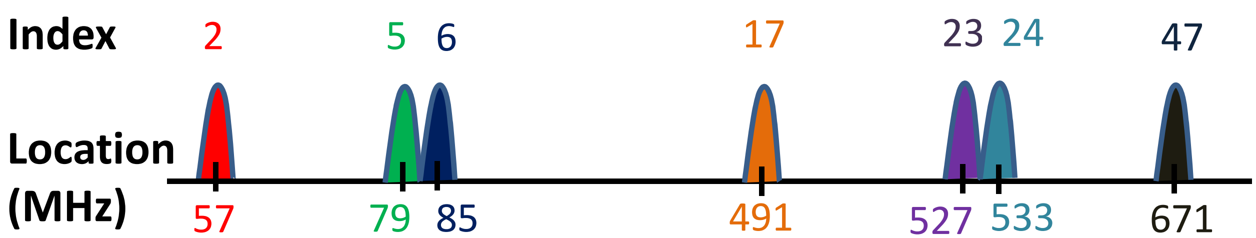
# Our Approach (Low Power ADC & DAC)

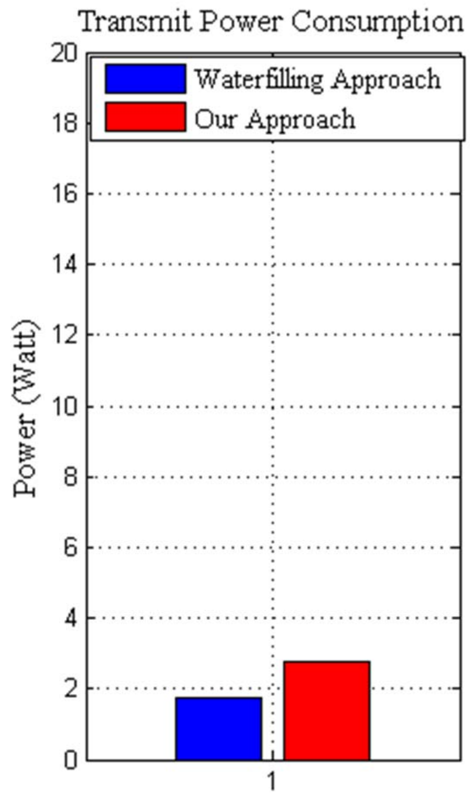


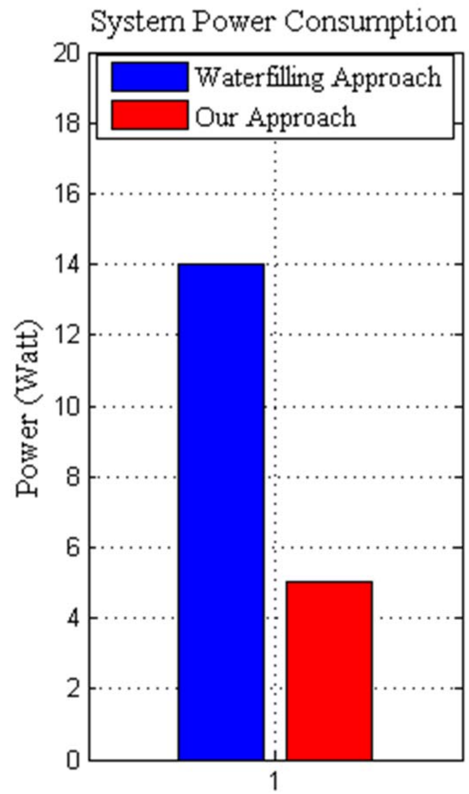



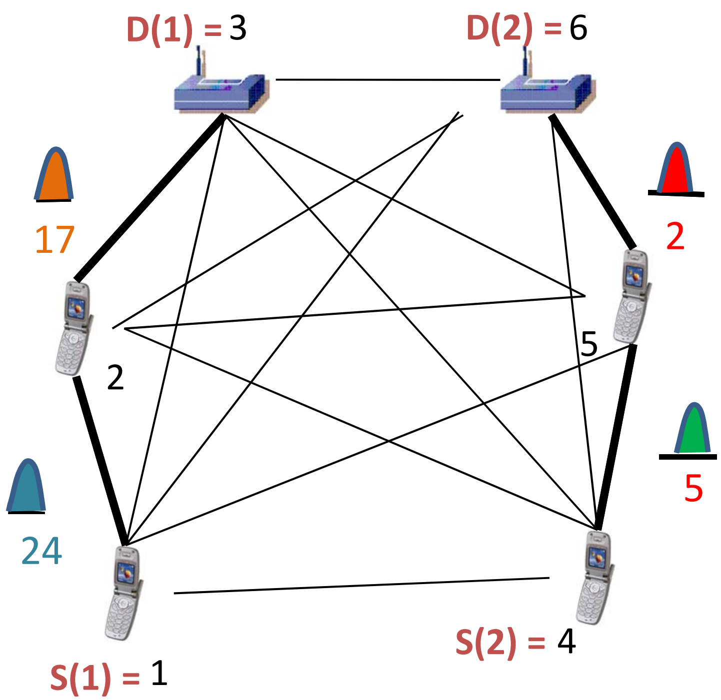
# Comparison with Waterfilling (Low Power ADC & DAC)

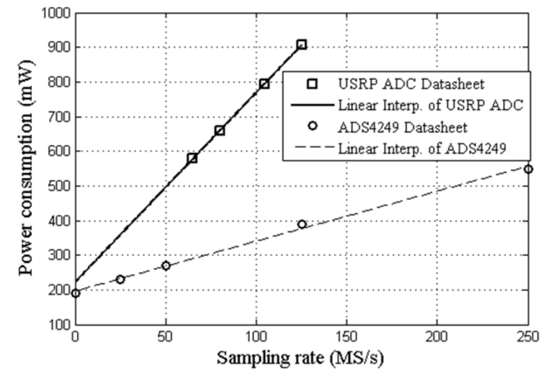


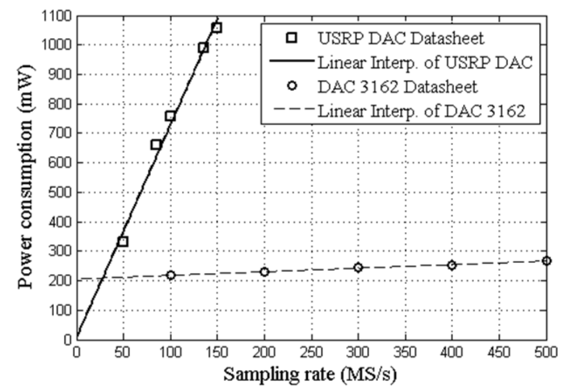



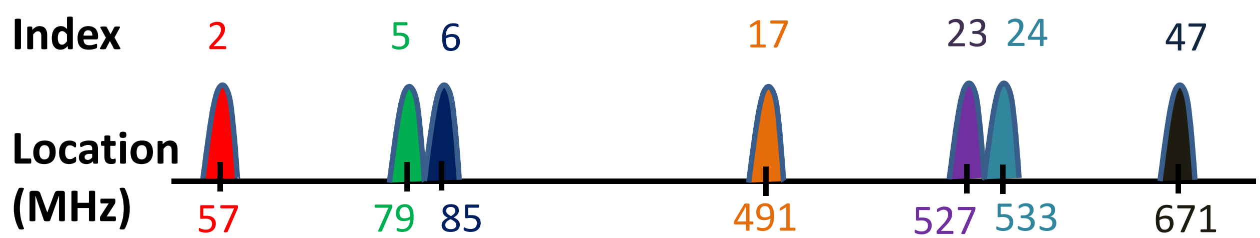

- Our approach reduces system power consumption by 4 dB.

# Our Approach (USRP ADC & DAC)

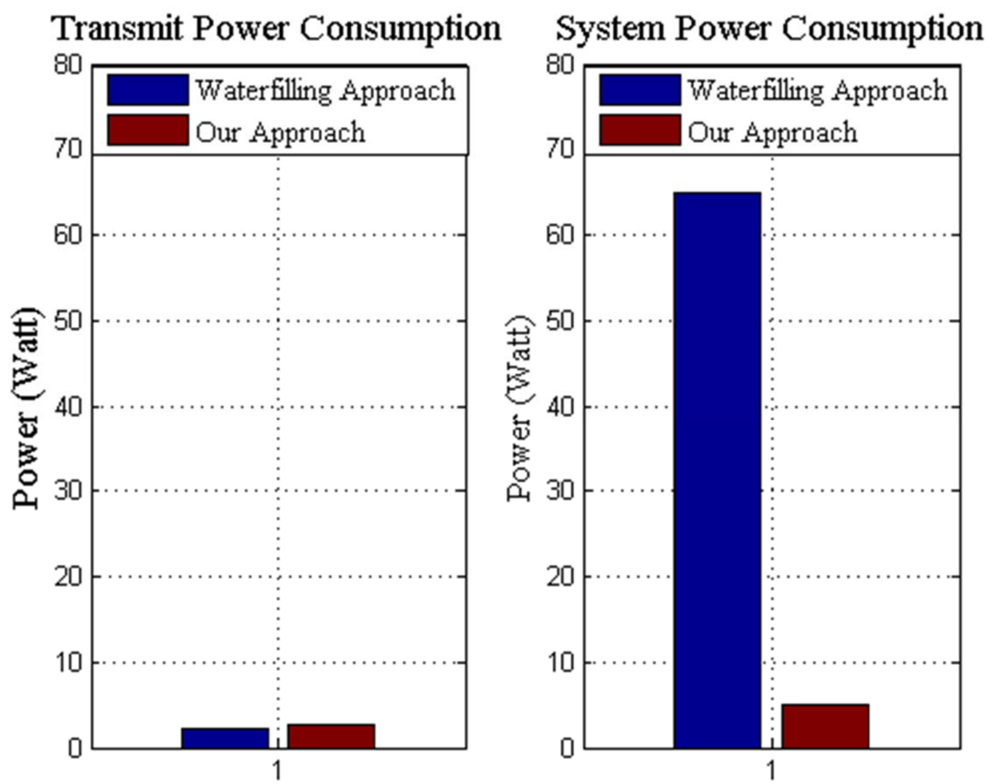


# Comparison with Waterfilling (USRP ADC & DAC)




- USRP ADC and DAC's power consumption curves are steeper.
  - Waterfilling spans more spectrum and consumes a lot of system power
- Our approach reduces system power consumption by 10 dB!

# Conclusion

- Researchers focus on channel gains and traffic demands to determine power control, scheduling and routing variables
- Our results reveal that hardware configuration of the radio front ends, e.g., slope of ADC and DAC power consumption curves, can influence these variables.

# Future Works

- Power consumption models of programmable amplifier
  - Non-linear due to “bandwidth gain product”

- Investigate multi-frond-end radio’s power consumption
  - Analog power may increase since there are multiple components
  - Digital power may decrease since each ADC/DAC spans narrower spectrum

# Questions ?

Thank You !

# Power Minimization

## Transmit Power Minimization (Waterfilling)

$$\min \sum_{m \in M} p_m$$

$$\text{s.t.} \sum_{m \in M} W \log_2\left(1 + \frac{p_m g_m}{N_0 W}\right) >= r$$

$$p_m >= 0 \quad \forall m \in M$$

## System Power Minimization (Our Approach)

$$\min \sum_{m \in M} p_m + \alpha_1 + \alpha_2 f_s + \beta_1 + \beta_2 f_s$$

$$\text{s.t.} \sum_{m \in M} W \log_2\left(1 + \frac{p_m g_m}{N_0 W}\right) >= r$$

Spectrum Span Constraints

$$p_m >= 0 \quad \forall m \in M$$

# References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