Millimeter Wave MIMO Precoding/Combining: *Challenges and Potential Solutions*

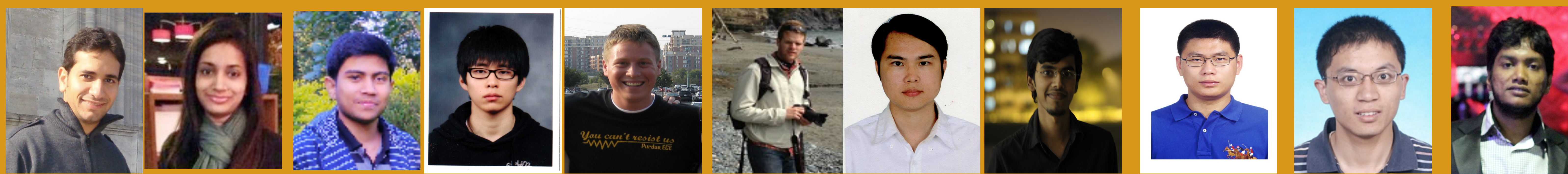
Robert W. Heath Jr., Ph.D., P.E.
Joint work with Ahmed Alkhateeb, Jianhua Mo, and Nuria González-Prelcic

Wireless Networking and Communications Group
Department of Electrical and Computer Engineering
The University of Texas at Austin

www.profheath.org

Cockrell School of Engineering

Heath Group in the WNCG @ UT Austin



11 PhD students

mmWave beamforming

mmWave communication and radar for car-to-car

mmWave wearables

mmWave for tactical ad hoc networks

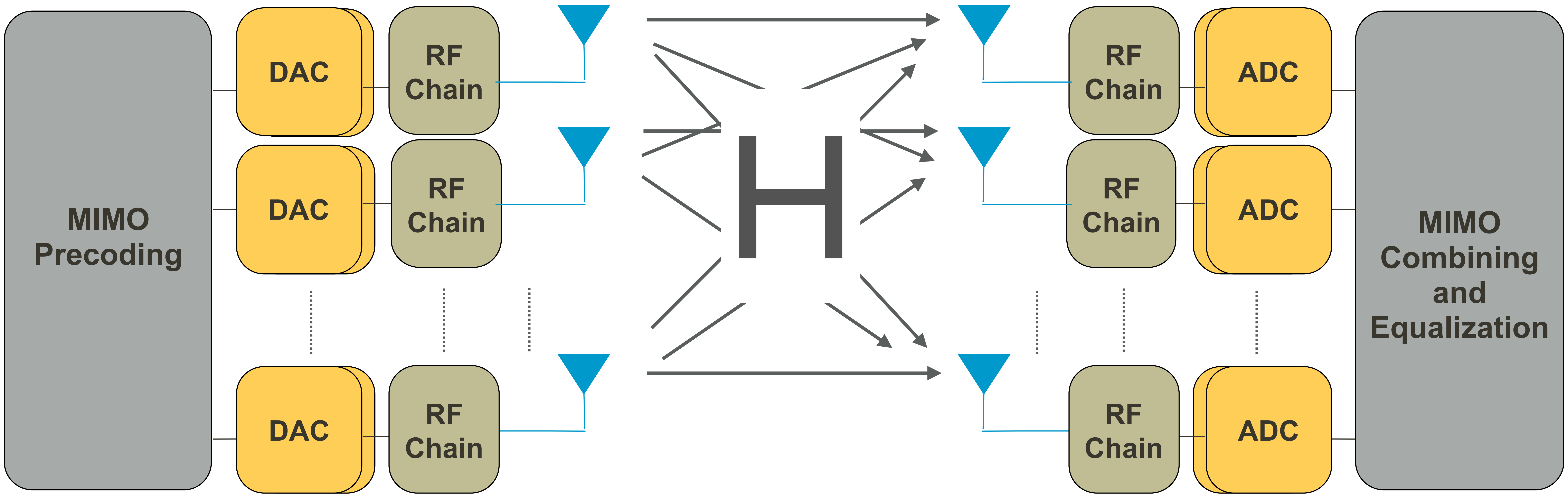
mmWave licensed shared access for 5G

next generation mmWave LAN

mmWave for infrastructure-to-car

mmWave 5G performance

MIMO precoding



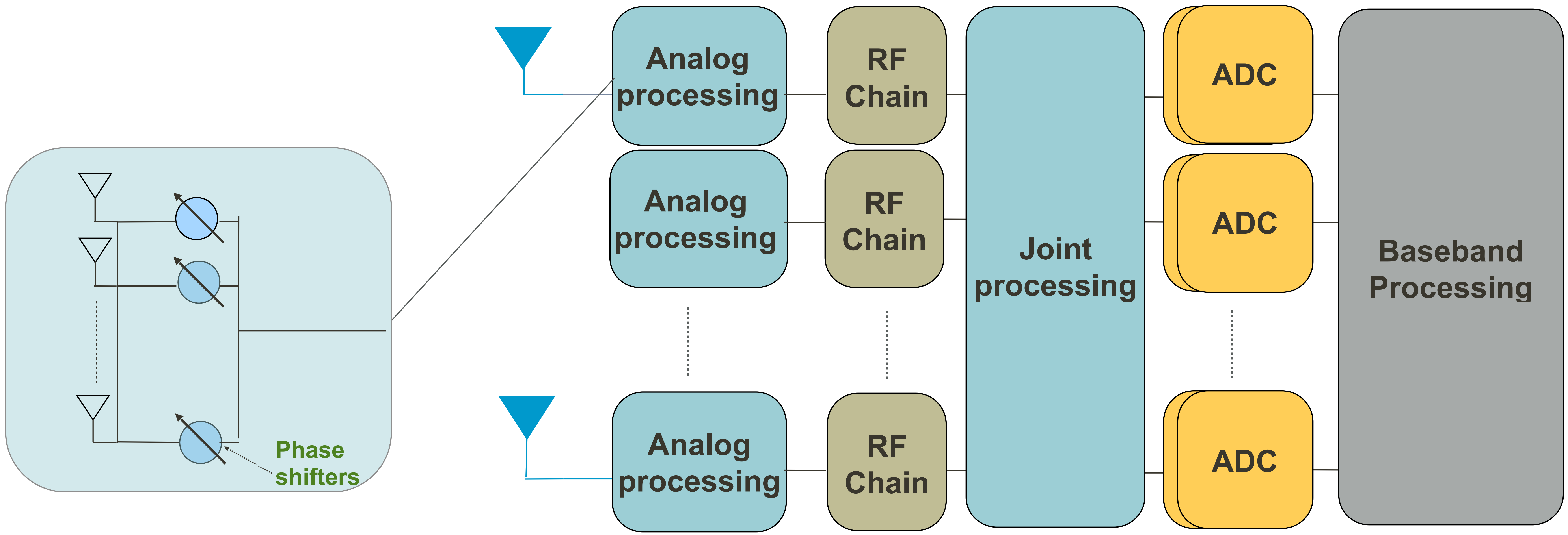
- Precoding is a staple of modern MIMO cuisine
  - Widely used in commercial wireless systems especially WLAN and cellular
- MIMO is a key feature of mmWave systems

Shu Sun, T. Rappaport, R.W. Heath, Jr., A. Nix, and S. Rangan, `` MIMO for Millimeter Wave Wireless Communications: Beamforming, Spatial Multiplexing, or Both?," IEEE Communications Magazine, December 2014.

How will MIMO precoding work in mmWave 5G?

mmWave Precoding is Different

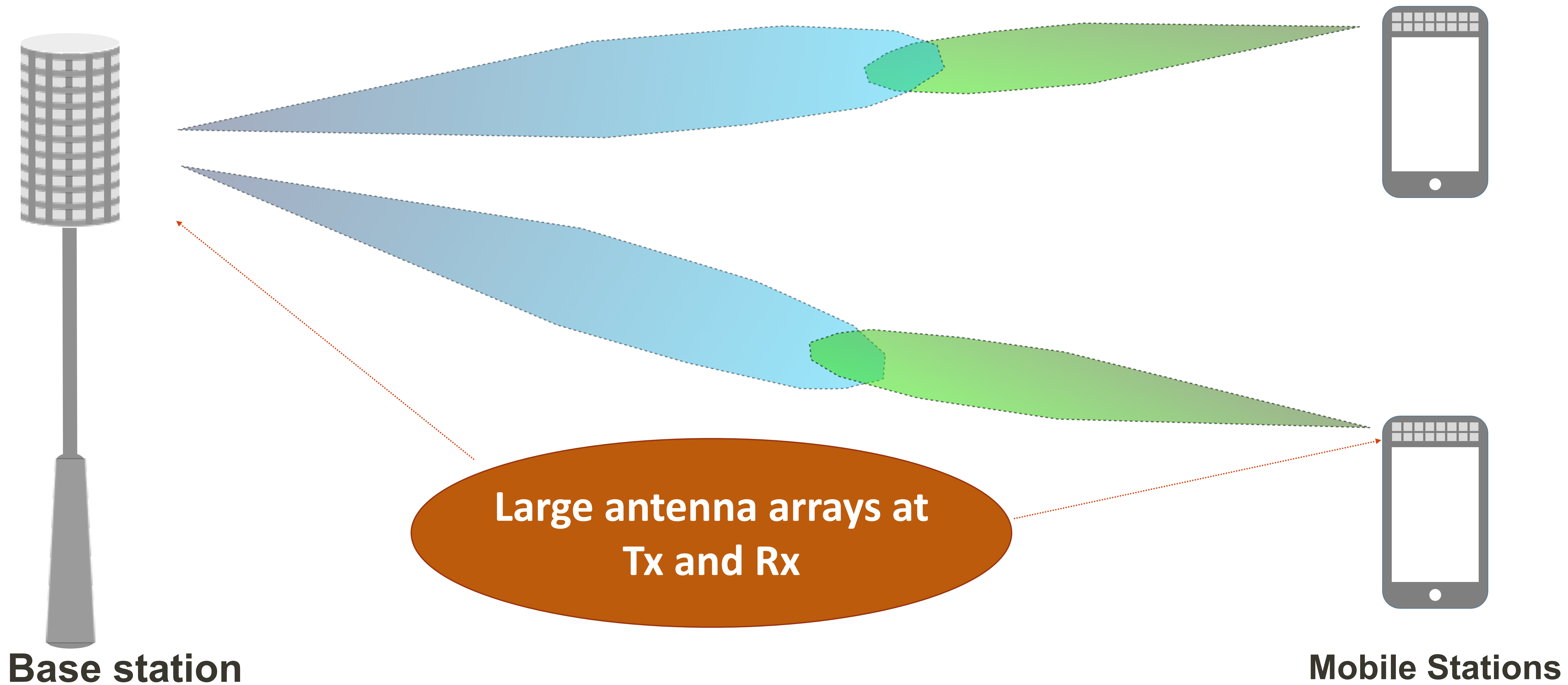
Different hardware constraints



- Cost, power, and complexity limit the # of RF chains (high-resolution ADCs)
  - Precoding and combining can not be done entirely in the baseband
- Analog beamforming usually uses a network of phase shifters
  - Additional constraints: Constant gain and quantized angles

Precoding and channel estimation algorithms should account for these constraints

Different antenna scales



- Large antenna arrays result in
  - Large-dimensional precoding/combining matrices
  - High channel estimation, training, and feedback overheads

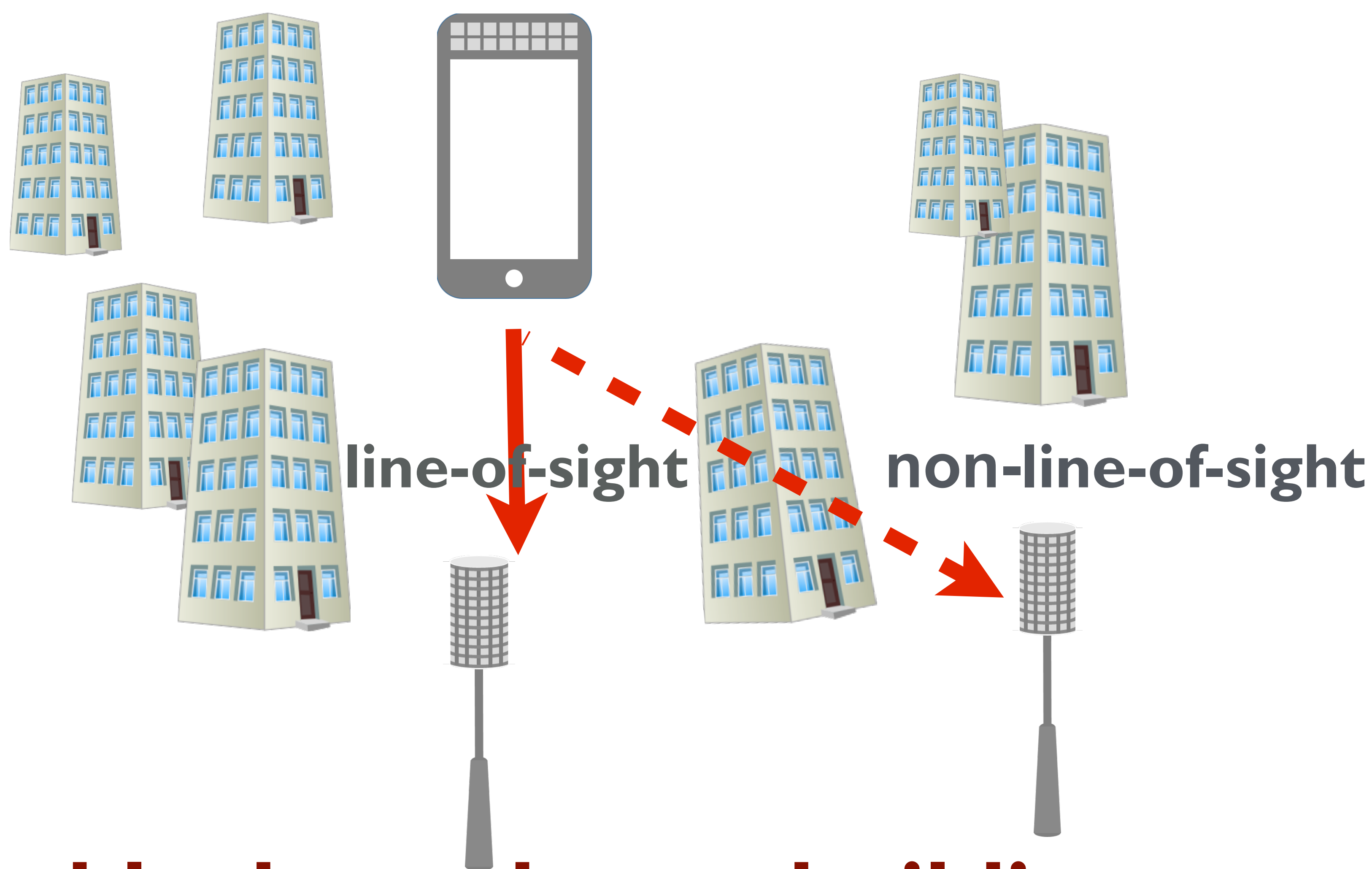
Need to design low-complexity precoding and channel estimation algorithms

Different channel characteristics

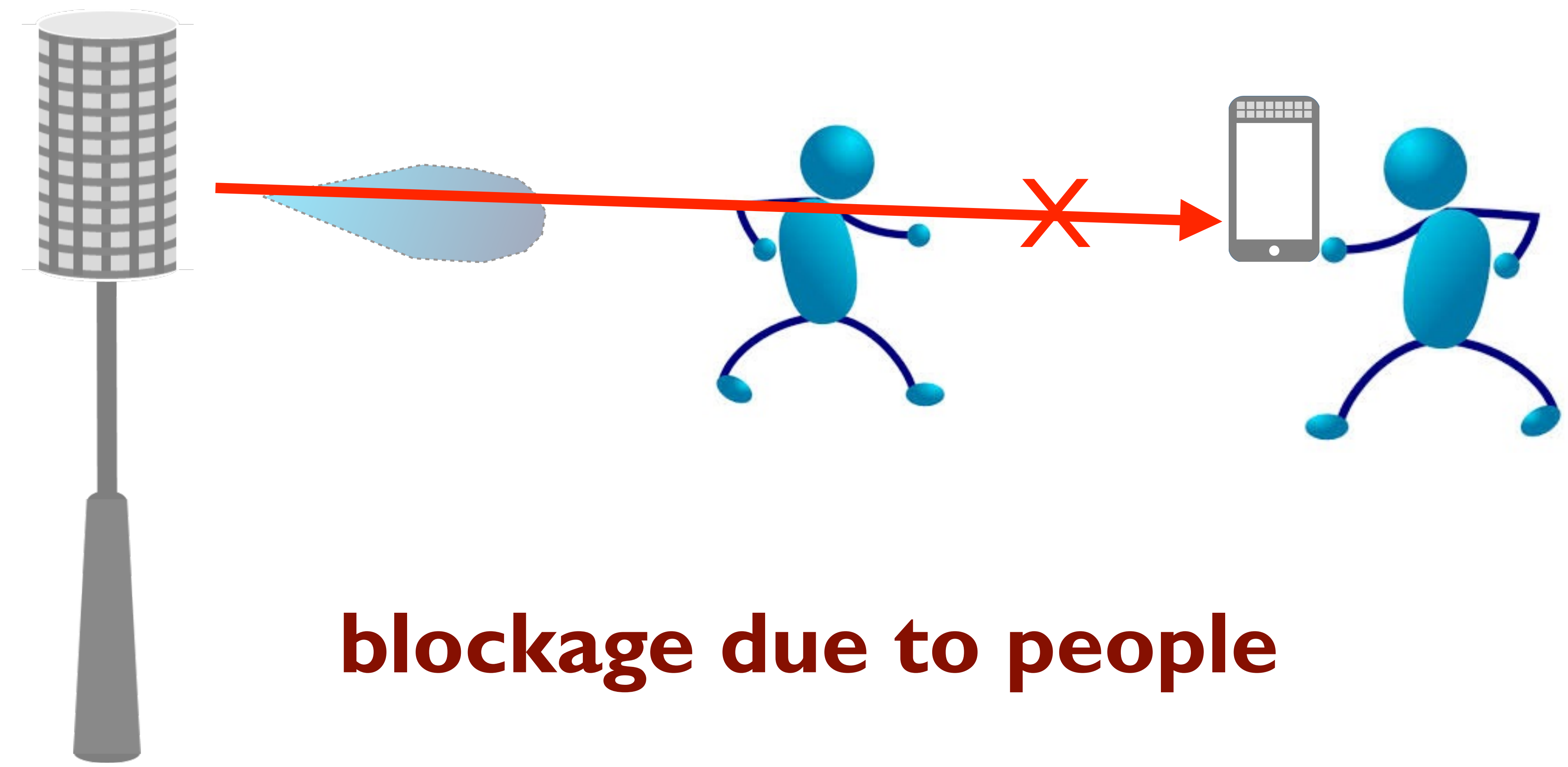
	microwave Wifi or Cellular	mmWave Wifi	mmWave 5G (???)
bandwidth	1.4 MHz to 160 MHz	2.16 GHz	100 MHz to 2 GHz
# antennas @ BS or AP	1 to 8	16 to 32	64 to 256
# antennas at MS	1 or 2	16 to 32	4 to 32
delay spread	100 ns to 10 us	5 to 47 ns	12 to 40 ns
angle spread	1° to 60°	60° to 100°	up to 50°
# clusters	4 to 9	< 4	< 4
orientation sensitivity	low	medium	high
small-scale fading	Rayleigh	Nakagami	non-fading or Nakagami
large-scale fading	distant dependent + shadowing	distant dependent + shadowing	distant dependent + blockage
path loss exponent	2-4	2 LOS, 2.5 to 5 NLOS	2 LOS, 3.5 to 4.5 NLOS
penetration loss	some	varies	possibly high
channel sparsity	less	more	more
spatial correlation	less	more	more

Some channel characteristics can be leveraged in the precoding design

Different sensitivity to blockages

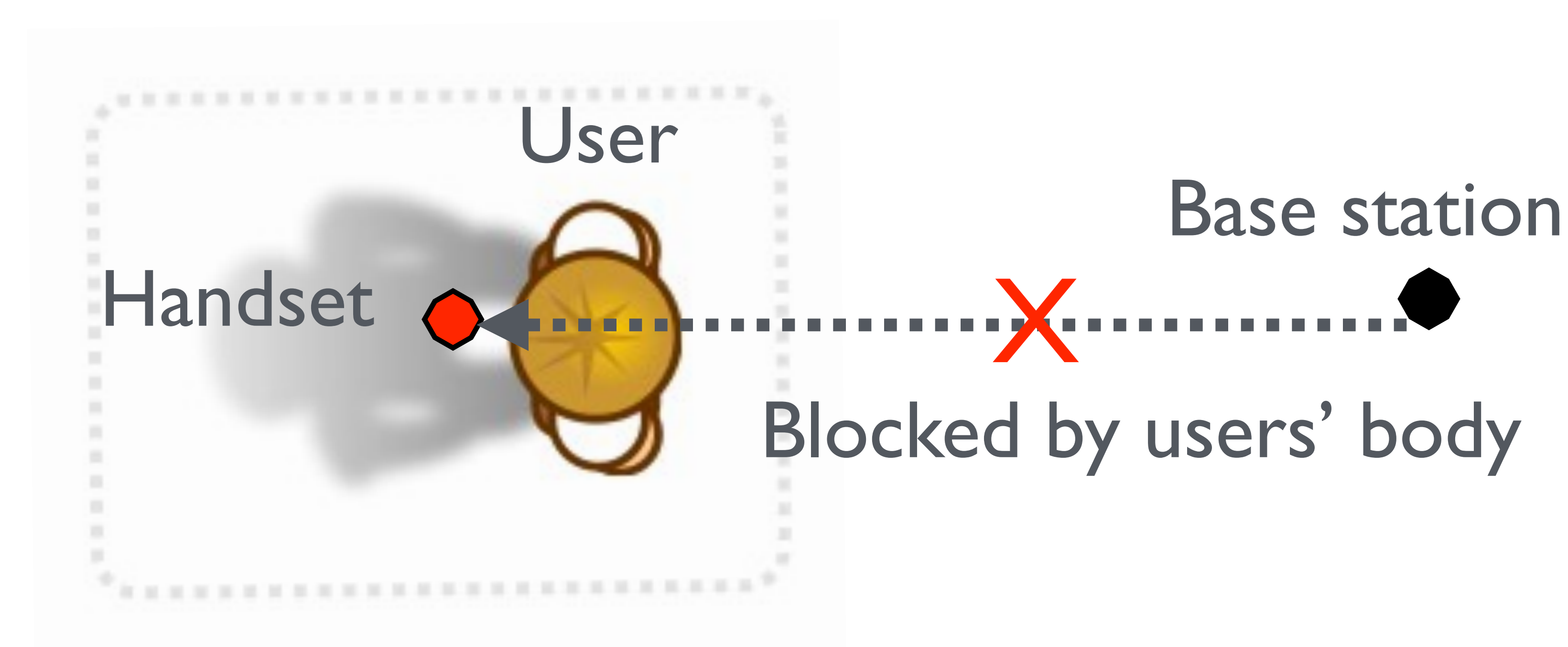


blockage due to buildings



blockage due to people

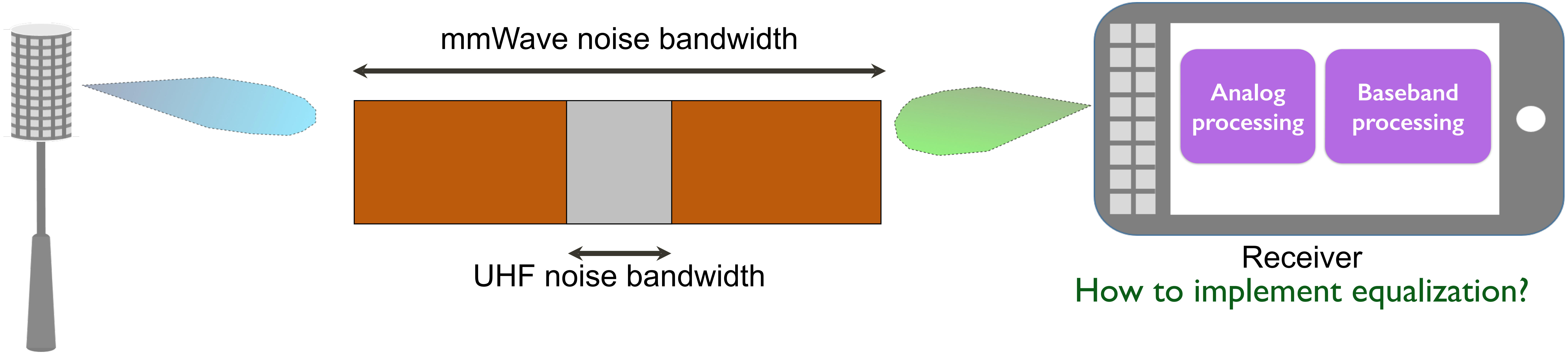
hand blocking



self-body blocking

Need models for these forms of blockage

Different communication channel bandwidth



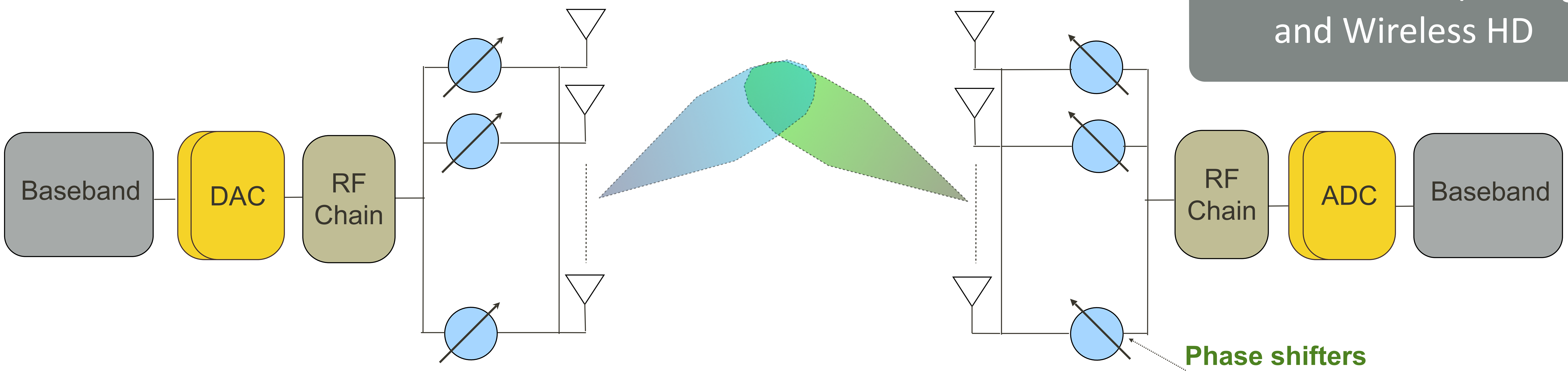
- Large channel bandwidth (high noise power, low SNR before beamforming)
  - Implementing random access, channel training and estimation functions is challenging
- Broadband channels coupled with delay spread
  - Equalization would likely be required at the receiver
  - Hardware constraints may make it difficult to perform equalization entirely in baseband

Need new algorithms and architectures for mmWave broadband communication

mmWave Suitable Precoding/Combining

Analog beamforming

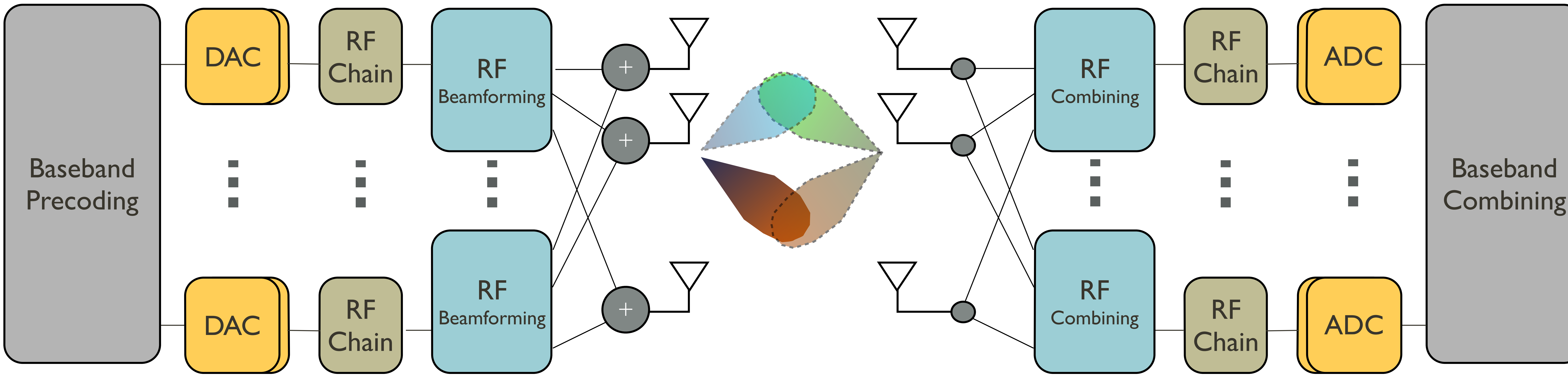
De-facto approach in IEEE 802.11ad / WiGig and Wireless HD



- Motivated by ADCs power consumption and implementation complexity
- Suitable for single-stream trans. (complicated for multi-stream or multi-user)
- Joint search for optimal beamforming/combining vectors with codebooks

* J. Wang, Z. Lan, C. Pyo, T. Baykas, C. Sum, M. Rahman, J. Gao, R. Funada, F. Kojima, H. Harada et al., "Beam codebook based beamforming protocol for multi-Gbps millimeterwave WPAN systems," IEEE Journal on Selected Areas in Communications, vol. 27, no. 8, pp. 1390–1399, 2009.
** S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," IEEE Transactions on Communications, vol. 61, no. 10, pp. 4391–4403, 2013.

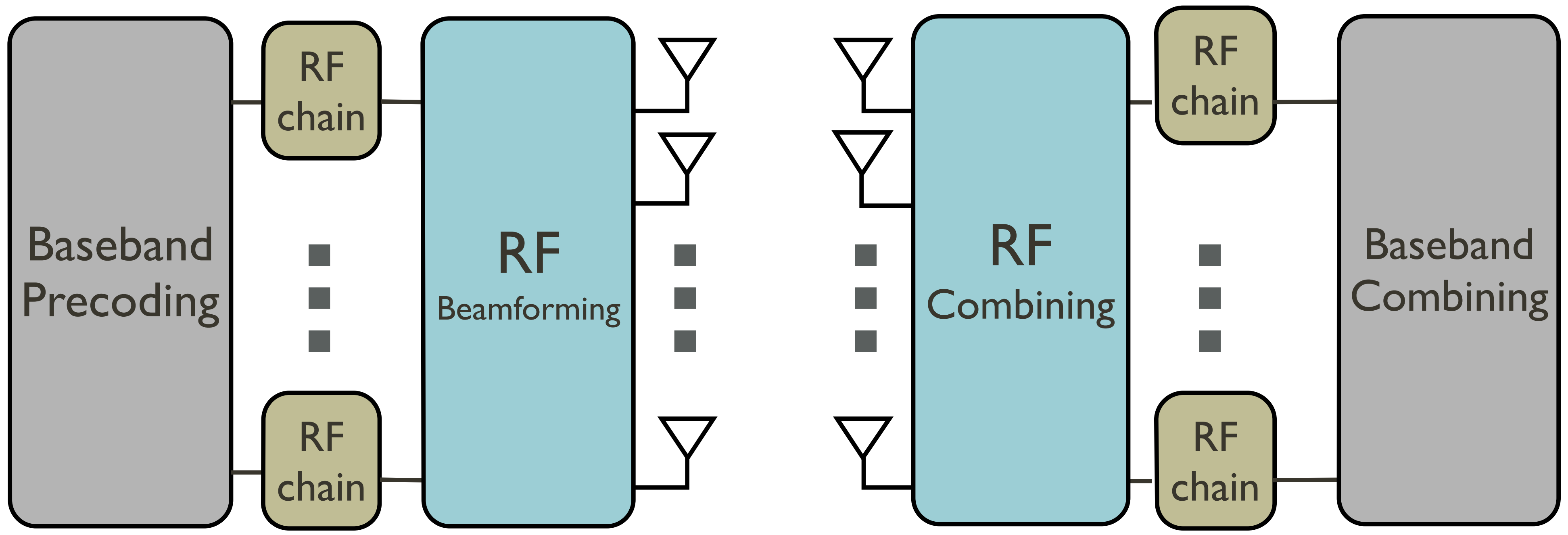
Hybrid analog-digital precoding/combining



- Makes compromise between hardware complexity and system performance
- Hybrid precoding enables multi-stream* and multi-user** transmissions
- Digital can correct for analog limitations
- Approaches the performance of unconstrained digital solutions

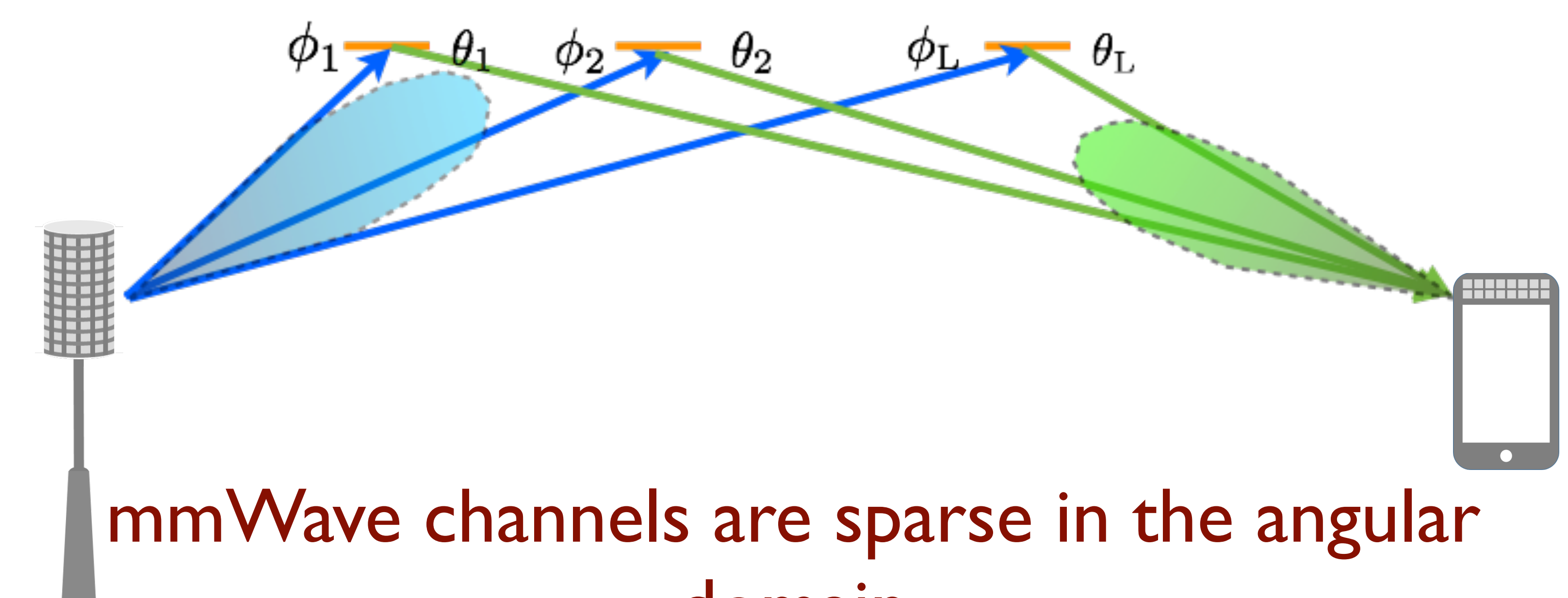
* O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath Jr., "Spatially sparse precoding in millimeter wave mimo systems," IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499–1513, March 2014.
** A. Alkhateeb, G. Leus, and R. W. Heath Jr, "Limited feedback hybrid precoding for multi-user millimeter wave systems," arXiv:1409.5162, 2014.

Design challenges: low-complexity precoding schemes



$$\mathbf{y} = \mathbf{W}_{\mathrm{BB}}^{*}\mathbf{W}_{\mathrm{RF}}^{*}\mathbf{H}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\mathbf{s} + \mathbf{W}_{\mathrm{BB}}^{*}\mathbf{W}_{\mathrm{RF}}^{*}\mathbf{n}$$

- Hybrid precoding design is non-trivial
  - Coupled analog and digital precoding matrices
  - RF phase shifters have constant modulus, quant. angles
  - Non-convex feasibility constraints

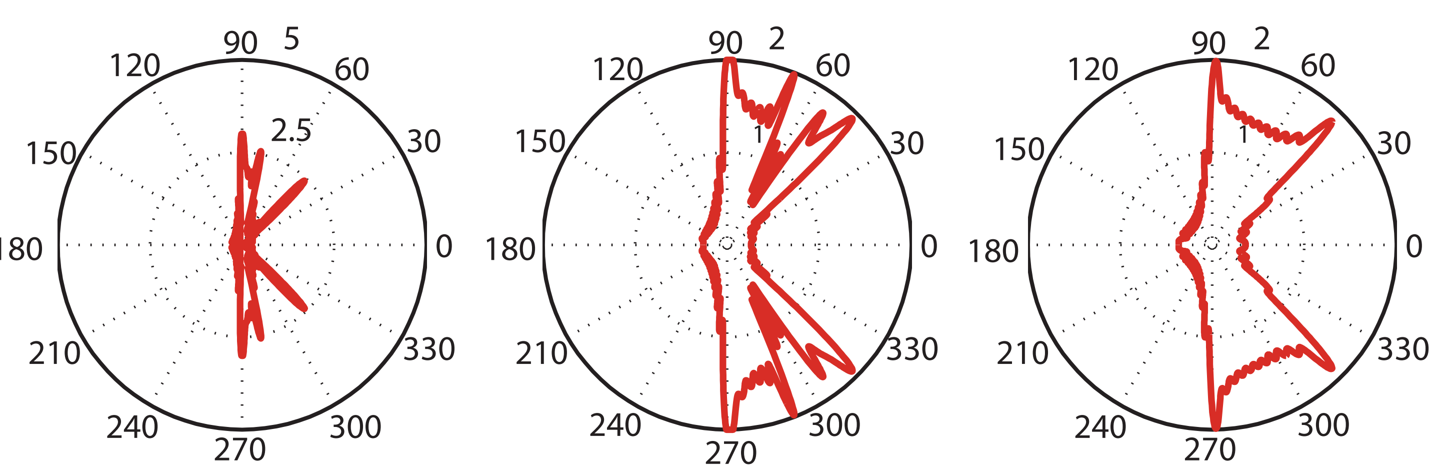


mmWave channels are sparse in the angular domain
(only a few paths exist)

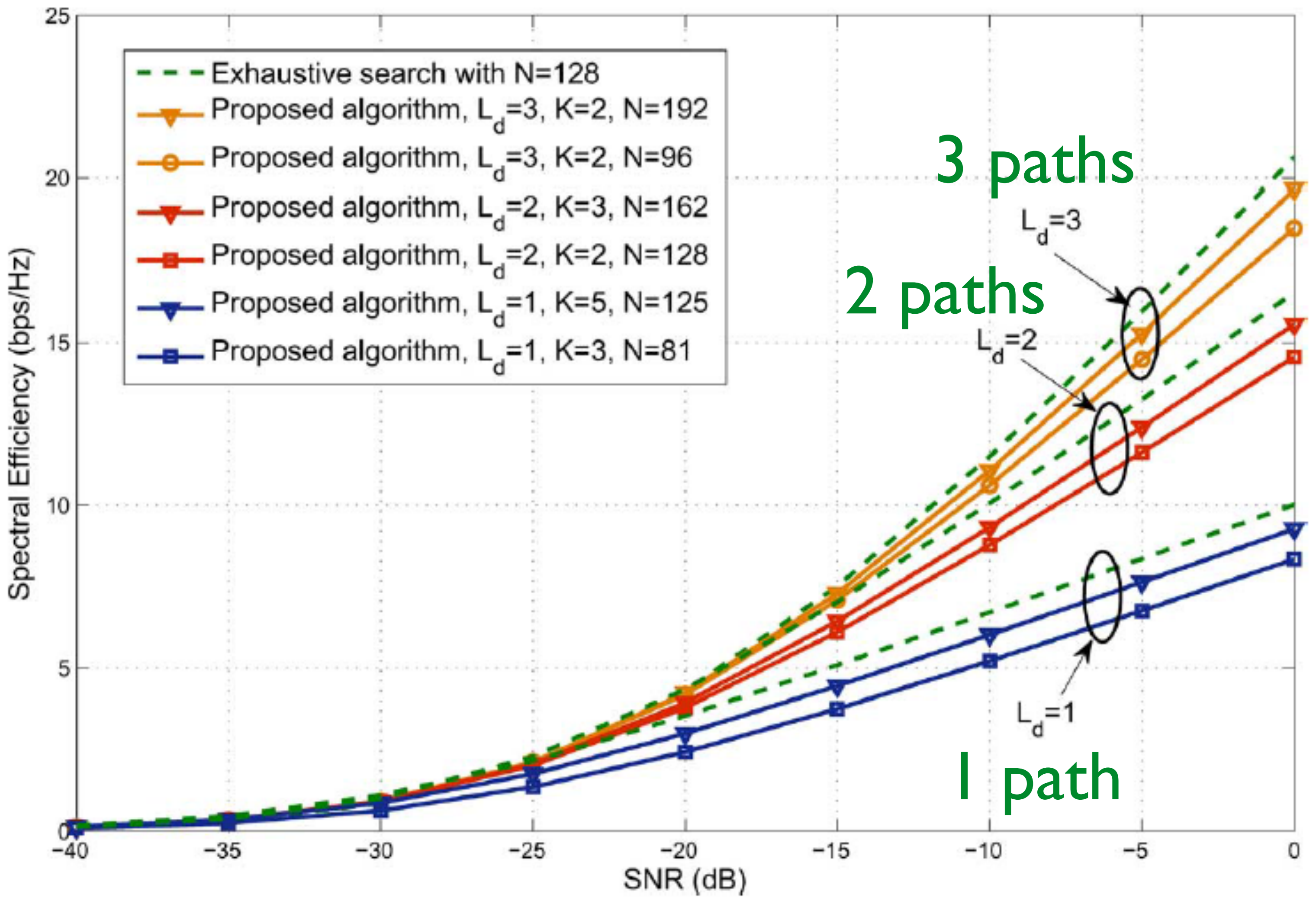
- Sparse precoding solutions
  - Joint analog/digital precoder design w/ matching pursuit*
  - Approaches performance of unconstrained solutions
  - Leverage lens antenna array structure**
  - Extension to multiuser interference channels ***

* O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath Jr., "Spatially sparse precoding in millimeter wave mimo systems," IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499–1513, March 2014.
** J. Brady, N. Behdad, and A. Sayeed, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," IEEE Trans. on Ant. and Propag., vol. 61, no. 7, pp. 3814–3827, July 2013.
*** M. Kim and Y.H. Lee, "MSE-based Hybrid RF/Baseband Processing for Millimeter Wave Communication Systems in MIMO Interference Channels", IEEE TVT, to appear.

Design challenges: channel estimation with hybrid precoding



Beams generated using hybrid precoders with different numbers of RF chains

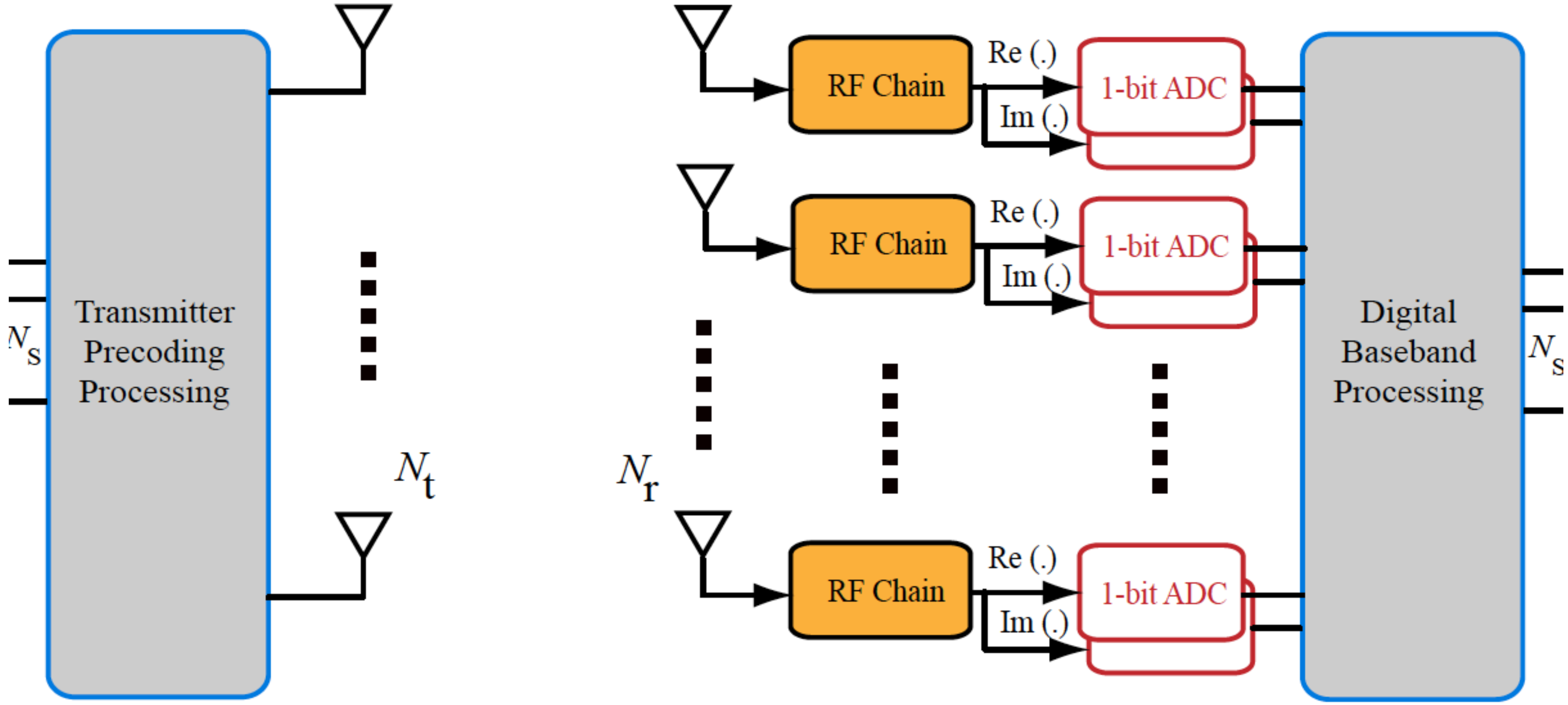


- mmWave channel estimation is challenging
  - Large channel matrices -> training/feedback overhead
  - Low SNR before beamforming design
  - In hybrid architecture, channel is seen through RF BF lens
- Adaptive compressed sensing solution*
  - Sparse nature of mmWave channel can be leveraged
  - mmWave Channel estimation -> parameter estimation
  - Low training overhead with compressed sensing (CS) tools
  - Adaptive CS estimation of multi-path mmWave channels
  - CS and hybrid precoders lead to efficient training codebooks

* A. Alkhateeb, O. E. Ayach, G. Leus, and R. W. Heath Jr, "Channel estimation and hybrid precoding for millimeter wave cellular systems." IEEE J. Selected Topics in Signal Processing (JSTSP), vol. 8, no. 5, May 2014, pp. 831-846

Combining with 1-bit ADCs

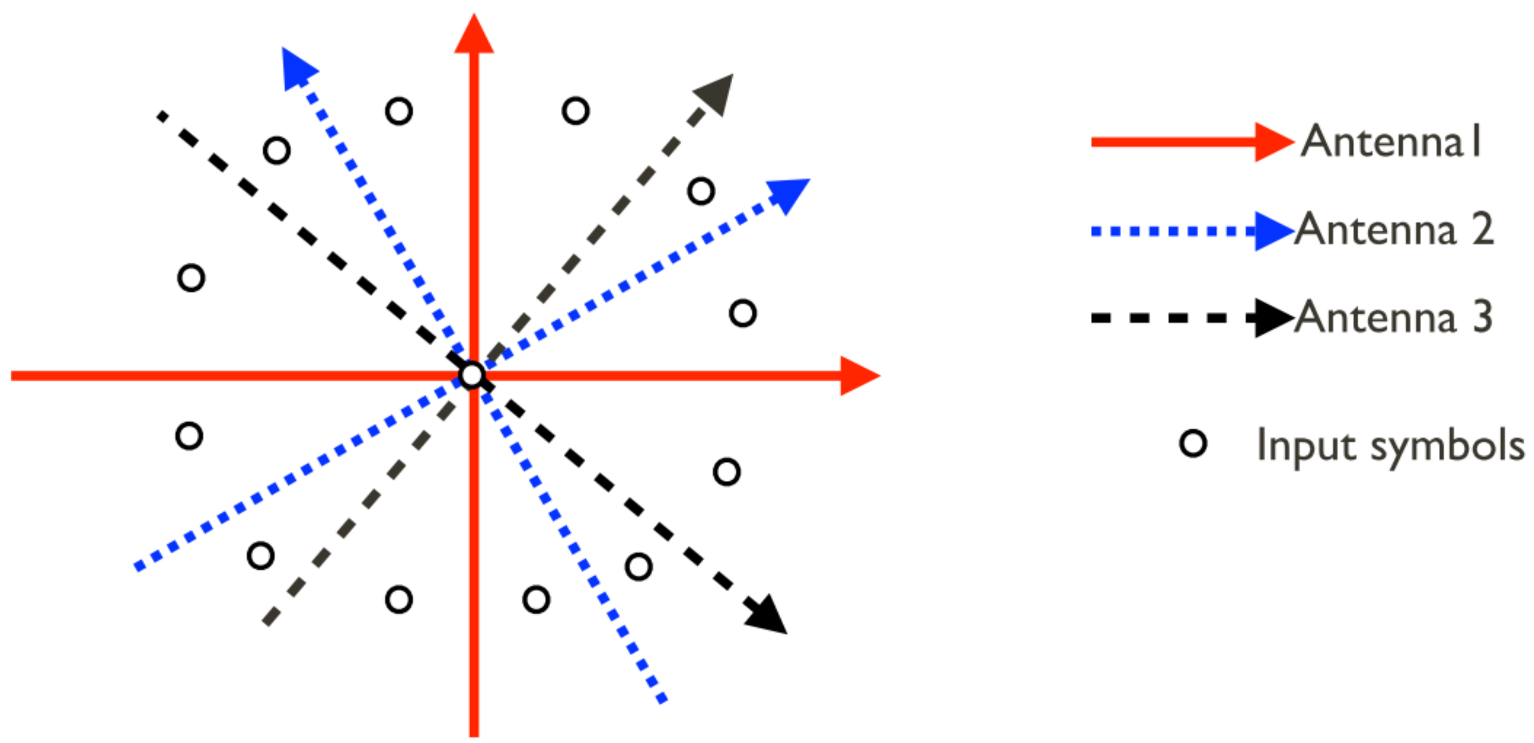
Different transmit architectures possible, analog, hybrid, or otherwise



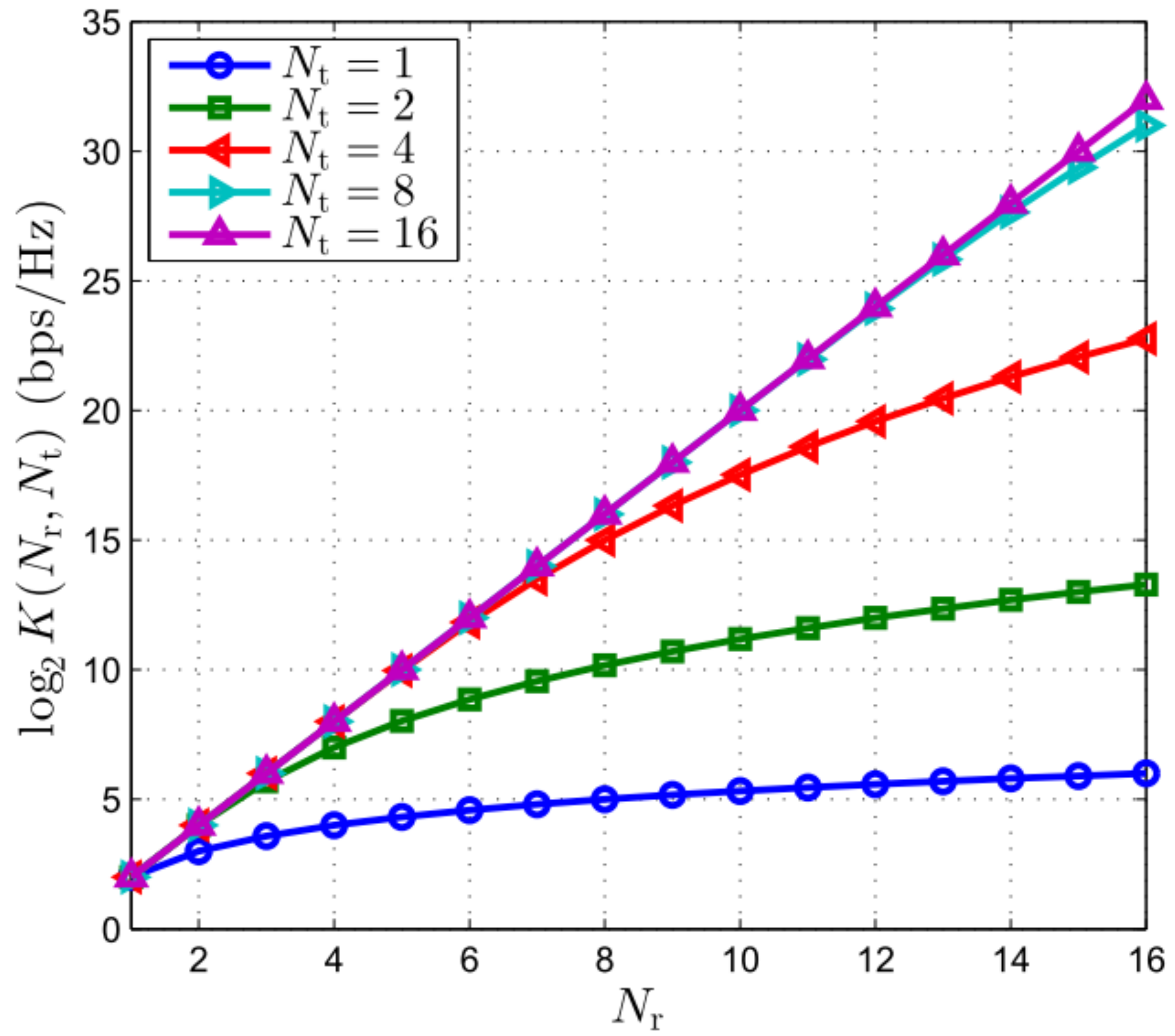
- Use 1-bit ADCs (pair) for each RF chain
- Perform digital combining for all the highly quantized received signals
- Ultra low power solution - only 1 comparator for each ADC, no need for AGC
- Limitation: Capacity is bounded by 2 N_r bps/Hz (important at high SNR)

* J. Mo and R.W. Heath, Jr., "Capacity Analysis of One-Bit Quantized MIMO Systems with Transmitter Channel State Information" arxiv 1410.7353
See also extensive work by research groups led by U. Madhow, J. Nossek, G. Fettweis, G. Kramer, and O. Dabeer and others

Design challenges: capacity analysis with 1-bit ADCs



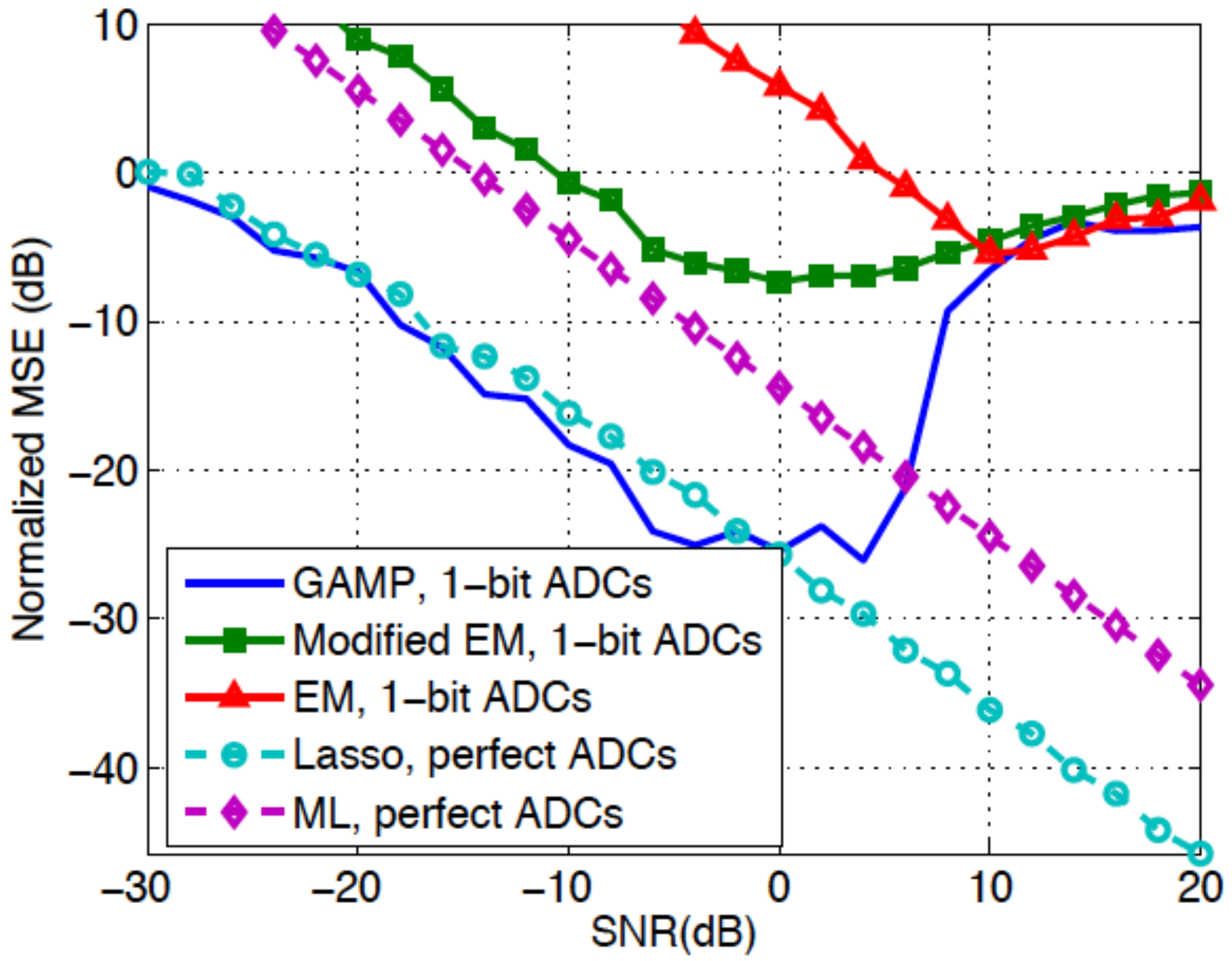
- Finding the exact capacity is challenging
  - Quantization is a nonlinear operation
  - Optimal input has discrete distribution
  - Special case: Rotated QPSK (optimal for SISO channel)*



- Initial contributions **
  - MISO optimal strategy is MRT + QPSK signaling
  - Derived high SNR capacity for SIMO and MIMO
  - Use numerical methods to find optimal inputs***
  - Assumption: Known CSI at transmitter

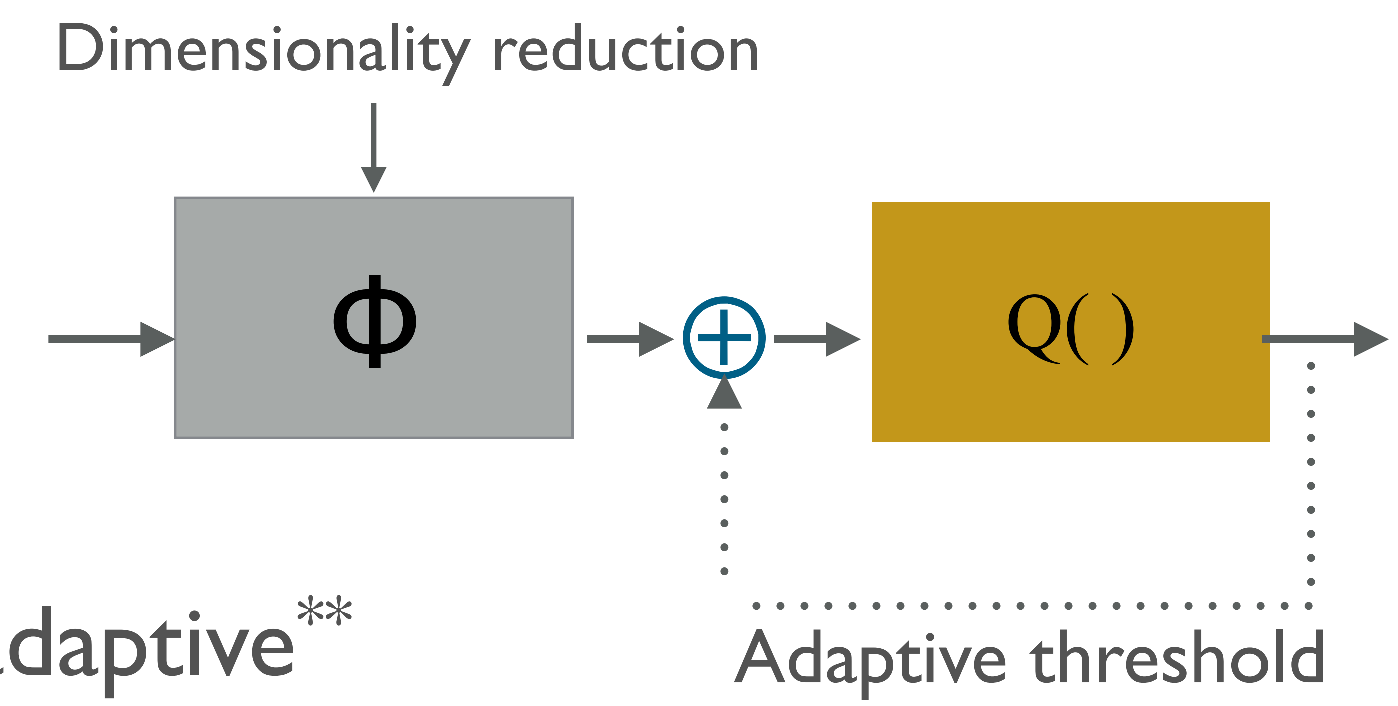
*J. Singh, O. Dabeer, and U. Madhow, "On the limits of communication with low-precision analog-to-digital conversion at the receiver," TCOM 2009
**J. Mo and R.W. Heath, Jr., "Capacity Analysis of One-Bit Quantized MIMO Systems with Transmitter Channel State Information" arxiv 1410.7353
***J. Huang and S. Meyn, "Characterization and computation of optimal distributions for channel coding," TIT 2005

Design challenges: channel estimation with 1-bit ADCs



mmWave with 2 paths, and 128-length training sequence

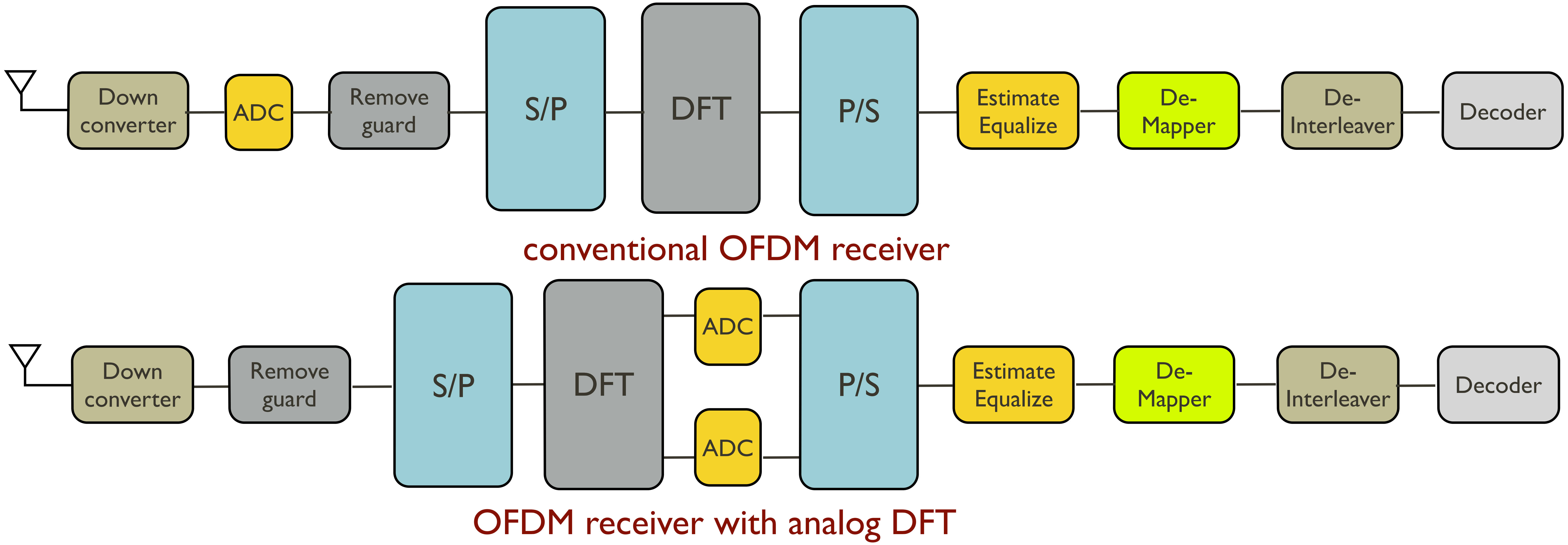
- Channel estimation is hard with 1-bit ADCs
  - Amplitude information is lost in the quantization
  - Conventional sparse reconstruction algorithms like LASSO do not work with 1-bit quantization
  - Stochastic resonance appears when using GAMP: estimation error may increase w/ SNR



- Possible approaches
  - Expectation-maximization algorithm*
  - Dithered quantization: Quantization threshold is adaptive**
  - Exploit sparse nature of mmWave channels with GAMP ***

*A. Mezghani, F. Antreich, and J. Nossek, "Multiple parameter estimation with quantized channel output," ITG 2010
**O. Dabeer and U. Madhow, “Channel estimation with low precision ADC”, ICC, 2010
***J. Mo, P. Schniter, N. G. Prelcic and R. W. Heath, Jr. “Channel Estimation in Millimeter Wave MIMO Systems with One-Bit Quantization”, Asilomar 2014

Design challenges: broadband channels with 1-bit ADCs

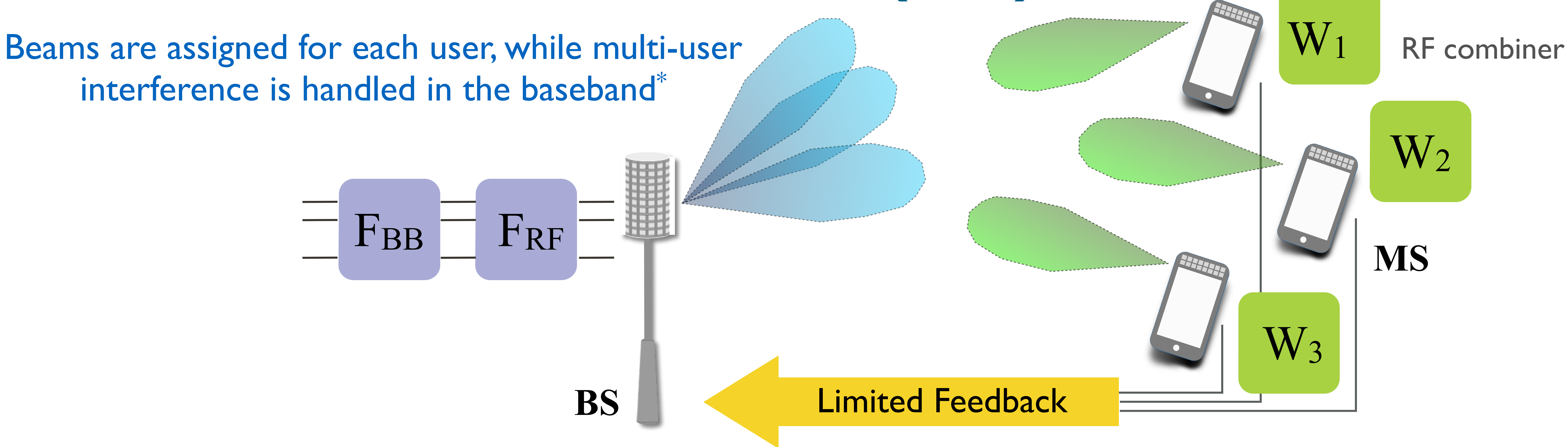


- mmWave has broadband channels
  - 10-40 ns delay spread in 2.16GHz BW in 11ad
  - Equalization after quantization is challenging
- Analog DFT
  - Orthogonalization: No inter-carrier interference
  - Lower PAPR: Low-resolution ADCs
  - Possibly lower power vs digital DFT

*S. Suh, A. Basu, C. Schlottmann, P. Hasler, and J. Barry, "Low-power discrete Fourier transform for OFDM: A programmable analog approach," IEEE Transactions on Circuits and Systems I: Regular Papers, 58.2, 2011

Future Research Directions

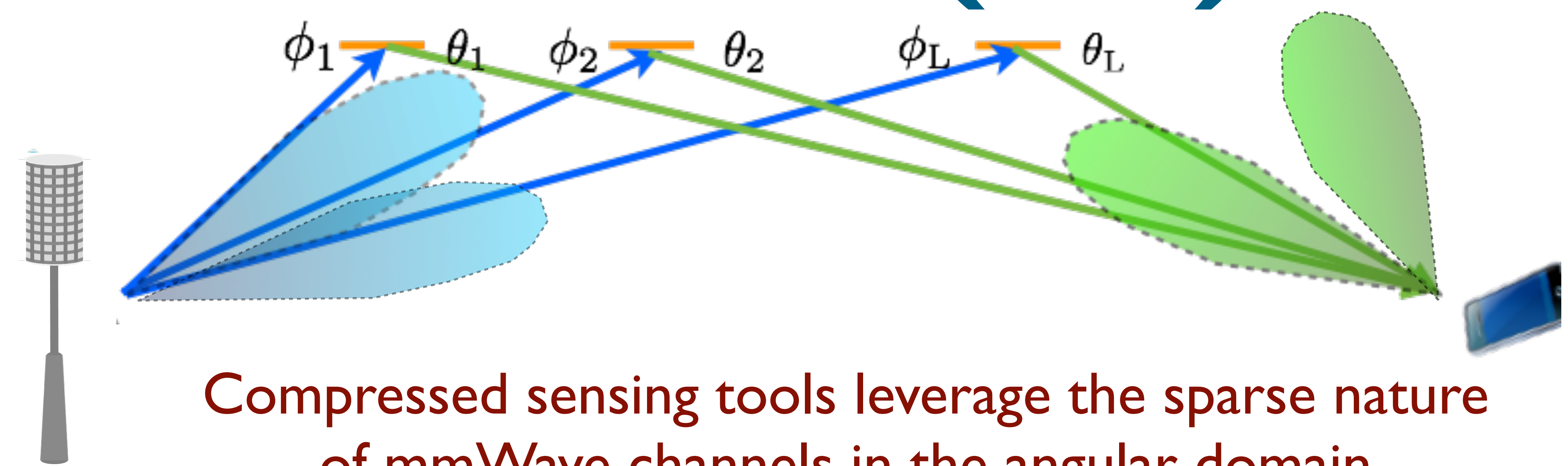
Future research directions (1/4)



- Multi-user mmWave systems with hybrid precoding
  - Enables different beams to be assigned to different users
  - Better interference management capability in digital domain
  - Initial work proposes two-stage hybrid precoding algorithm*
  - Considering out-of-cell interference is also interesting (extension to multi-layer precoding**)

* A. Alkhateeb, G. Leus, and R. W. Heath Jr., "Limited Feedback Hybrid Precoding for Multi-User Millimeter Wave Systems," submitted to IEEE Trans. Wireless Commun., arXiv preprint arXiv:1409.5162, 2014.
** Ahmed Alkhateeb, Geert Leus, and Rober W. Heath Jr, "Multi-Layer Precoding for Full-Dimensional Massive MIMO Systems ," in Proc. of Asilomar Conference on Signals, Systems and Computers , Pacific Grove, CA, November 2014.

Future research directions (2/4)



Compressed sensing tools leverage the sparse nature of mmWave channels in the angular domain

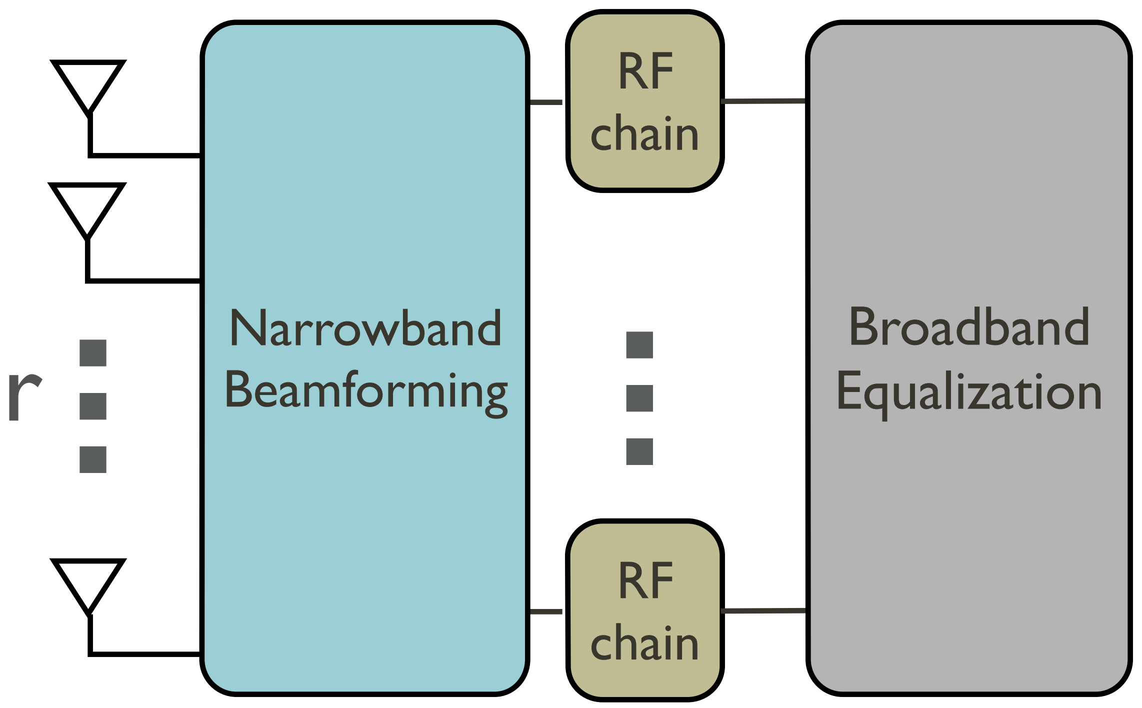
- Compressed sensing (CS) mmWave channel estimation
  - CS can leverage mmWave channel sparsity for efficient channel training/estimation
  - Designing CS-based pilot signals* for mmWave systems is an interesting open problem
  - Challenges are mainly due to the different hardware constraints (e.g., w/ hybrid precoding)

- Body, hand and self-body blockages
  - Consider blockage model into the channel matrix
  - Precoding and channel estimation with array diversity** on the handset

* D. Ramasamy, S. Venkateswaran, and U. Madhow, "Compressive adaptation of large steerable arrays," in Proc. of 2012 Information Theory and Applications Workshop (ITA), CA, 2012, pp. 234–239.
** W. Roh et al., "Millimeter-Wave Beamforming as an Enabling Technology for 5G Cellular Communications: Theoretical Feasibility and Prototype Results", IEEE Communications Magazine, Feb. 2014

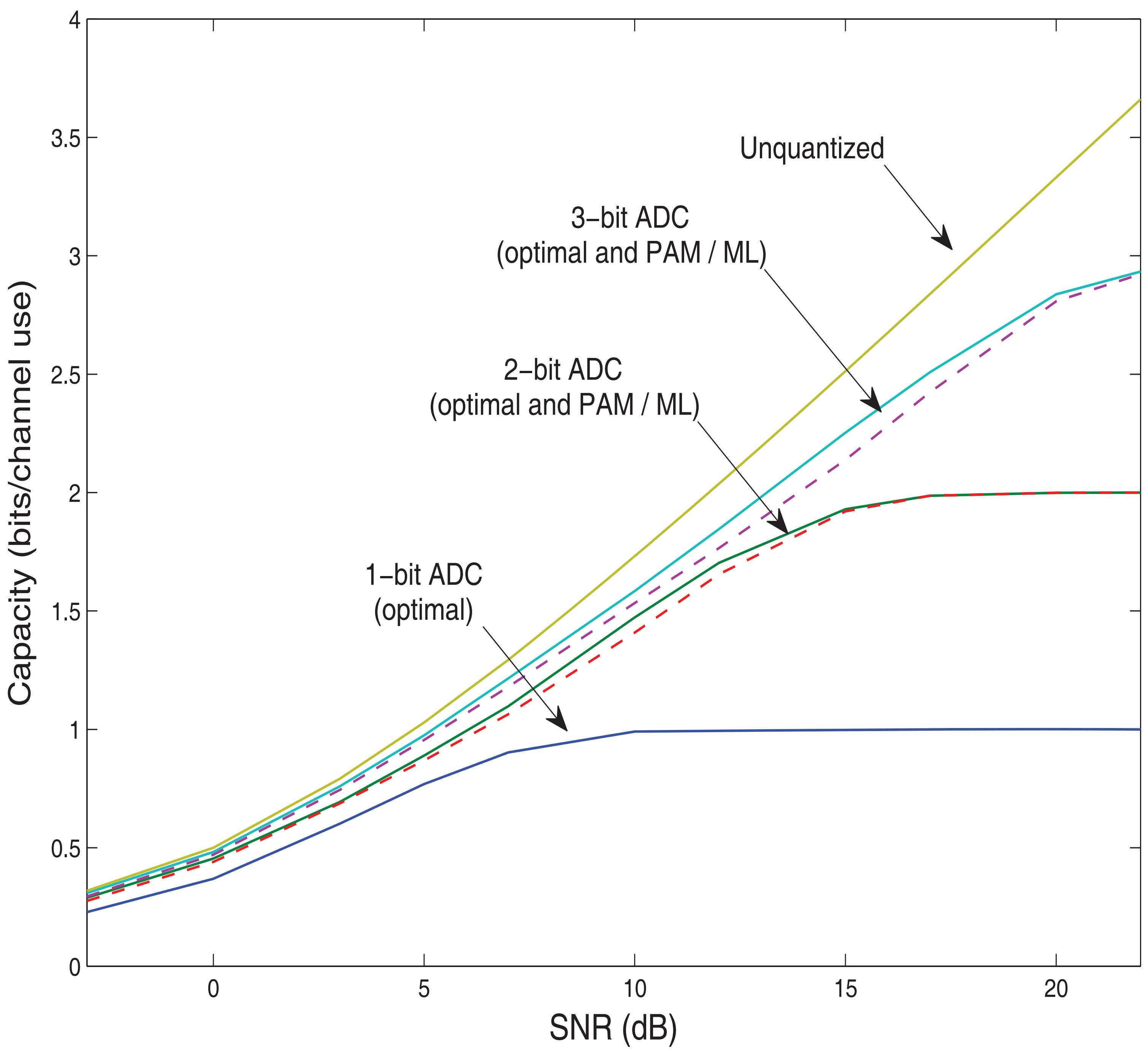
Future research directions (3/4)

- MIMO with limited feedback
  - Feedback help establishing forward link
  - Feedback has to be limited due to large channel dimensions and low rate during initial access
  - Need to design efficient precoding codebooks* (for hybrid architectures, 1-bit ADCs, …)
  - Channel sparsity may be leveraged for low-complexity solutions**
  - Initial hybrid beamforming codebooks based on adaptive refining***
- MIMO over broadband channels
  - Narrowband analog and broadband digital equalization
  - Exploiting channel sparsity, analog beams can be designed per cluster
  - Adjusting analog / beam switching in OFDM, SC-FDMA****



* J. Singh, and R. Sudhir, "On the feasibility of beamforming in millimeter wave communication systems with multiple antenna arrays." arXiv preprint arXiv:1410.5509, 2014.
** A. Alkhateeb, G. Leus, and R.W. Heath Jr., "Limited Feedback Hybrid Precoding for Multi-User Millimeter Wave Systems," submitted to IEEE TWC, arXiv preprint arXiv:1409.5162, 2014.
*** A. Alkhateeb, O. E. Ayach, G. Leus, and R.W. Heath Jr, "Channel estimation and hybrid precoding for millimeter wave cellular systems." IEEE JSTSP, vol. 8, no. 5, May 2014, pp. 831-846
**** A. Ghosh et. al. "Millimeter-wave Enhanced Local Area Systems: A high-data-rate approach for future wireless networks", IEEE JSAC vol. 32, no. 6, pp. 1152-1163, June 2014.

Future research directions (4/4)



Capacity plots for different ADC precisions in SISO channel (from *)

- Training signal design for systems with 1-bit ADCs
  - Discrete input discrete output
  - Need not to estimate the exact channel state
  - Estimate the channel response to certain training symbols
- Performance analysis with >1-bit ADCs
  - Tradeoff between achievable rate and power consumption
  - Achievable rates of quant. MIMO channels are unknown**
  - Uniform quantization is near-optimal**
- Other channel state assumptions
  - Connections with non-coherent MIMO techniques

*J. Singh, O. Dabeer, and U. Madhow, “On the limits of communication with low-precision analog-to-digital conversion at the receiver,” TCOM 2009
**Q. Bai, J. A. Nossek, “Energy efficiency maximization for 5G multi-antenna receivers”, ETT 2014

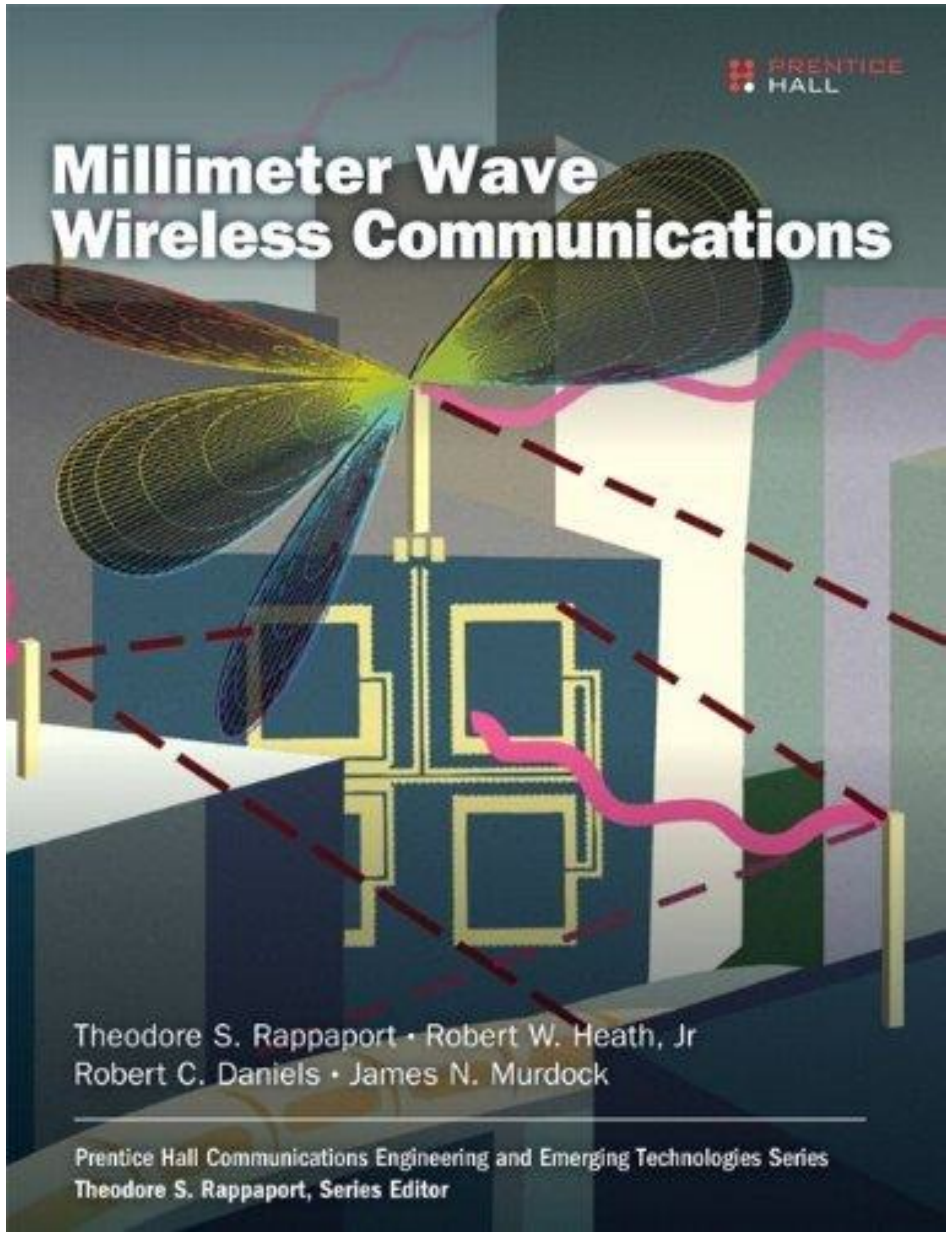
Conclusions

- mmWave precoding/combining is different than traditional UHF solutions
  - Different hardware constraints, antenna scales, channel characteristics, channel bandwidth
- New transceiver architectures, precoding/combining solutions are needed
  - Promising solutions: Hybrid precoding/combining and combining with low-resolution ADCs
  - Design challenges with these solutions need to be addressed
  - Many research directions (multi-user extensions, new architectures, ….)

Submit your work to the forthcoming IEEE JSTSP special issue on Millimeter Wave Communication - Manuscripts are due May15

Ahmed Alkhateeb, Jianhua Mo, Nuria González Prelcic and Robert W. Heath, Jr., ``MIMO Precoding and Combining Solutions for Millimeter Wave Systems," *IEEE Communications Magazine*, December 2014.

http://www.profheath.org/research/millimeter-wave-cellular-systems/



Questions?

Robert W. Heath Jr.
The University of Texas at Austin

THE UNIVERSITY OF TEXAS AT AUSTIN

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