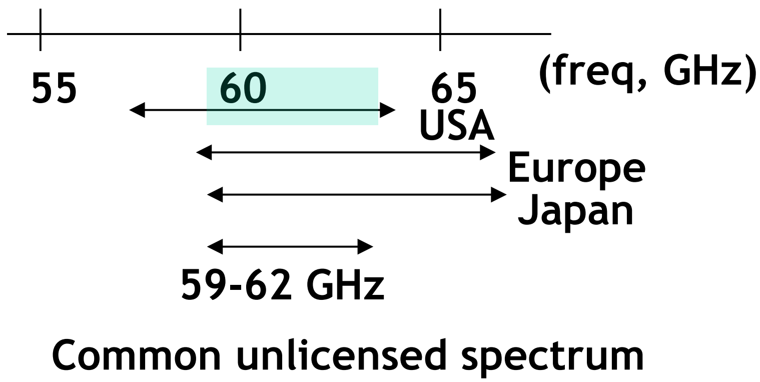
A bullish view from UCSB

Upamanyu Madhow

Current collaborators: Prof. Mark Rodwell, Prof.Heather Zheng

The end of spectral hunger (at short ranges)

60 GHz: 7 GHz of unlicensed spectrum in US, Europe, Japan

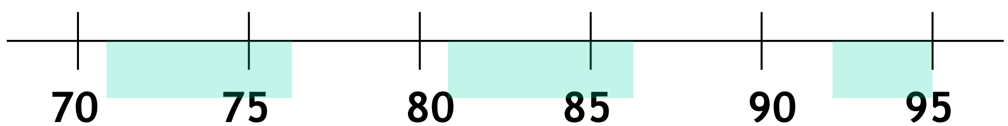


Oxygen absorption band

Ideal for short-haul multihop

(reduced interference)

E/W bands: 13 GHz of spectrum in US with minimal licensing/registration



Avoids oxygen absorption

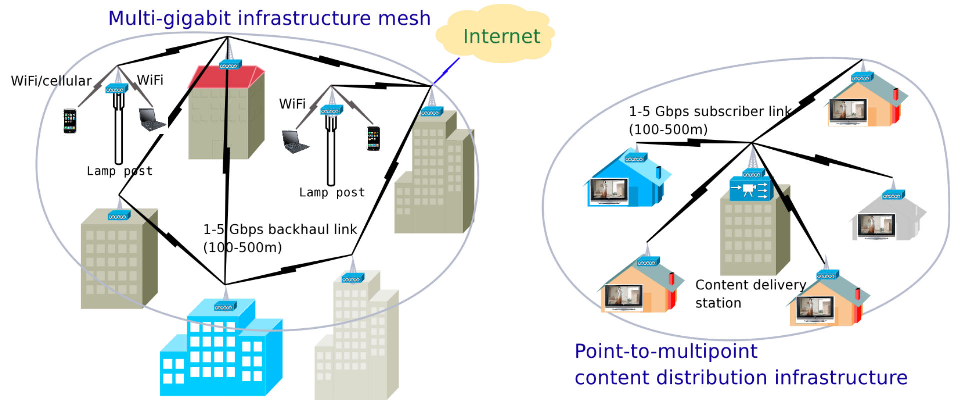
Good for long-haul P2P

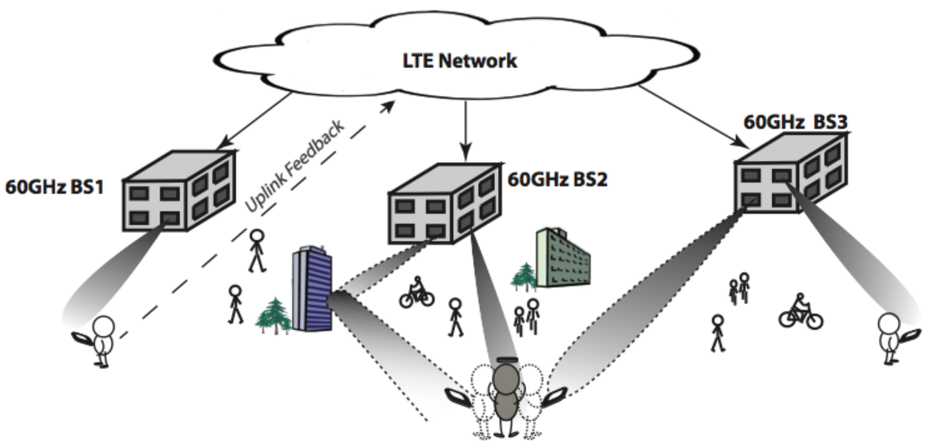
Bands beyond 100 GHz will become accessible as RFIC and packaging technology advances

What's different about mm wave comm?

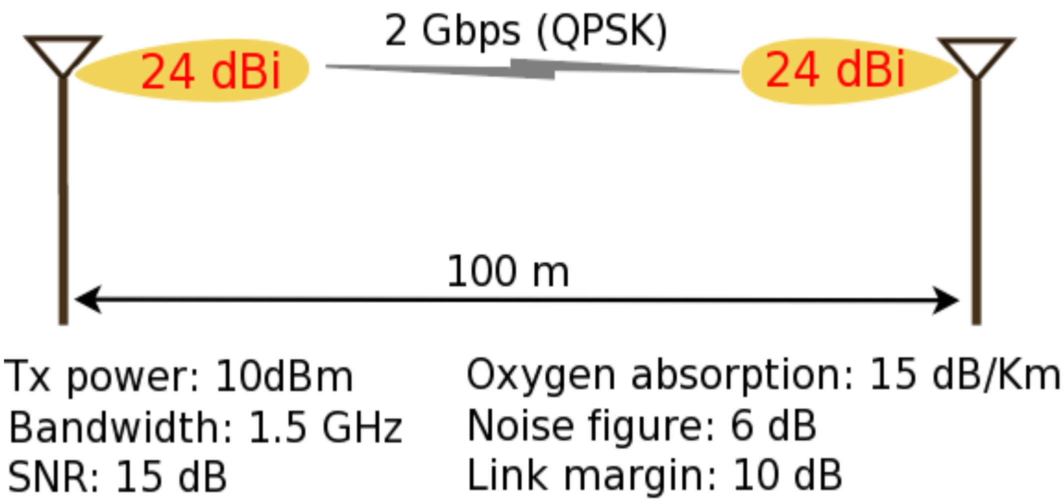
- Fundamental difference: tiny wavelengths
- MIMO geometry is different
  - LoS spatial muxing, quasi-deterministic diversity
- Need highly directional links
  - λ^2 scaling of path loss unacceptable
- Can realize highly directional electronically steerable links
  - 1000 element antenna array can fit in our palm
- Blockage kills (obstacles look bigger at small wavelengths)
  - Need to steer around, not burn through
- MAC protocols must account for directionality
  - No carrier sense but reduced spatial interference

Emerging applications





Fighting physics?



100-200m very doable
Kilometers range is overreach even without oxygen absorption (rain loss as high as 30 dB/km)

Steer around obstacles (reflections or relays)

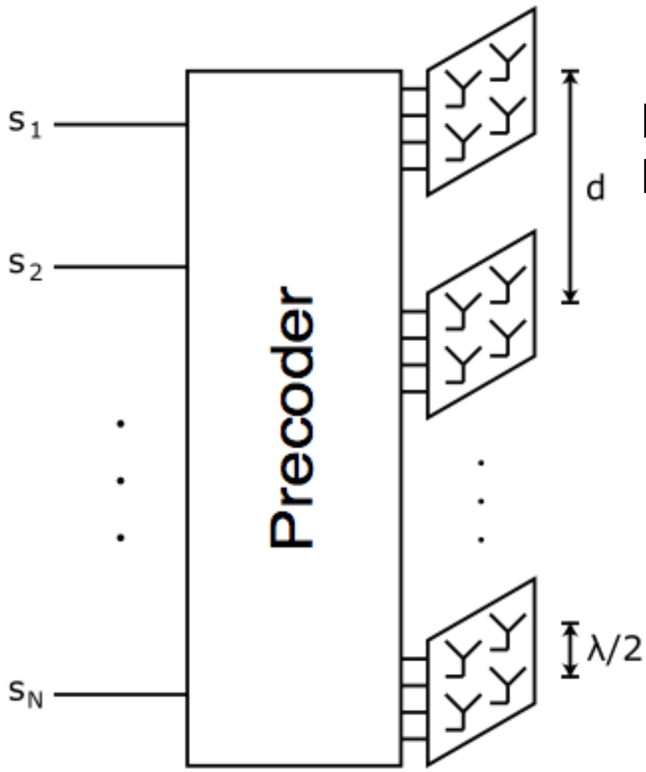
Research Opportunities

UCSB

- Revisiting MIMO
  - For tiny wavelengths
- Revisiting signal processing architectures
  - The ADC bottleneck
- Revisiting networking
  - Highly directional links change MAC design considerations
  - Multi-band operation (e.g., 1-5 GHz and 60 GHz)
- Inherently cross-layer even at the level of comm theory
  - Node form factor, hardware constraints, propagation geometry

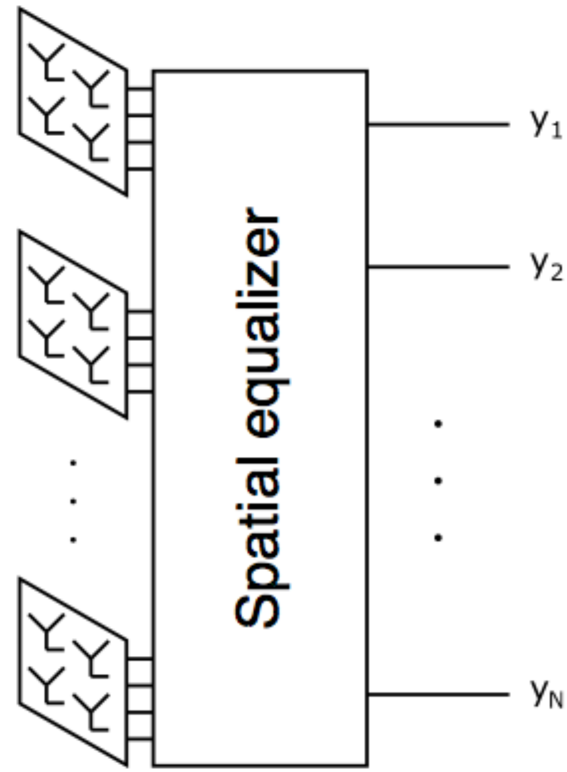
CTW-oriented examples of recent research

Array of subarrays architecture



Beamforming with subarrays
DoF depends on form factor

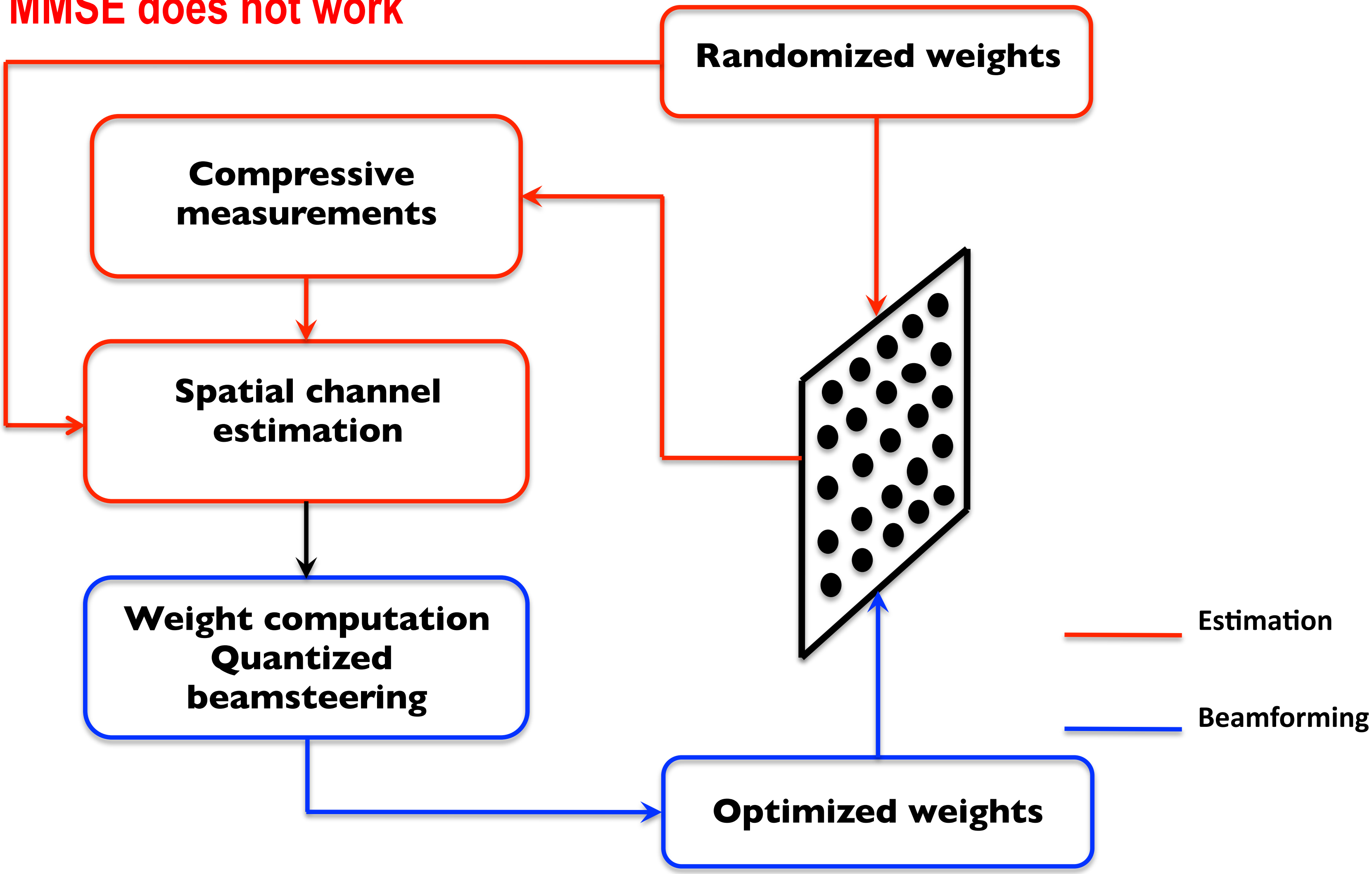
$$DoF \approx \frac{L_{TX} L_{RX}}{\lambda R}$$



Much room for comprehensive exploration…

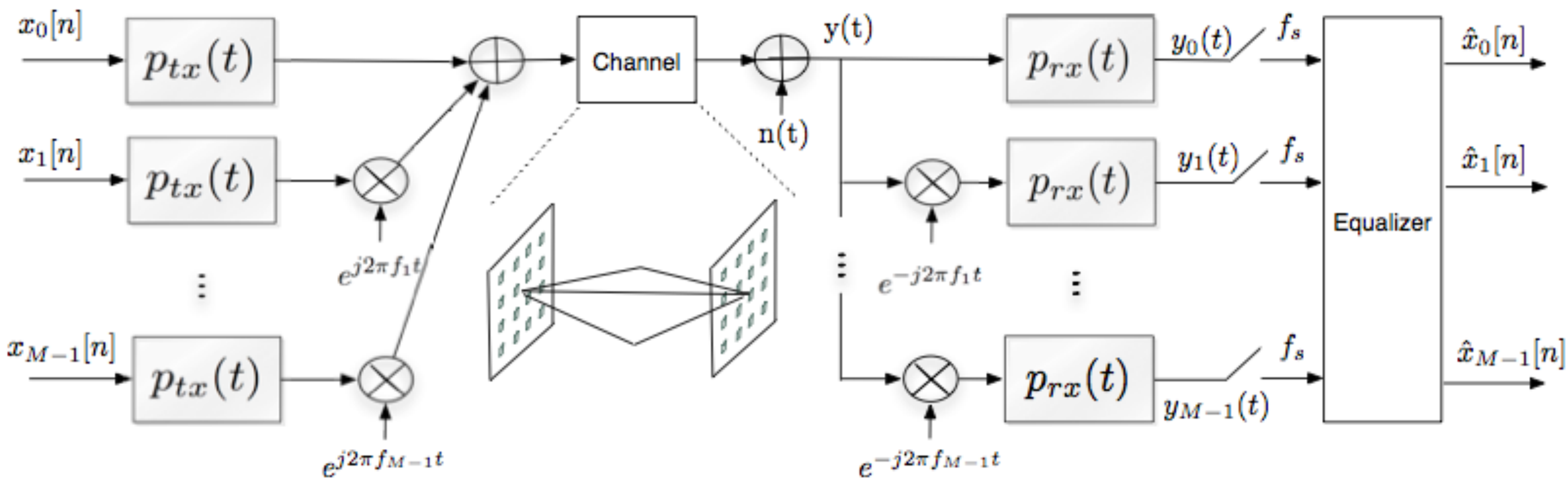
Adaptation of very large arrays

Constrained to RF beamforming
MMSE does not work



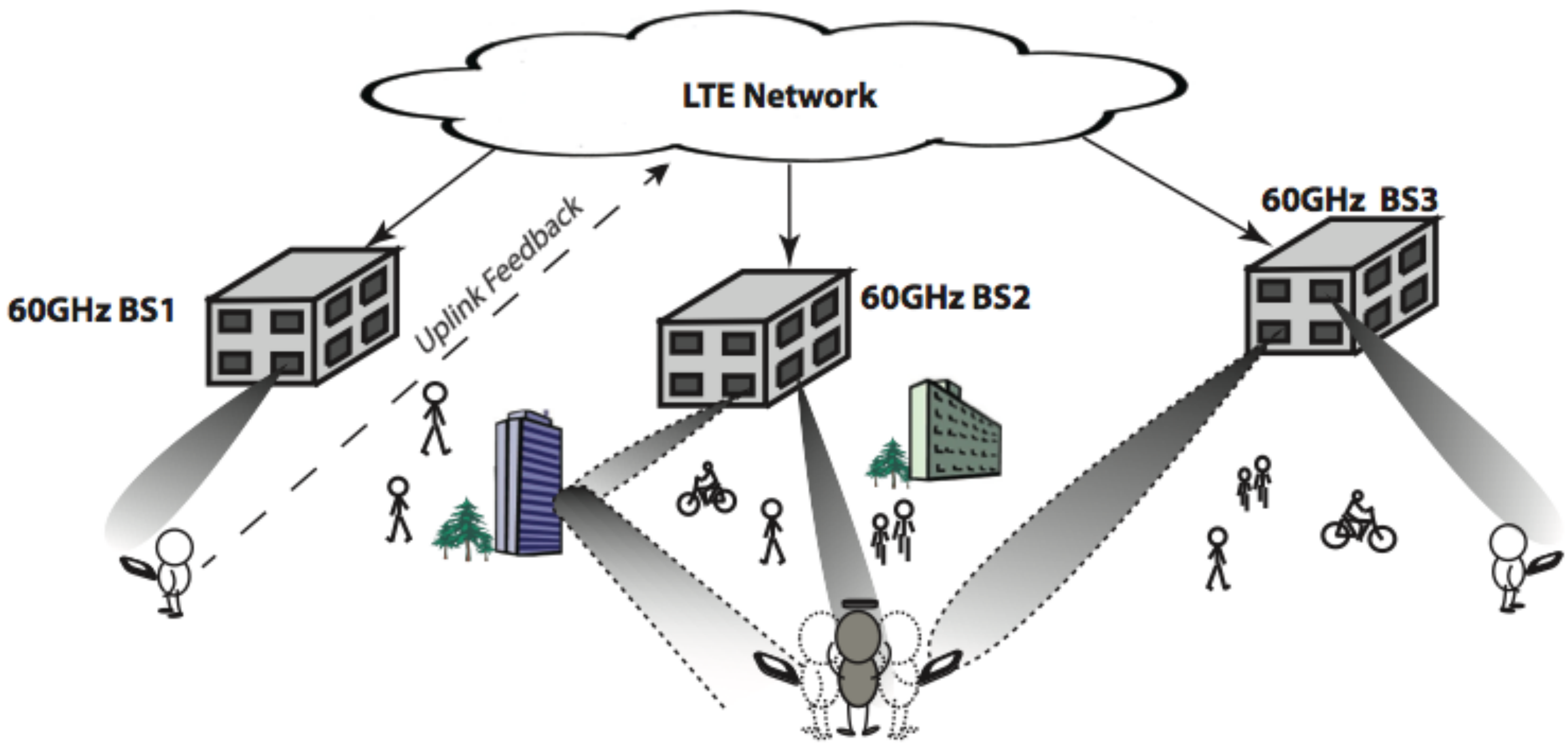
Just at the beginning of hardware-constrained signal processing design…

Back to the future: Analog Multitone



How to scale communication bandwidth?
--without ADC advances?
--still leveraging Moore's law
Sloppy analog channelization, "slow" ADCs and DSP in parallel

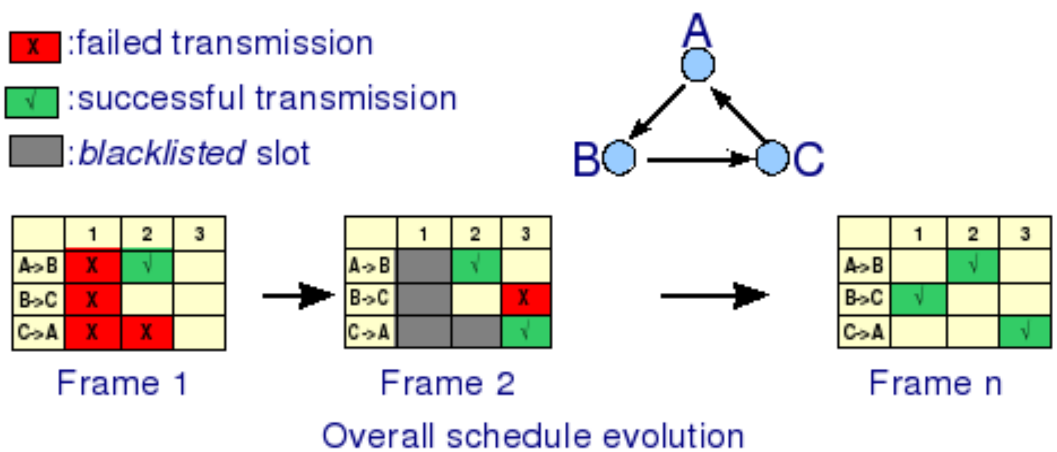
WiGig extension to outdoor cellular



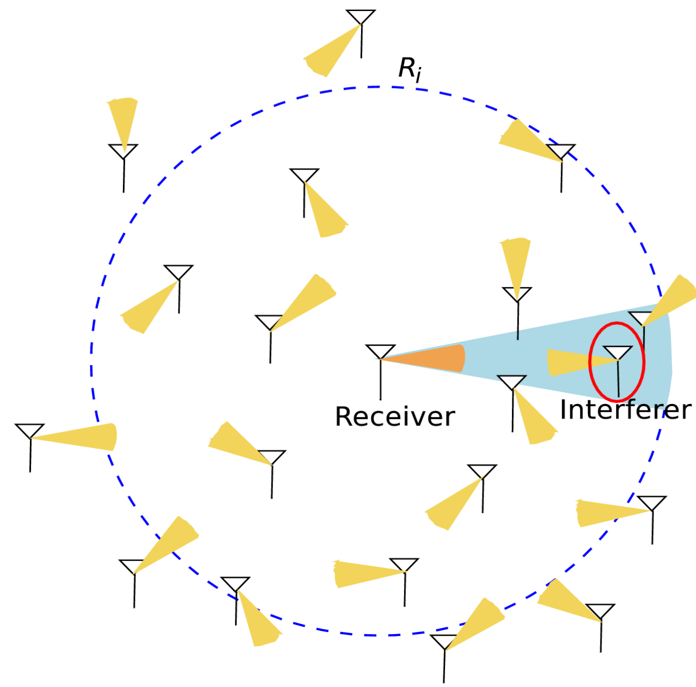
5 Gbps to the mobile device at pedestrian speeds
10 Gbps to vehicles

Mesh networking with highly directional links

- Pencil beams lead to very high spatial reuse
  - Especially when beamforming is coupled with nullforming
- Recently developed techniques for highly directional networking can be applied
  - Interference analysis
  - MAC protocols that handle deafness



Singh, Mudumbai, Madhow, IEEE Infocom 2010.



Singh, Mudumbai, Madhow, IEEE/ACM Trans. Networking, 2011; **Mudumbai, Singh, Madhow,** IEEE Infocom 2009.

mm waves: exploring further

Survey

U. Madhow, S. Singh, *60 GHz communication,* chapter in *Handbook of Mobile Comm.* (ed. J. Gibson), 2012.

MIMO techniques and channel modeling

Sheldon, Seo, Torkildson, Madhow, Rodwell*, A 2.4 Gb/s millimeter-wave link using adaptive spatial multiplexing,* APS-URSI 2010.

Ramasamy, Venkateswaran, Madhow, *Compressive adaptation of large steerable arrays,* ITA 2012.

Torkildson, Madhow, Rodwell, *Indoor millimeter wave MIMO: feasibility and performance,* IEEE Trans. Wireless Comm., Dec 2011. (see also mmCom 2010)

Zhang, Venkateswaran, Madhow, *Channel modeling and MIMO capacity for outdoor millimeter wave links,* WCNC 2010. (see also mmCom 2010)

Torkildson, Ananthasubramaniam, Madhow, Rodwell, *Millimeter wave MIMO: wireless links at optical speeds,* Allerton 2006.

Compressive adaptation

Ramasamy, Venkateswaran, Madhow, *Compressive adaptation of large steerable arrays* ITA 2012.

Ramasamy, Venkateswaran, Madhow, *Compressive tracking with 1000-element arrays…,* Allerton 2012.

Ramasamy, Venkateswaran, Madhow, *Compressive estimation in AWGN…,* Asilomar 2012.

Networking with highly directional links

Singh, Mudumbai, Madhow*, Interference analysis for highly directional 60-GHz mesh networks: the case for rethinking medium access control,* IEEE/ACM Trans. Networking, October 2011.

Singh, Mudumbai, Madhow, *Distributed coordination with deaf neighbors: efficient medium access for 60 GHz mesh networks,* IEEE Infocom 2010.

Singh, Ziliotto, Madhow, Belding, Rodwell, *Blockage and directivity in 60 GHz wireless personal area networks,* IEEE JSAC, October 2009.

Singh, Ziliotto, Madhow, Belding, Rodwell, *Millimeter wave WPAN: cross-layer modeling and multihop architecture,* IEEE Infocom 2007 mini-symposium.

ADC Bottleneck: Analog multitone, TI-ADC, low-precision ADC