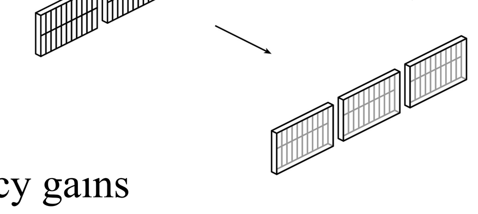
MASSIVE EXTENDED-ARRAY TRANSCEIVERS FOR ROBUST SCALING OF ALL-DIGITAL MMWAVE MIMO (2148303)

RINGS
Resilient and Intelligent NextG Systems

Motivation & Applications

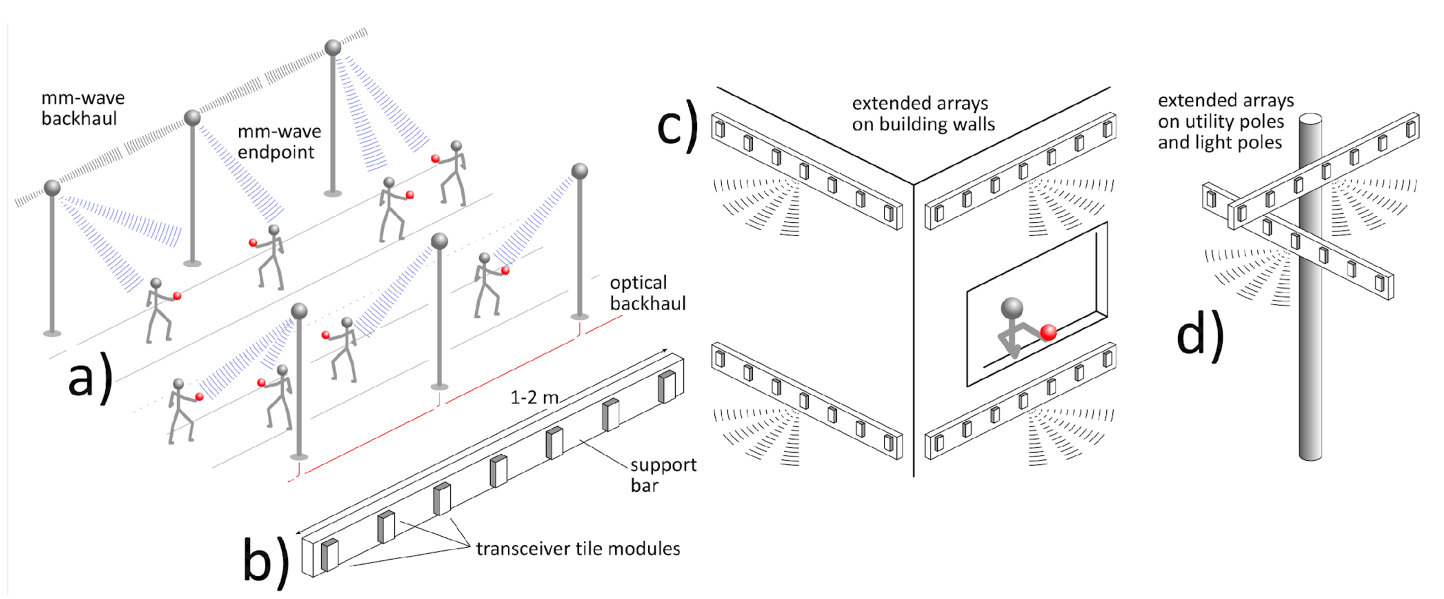
- Millimeter wave (mmWave) bands will play a crucial role in next-generation wireless systems:
  - More available bandwidth ➔ Higher data rates.
  - Small wavelengths ➔ compact antenna arrays ➔ increased capacity with massive MIMO.
- Challenges at tiny wavelengths and huge bandwidths ➔ hardware/signal processing co-design
- **Project focus: massive scaling via tiled architectures & simplified electronics**
- Fully digital beamforming
  - Bandwidth scaling: reduce required dynamic range
  - Computational scaling: exploit channel sparsity

$$\frac{P_{RX}}{P_{TX}} = \frac{N_{TX} N_{RX}}{\Omega_{scan,TX}\Omega_{scan,RX}}\left(\frac{\lambda^2}{R^2}\right)e^{-\alpha R}$$



- Radically simplified RF beamforming
  - Switch-based phase control for large power efficiency gains
  - RF and hybrid beamforming via tiling

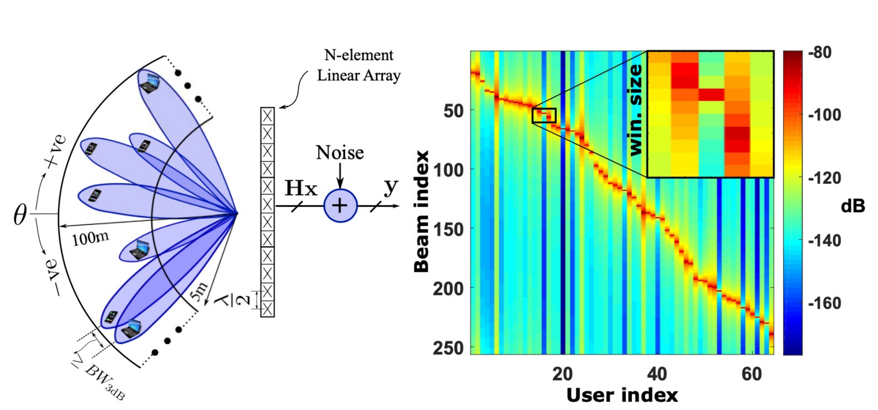
- Modularity of tiled architecture enables scaling to diverse applications



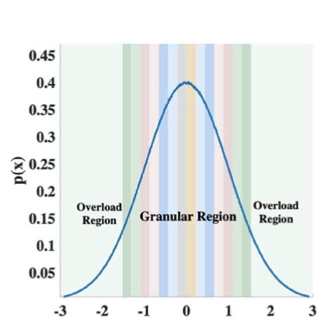
a) Lamppost based urban picocellular deployment
b) Tiling to create a giant array
c) Giant arrays on walls
d) Giant arrays for LoS MIMO backhaul

Insights from prior work

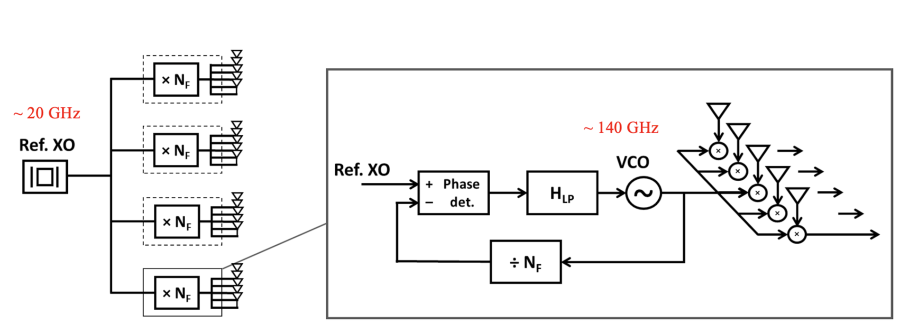
All-digital multiuser (MU) massive MIMO over sparse mmWave channels



Channel sparsity can be exploited by going to beamspace (significant reduction in signal processing complexity)



Severe nonlinearities can be tolerated with scale (hardware specs can be relaxed)

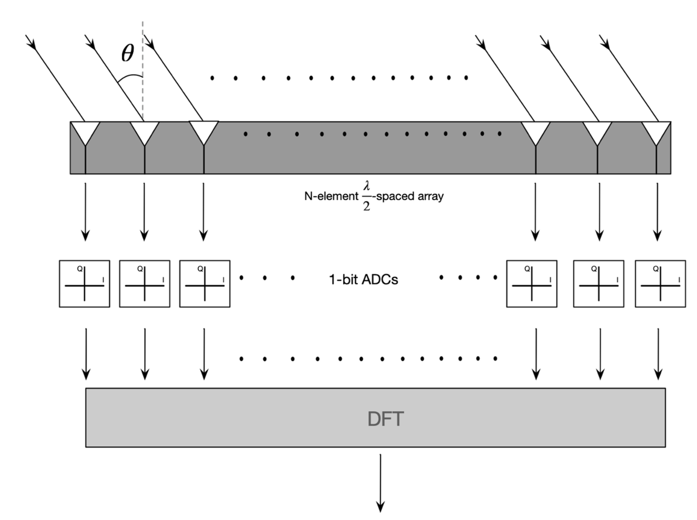


Scale can be attained with tiling (phase noise specs can be relaxed)

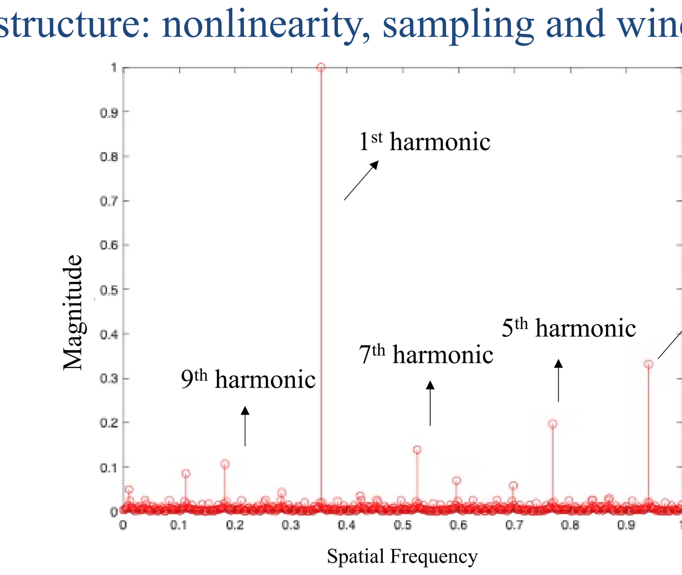
Efficient scaling for digital, RF and hybrid beamforming

Drastically reduced ADC Precision

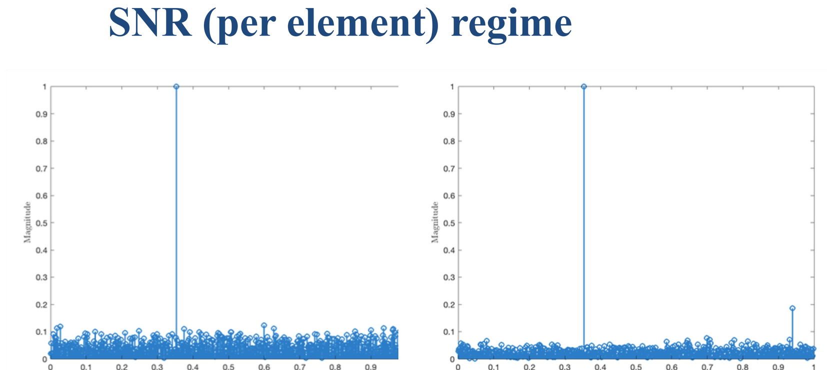
- Fundamental bottleneck in bandwidth scaling for fully digital massive MIMO: hardware cost, complexity & power consumption of analog-to-digital converters (ADCs)
- Can we push ADC precision down to 1 bit?
- Prior work: average quantization noise across antennas can work well
  - Bussgang linearization for performance evaluation and design
  - Assumes input to ADC approximately Gaussian
  - OK for Rayleigh fading channels or for sparse channels with enough users
- **Our initial focus: what can go wrong with 1 bit ADCs?**
  - Fast-moving users in a small picocell, no power control ➔ Gaussian input approximation not valid, SNR per antenna element too high (not enough noise dithering)
- **Back to basics Fourier analysis for design and operating regime of beamspace MIMO**



Fourier analysis for 1 user reveals spatial harmonic structure: nonlinearity, sampling and windowing

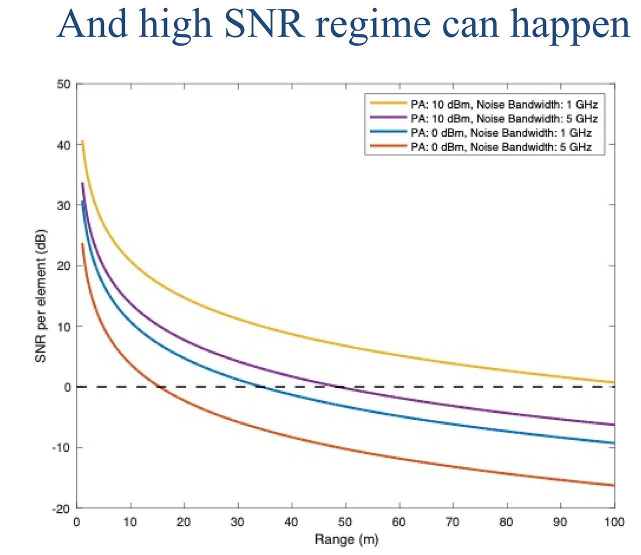


Harmonic structure prominent **in high SNR (per element) regime**



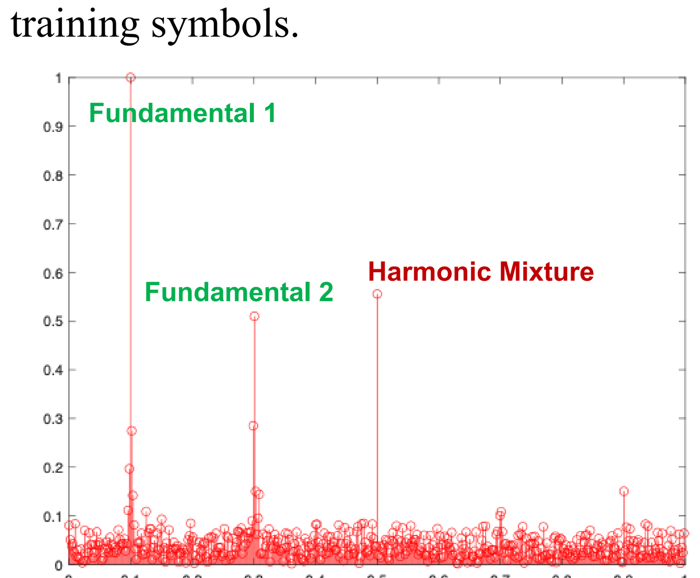
(a) SNR per antenna: 0 dB (b) SNR per antenna: 5 dB

And high SNR regime can happen

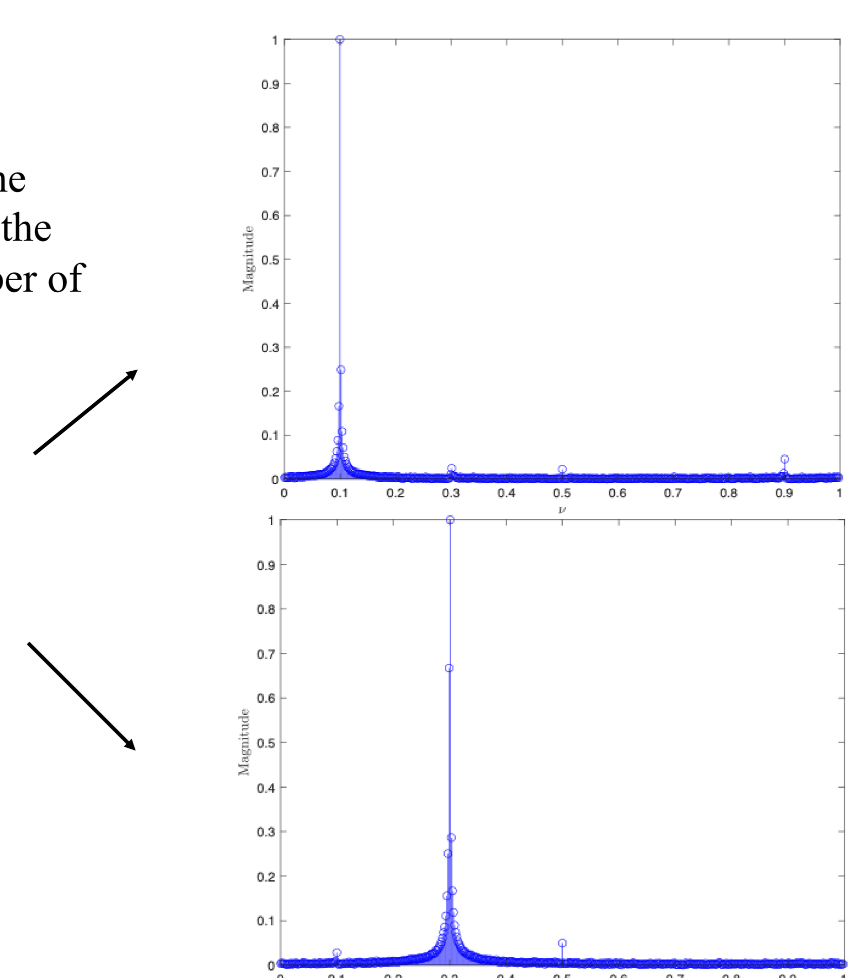


Naïve selection of strong peaks in beamspace may not work ➔ must suppress higher order harmonics to isolate fundamental spatial frequencies

A standard training sequence does not suppress harmonics : We introduce an additional phase ramp into the training sequence. For the mth training symbol, the phase is $\phi[m] = m\frac{\pi}{N_t} + \psi[m]$ where $\psi[m]$ is the phase due to the signaling, N_t is the number of training symbols.



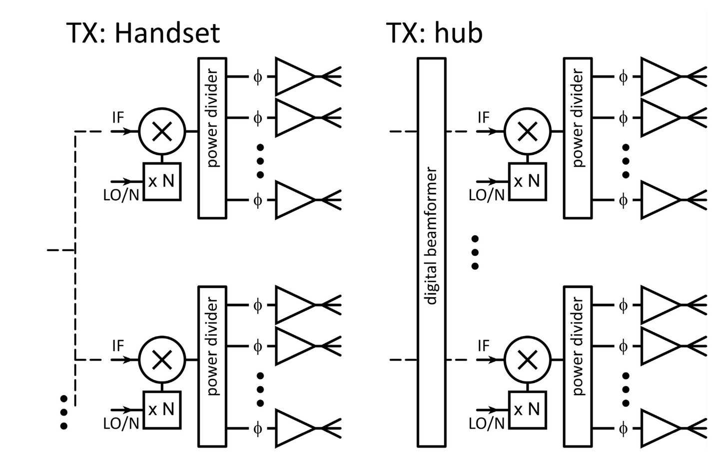
DFT magnitude vs spatial frequency plot of a mixture of two users with fundamental spatial frequencies 0.1 and 0.3. SNR per antenna element is 6 dB for both users. We see a harmonic mixture component stronger than the fundamental of user 2.

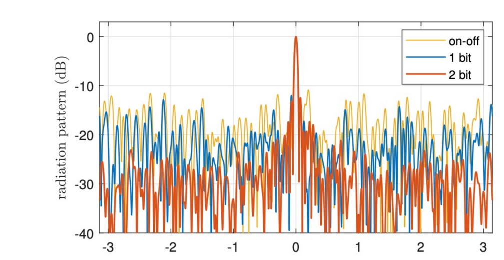


Training sequences with a ramped phase successfully isolate the fundamental spatial frequencies for both users.

Radically simplified RF beamforming

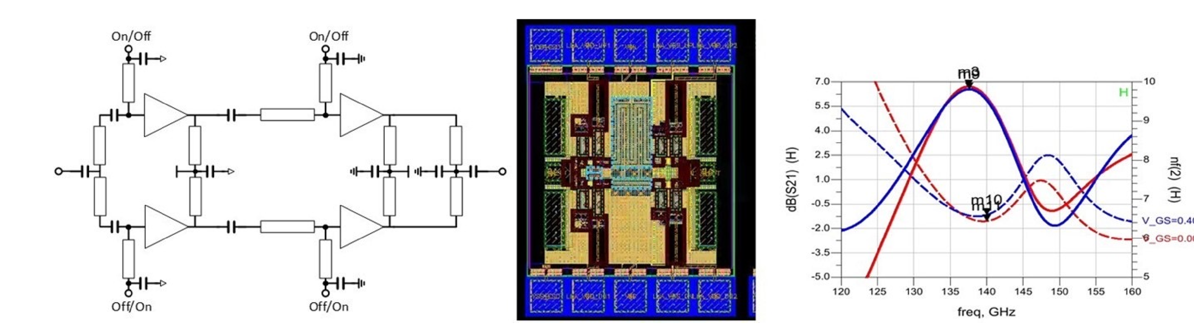
- Scaling the number of antennas ➔ packaging challenges
- RF beamformers with switched phase control ➔ compact electronics
- Tiling to create large arrays ➔ enable RF or hybrid beamforming
- CMOS electronics + dielectric lenses





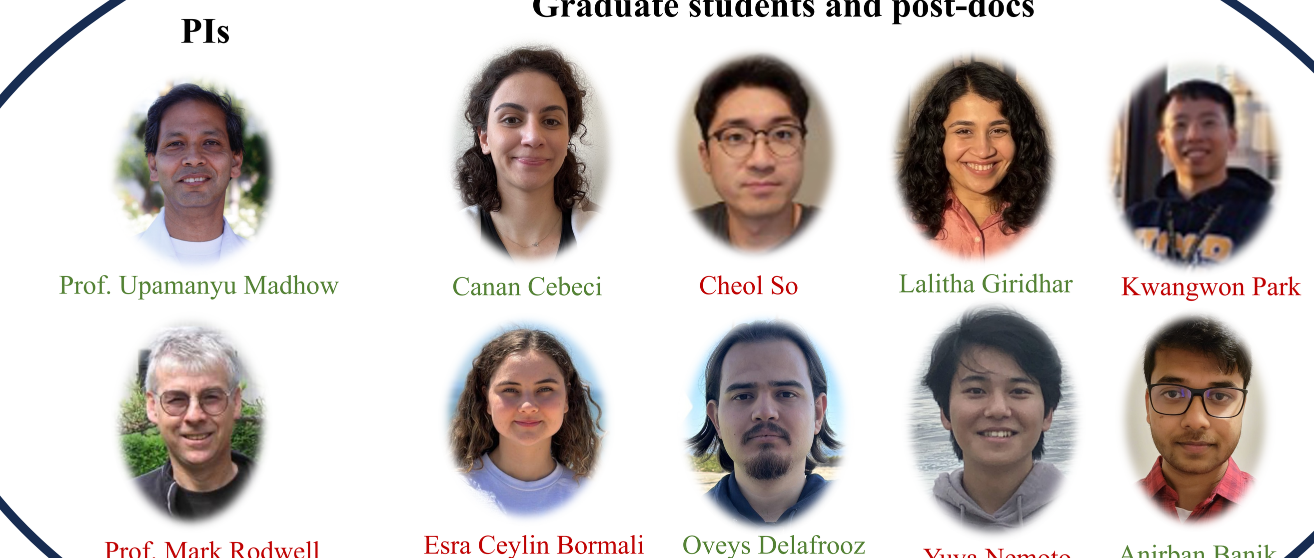
Beam patterns with switched phase control

- **Further challenges:** GF 45RFSOI process used for initial designs discontinued!



- Promising test structures in GF 45RFSOI: 6.5 dB gain, 6.5 dB noise figure, 10 mW DC power per element
- Now upgrading and transitioning designs to GF 22FDX

Interdisciplinary Team



Signal processing for wireless (Madhow group)
mmWave hardware design (Rodwell group)

Conclusion & Future Work

- System regimes matched to hardware/signal processing constrained primitives
  - Tiling, precision-constrained beamspace, RF beamforming with switched phases
  - Protocols ensuring operation at "low enough" SNR per antenna element
  - MU-MIMO, long-range backhaul, joint communication and sensing
- Tapeout and fabrication of RF beamformers (in 22FDX) with switched phase control
  - New approaches to packaging bottleneck
  - Hardware/signal processing co-design: calibration, tiled processing architectures