Qualcomm Research

New Jersey

mm-wave beam search

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Outline

- Introduction
- System Model
- Beam Search
- Beam Tracking
- Simulation Results
- Discussion
- References

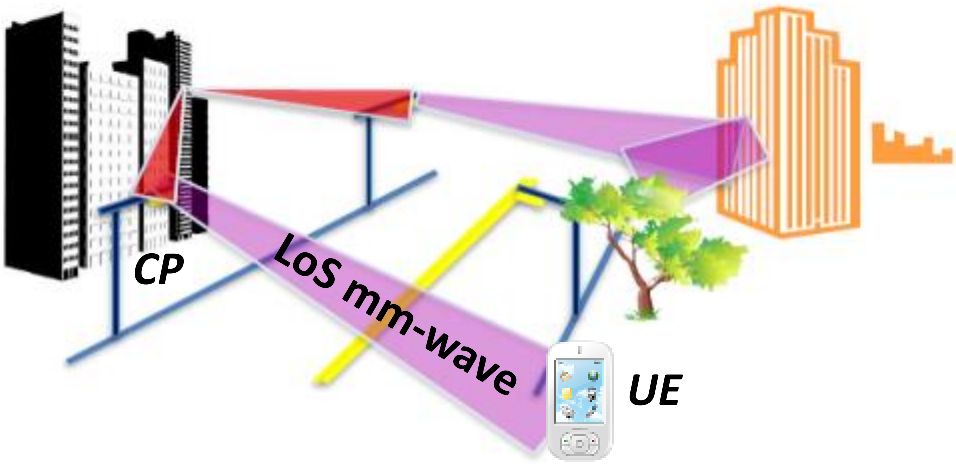
Introduction: mm-wave access

Advantages:

- Large Bandwidths
- High Antenna Density
- Integration with LTE

Challenges:

- High Path Loss
- Need for Beam Search
- Need for Beam Tracking



System Model: MIMO

$$\boldsymbol{y}[m] = \boldsymbol{H}[m]\boldsymbol{x}[m] + \boldsymbol{w}[m]$$

where $\boldsymbol{H}[m] \in \mathbb{C}^{N_R \times NT}$, $\mathbf{w} \sim \mathcal{CN}(0, N_0\boldsymbol{I})$

At time m:

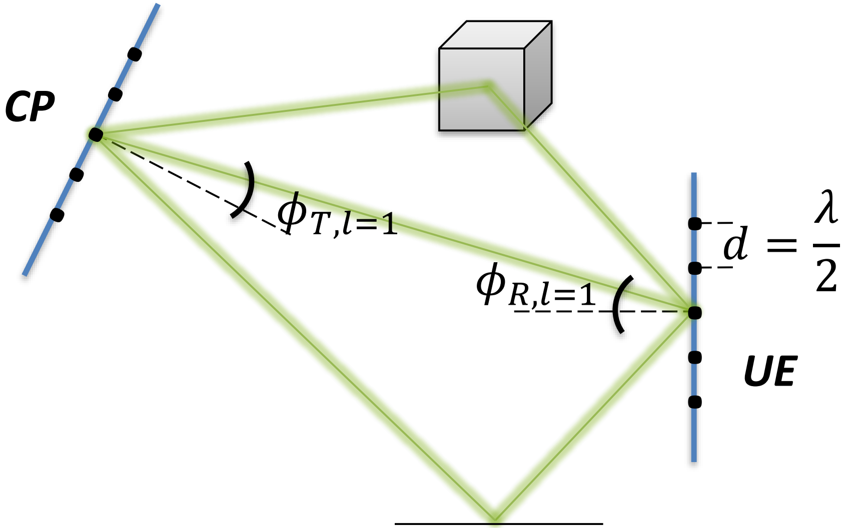
$$\boldsymbol{H} = \sum_{l=1}^{L} g_l \boldsymbol{u}_R[\theta_{R,l}] \boldsymbol{u}_T{}^*[\theta_{T,l}]$$

where $g_l \sim CN(0, \sigma^2)$, $\theta_l = \frac{d}{\lambda}\sin(\phi_l)$

and $\boldsymbol{u}[\theta] = \left[\boldsymbol{e}^{-j2\pi\frac{\theta k}{N}}\right]$ with

$k \in \left\{i - \frac{N-1}{2}:\ i = 0, \ldots, N-1\right\}$.

Uniform Linear Array (ULA)



System Model: Channel

- Channel model is based on outdoor measurements in NYC [2]:

  Carrier: 28 GHz **BW**: 1.3 GHz

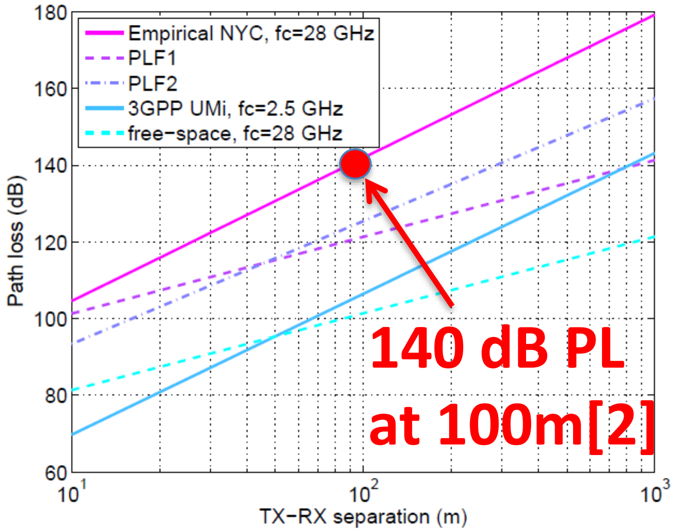
  $\mathbf{P_{TX}}$ (UE): 20dBm $\mathbf{P_{TX}}$ (CP): 30dBm

  Path Loss: 140dBm@100m

  Noise Floor: -83dBm@200MHz

  Antenna Gain: $10\log_{10}(NT \times NT)$ (2D array)

  $\mathbf{T_{COH}}$ = 0.15-2ms $\mathbf{F_{COH}}$ = 10-100 MHz



$$\boldsymbol{H} = \sum_{l=1}^{L} g_l \boldsymbol{u}_R[\theta_{R,l}] \boldsymbol{u}_T{}^{*}[\theta_{T,l}]$$

$$g_l \sim \mathcal{CN}(0, GK), GK = \frac{K}{L} 10^{-0.1PLK}$$

$$\theta \sim Unif\left[-\frac{\pi}{2}, +\frac{\pi}{2}\right]$$

Parameter	Value
K (# of clusters)	3
L (# of subpaths)	100
PL_K (path loss)	$75.85 + 37.3\log_{10} d + SK$
S_K (shadowing)	$\sim Log\mathcal{N}(0, \sigma^2), \sigma = 8.36$ dB

System Model: Beam Search and Tracking

- Beam Search:

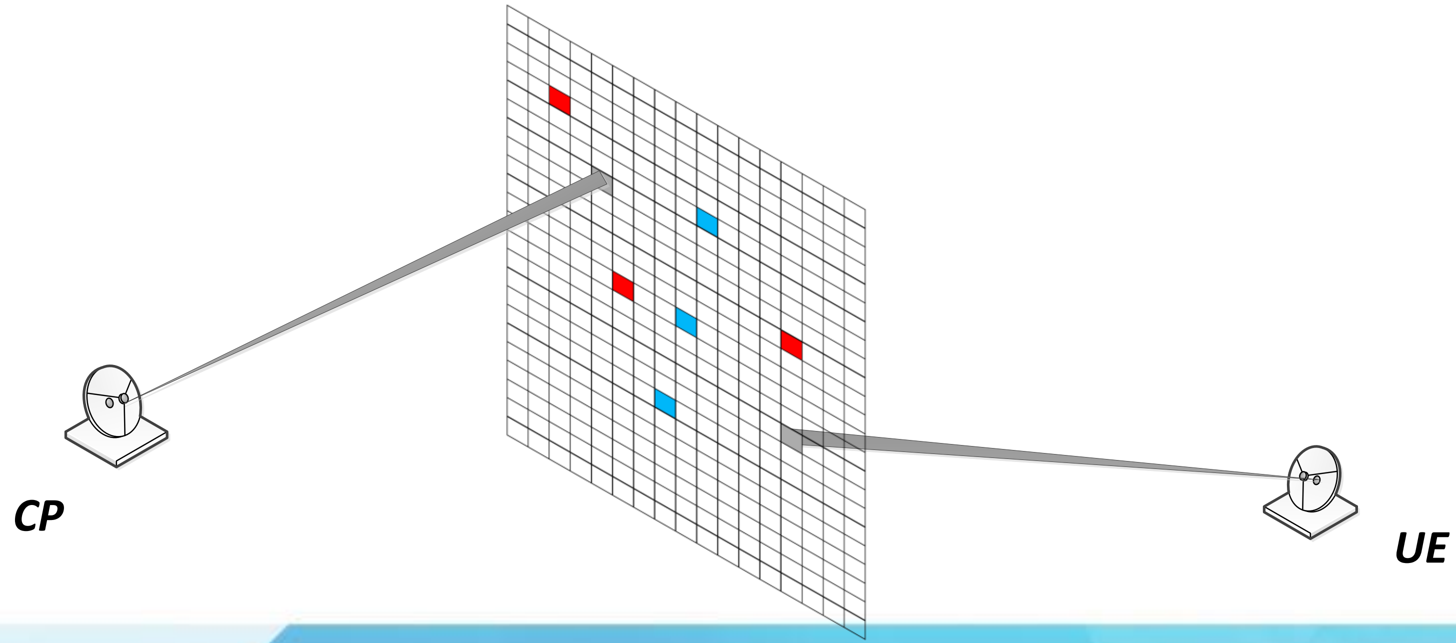
$$(\hat{\theta}_T, \hat{\theta}_R) = \underset{\left\{(\theta_T, \theta_R): -\frac{\pi}{2} \leq \theta_{T,R} \leq \frac{\pi}{2}\right\}}{\operatorname{argmax}} \mathbb{E}\left[\left|\boldsymbol{w}_R{}^*(\theta_R, m)\boldsymbol{H}[m]\boldsymbol{w}_T(\theta_T, m)\right|\right]$$

where $\boldsymbol{w}(\theta, m) = \left[\boldsymbol{e}^{-\boldsymbol{j2\pi}\frac{\theta(m)\boldsymbol{k}}{\boldsymbol{N}}}\right]$ are the beamforming vectors and $\boldsymbol{H}[m] \in \mathbb{C}^{N_R \times NT}$ channel matrix at time m.

- Beam Tracking:

$$\min_{g_l, \theta_T, \theta_R} \mathbb{E}\left\|\boldsymbol{H}[m] - \widehat{\boldsymbol{H}}[m]\right\|_F$$

- Baseline:
  - Exhaustive Search
  - Complexity: $\mathcal{O}(N^2)$



System Model: Power Allocation

- Power Allocation for Beam Tracking (full CSI):

$$C = \sum_{i=1}^{n_{min}} \log(1 + \frac{P_i |h_i|^2}{N_0}) \text{ subject to } P = \sum P_i{}^*$$

- Optimum allocation: $P_i{}^* = \left(\frac{1}{\mu} - \frac{N_0}{|h_i|^2}\right)^+$
- Let $\boldsymbol{H} = \boldsymbol{U} \sum \boldsymbol{V}^* = \sum_{i=1}^{n_{min}} \sigma_i \boldsymbol{u}_i \boldsymbol{v}_i{}^*$; $nmin = \min(NT, NR)$
- At high SINR:

$$C = \sum_{i=1}^{K} \log\left(1 + \frac{1}{K} \frac{P_i |\sigma_i|^2}{N_0}\right) \approx \mathrm{K} \times \log(\mathrm{SNR}) + \sum_{i=1}^{K} \log\left(\frac{|\sigma_i{}^2|}{K}\right)$$

$$\text{where } \mathrm{K} = \mathrm{rank}(\mathbf{H})$$

Equal Power Allocation

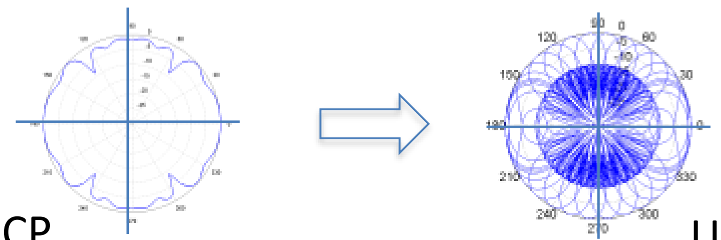
- At low SINR:

$$C = \sum_{i=1}^{K} \log\left(1 + \frac{1}{K} \frac{P_i |\sigma_i|^2}{N_0}\right) \approx SNR \left(\max_i \sigma_i{}^2\right) \log_2 \mathrm{e}$$

Strongest Eigenmode

Beam Search: M+N

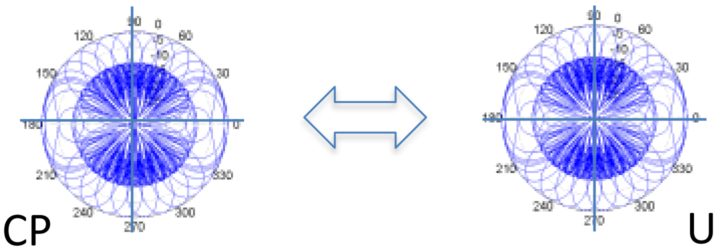
Stage 1:



CP UE

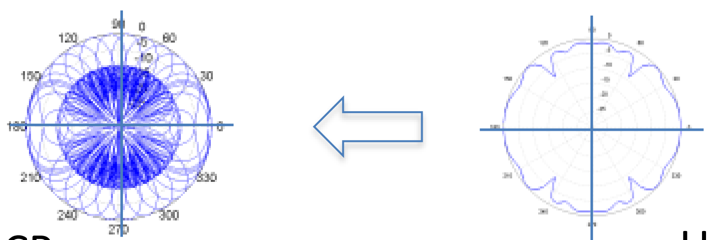
K out of N_{UE} best SINR beams

Stage 2:



CP UE

$K_{CP} \times KUE\ search$



CP UE

K out of M_{CP} best SINR beams

$$SINR_k = 10\log\left(\frac{|\boldsymbol{w}_{R,k}{}^{*}\boldsymbol{H}\boldsymbol{w}_{T,k}|^2 P_K}{\sum_{i\neq k}|\boldsymbol{w}_{R,i}{}^{*}\boldsymbol{H}\boldsymbol{w}_{T,i}|^2 + N_0}\right)$$

- Number of Messages Tx'd:

  $$M_{CP} + NUE + KCP \times KUE$$

  where $M_{CP} = 15, NUE = 15, KCP = 4, KUE = 4$

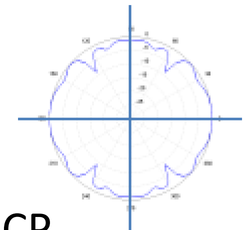
- Search Time:

  $$G_{128}M_{CP} + G_{128}N_{UE} + G_{64}(K_{CP} \times KUE) \approx \mathbf{0.35\mu s}$$

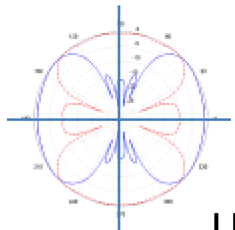
  where G_N is a Golay sequence of length N.

Beam Search: Hierarchical

Omni Stage:

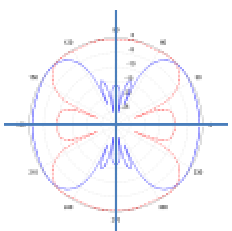


CP



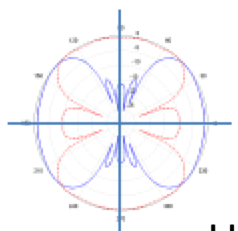
UE

max $SINR$ beam



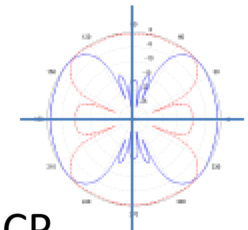
CP

max $SINR$ beam

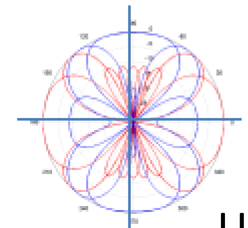


UE

Sector Stage:

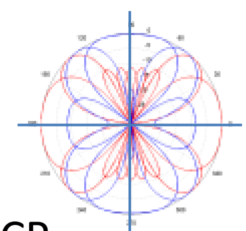


CP



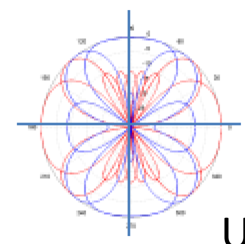
UE

max $SINR$ beam



CP

max $SINR$ beam

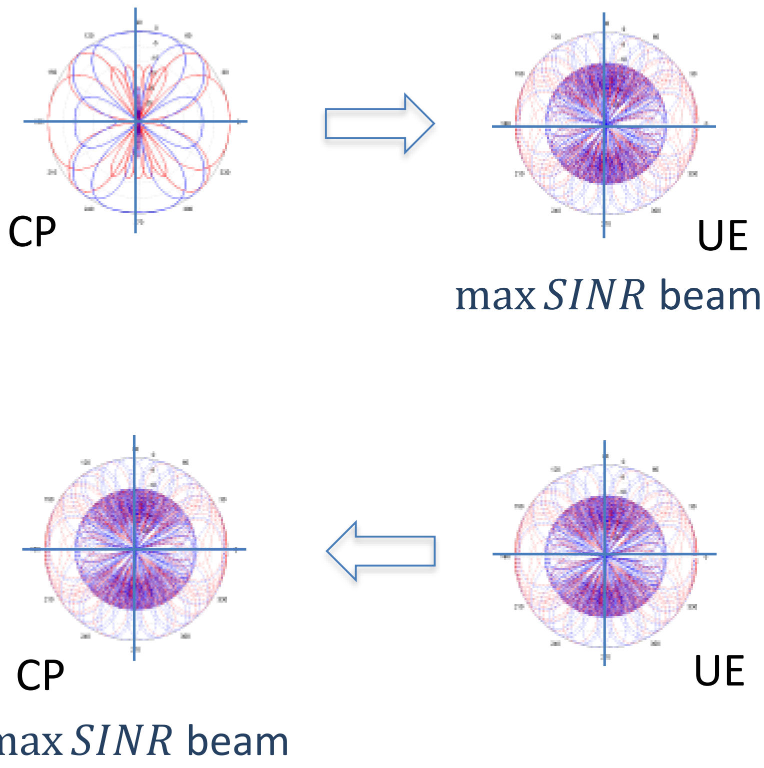


UE

$$SINR_k = 10 \log \left(\frac{|\boldsymbol{w}_{R,k}{}^{*} \boldsymbol{H} \boldsymbol{w}_{T,k}|^2 P_K}{\sum_{i \neq k} |\boldsymbol{w}_{R,i}{}^{*} \boldsymbol{H} \boldsymbol{w}_{T,i}|^2 + N_0} \right)$$

Beam Search: Hierarchical

Beam Stage:



- Number of Messages Tx'd:

  $$\mathrm{N}_{zc} + Nom_{ni} + Nse_{ctor} + Nbe_{am}$$

  where $\mathrm{N}_{zc} = 1, Nomni = 2, Nsector = 2, Nbeam = 8$

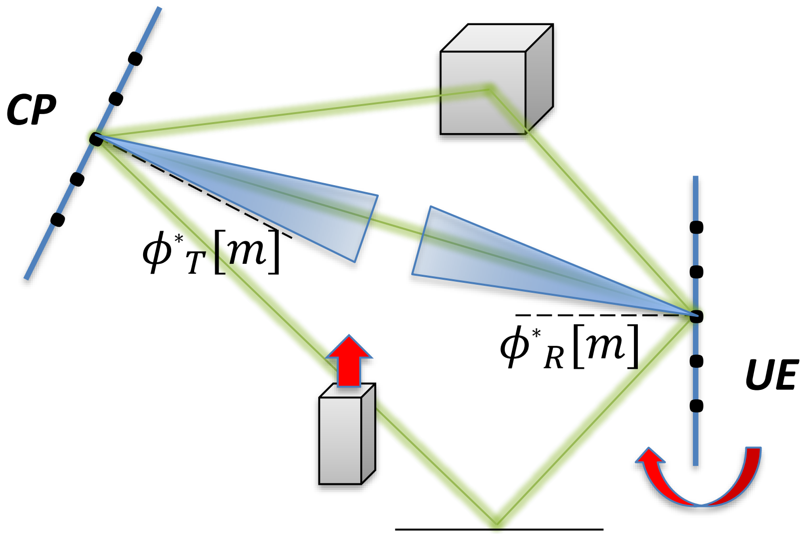
- Search Time:

  $$G_{128}(2\mathrm{N}_{zc}) + G_{128}(2N_{omni}) + G_{64}(N_{sector} + N_{beam}) + G_{32}(N_{beam}) \approx \mathbf{0.12}\ \boldsymbol{\mu s}$$

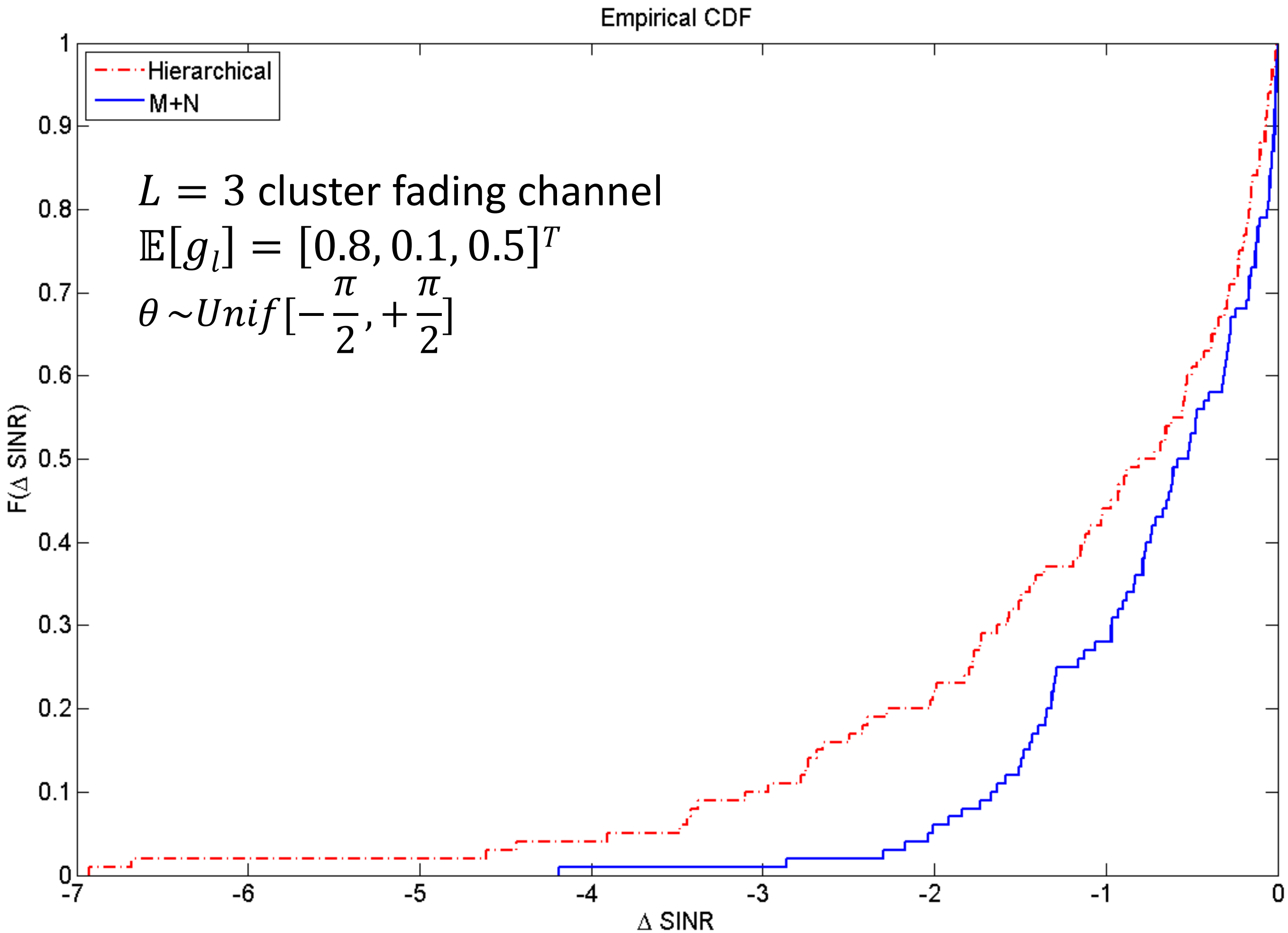
  where G_N is a Golay sequence of length N.

Beam Tracking

- Beam Switching:
  - Switch to 1 of K beams in a group of high SINR beams
  - Track SINR for the K beam group
- Additional Techniques:
  - Kalman Filter
  - Compressive Tracking [5]
  - Finite Rate of Innovation [6]

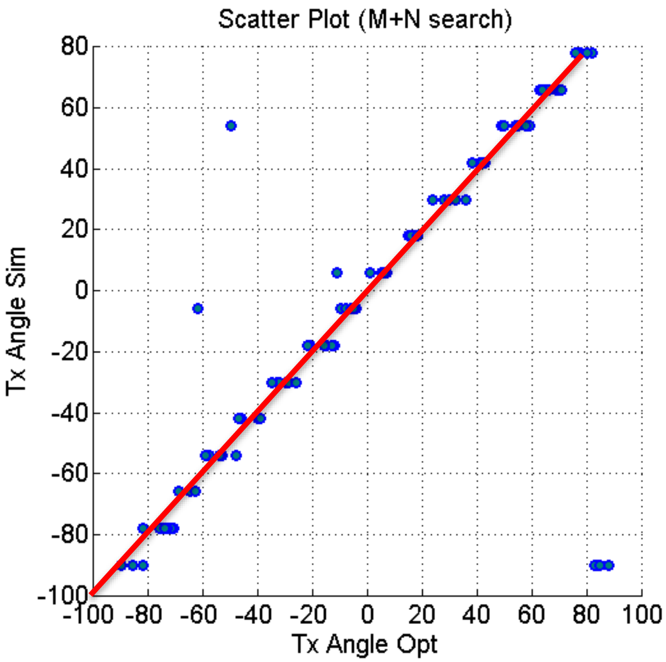


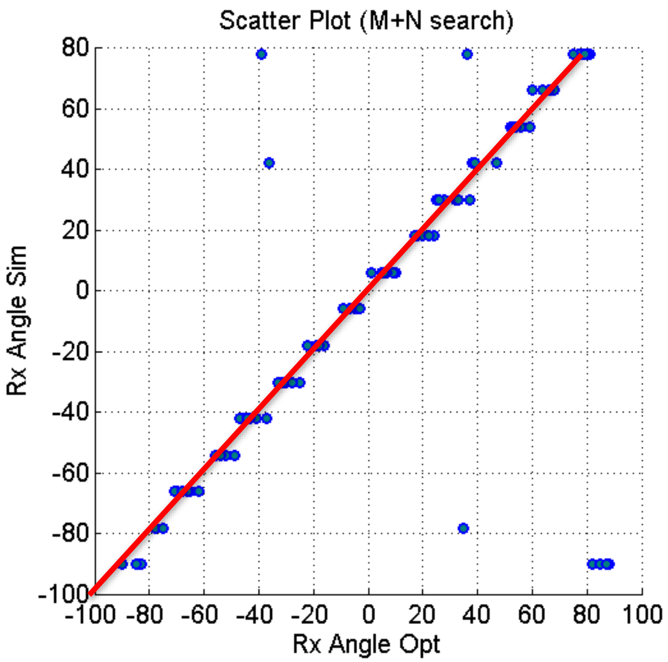
Simulation Results: Empirical CDF



$\Delta\, SINR = SINR$ beam search – $SINR$ of exhaustive search

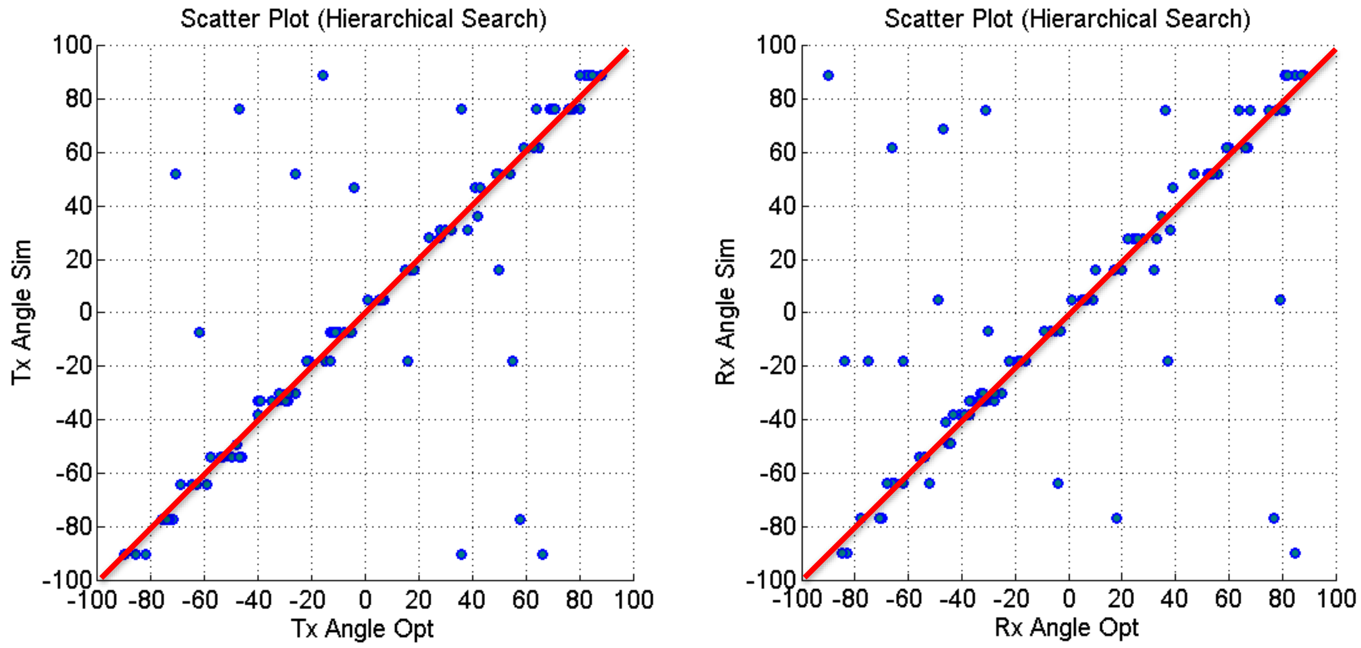
Simulation Results: Scatter Plot





If points are on the diagonal : ***M+N search*** found the correct beam angle

Simulation Results: Scatter Plot



If points are on the diagonal : ***hierarchical search*** found the correct beam angle

Discussion: Beam Search

M+N Beam Search

- $\mathbb{P}\{\Delta SINR < -3.01 \text{ dB}\} = 0.01$
- $\mathbb{P}\{\hat{\phi}_T \neq \phi_T\} = 0.07$
- $\mathbb{P}\{\hat{\phi}_R \neq \phi_R\} = 0.08$
- Simpler to configure (fewer parameters)
- Finds K strongest paths during the last search stage for beam tracking
- $T_{mpn} = 0.35\ \mu s$

Hierarchical Search

- $\mathbb{P}\{\Delta SINR < -3.01 \text{ dB}\} = 0.1$
- $\mathbb{P}\{\hat{\phi}_T \neq \phi_T\} = 0.13$
- $\mathbb{P}\{\hat{\phi}_R \neq \phi_R\} = 0.16$
- More involved: requires omni, sector and beam pattern design
- Finding K strongest paths requires re-running the full search
- Often finds 2^{nd} strongest (reflected) path resulting in higher $\mathbb{P}_{\Delta SINR}$
- $T_{hierarchical} = 0.12\ \mu s$

Similarities:

- Overlapping beams reduce $\mathbb{P}_{\Delta SINR}$
- $\mathbb{P}_{\Delta SINR}$ can be improved by increasing the number of beams at the expense of increased complexity

Discussion: Beam Tracking

Beam Tracking:

- Propagation may change very quickly due to motion, foliage blocks, hand/human body blockage (high reflectivity) [include diagram of cars and CPs from review slides or your own]
- Requires ability to quickly switch / track changing direction
- Parameter learning techniques may not be computationally fast enough.

Robustness:

- Environmental factors (e.g. wind, gust, rain) can disturb ϕ_T by $\pm 5°$
- HPBW = -10; losses expected; formula for beam width
- Beam search and tracking can be controlled at lower carrier frequencies.

Discussion: mm-wave access

- CAP-MIMO: Increasing number of antennas requires, dedicated ADC/DAC chains –infeasible as N increases (esp. for UE) [11] (Beamforming by antenna weights/phase shifts (No separate RF chains)
- Noise-limited rather than interference limited
- Large bandwidth -> power limited regime (BPSK, QPSK constellations, good PAPR properties)
- High reflectivity of materials supports outdoor-outdoor communication
- Propagation may change very quickly due to motion, foliage blocks, hand/human body blockage (high reflectivity)

Future Work

- Multiple CP simulation of UE connected to multiple CPs (network level diversity) (slide 37 review)
  - Dense deployment of CPs, fast handover, diversity at the network level
- Multiple UE simulation:
  - UE to UE relaying for UEs without strong paths to any CP
  - Inter-CP load balancing due to limited backhaul
- Research and comparison of beam tracking techniques
- Multiplication of point sources by actual antenna responses
- Extension to large antenna arrays (CP) and realistic number of antennas (UE)
- Different mobility models / studies
- Large antenna arrays with coarse beamforming
- Understanding angular diversity (averaging over available angles / DoFs)

References

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[2] M. Akdeniz, Y. Liu, S. Rangan, E. Erkip, “Millimeter Wave Picocellular System Evaluation for Urban Deployments,” *CoRR*, pp. 1-9, April 2013.

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[11] A. Sayeed, “Continuous Aperture Phased MIMO: Basic Theory and Applications”, *Allerton*, Sep. 2010

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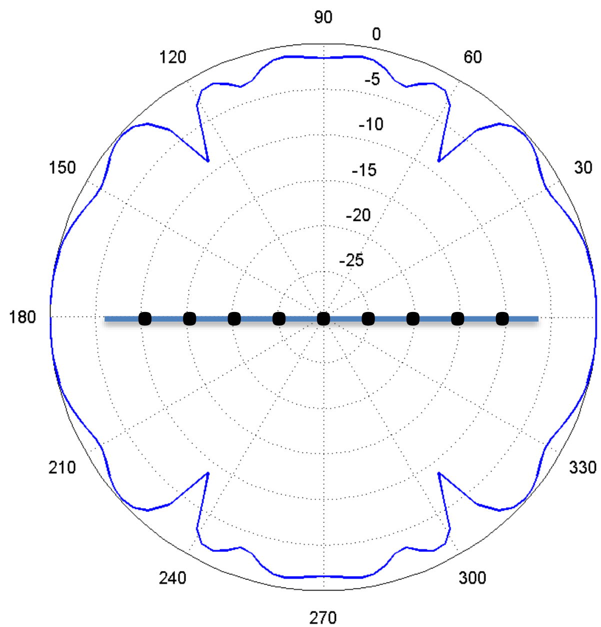
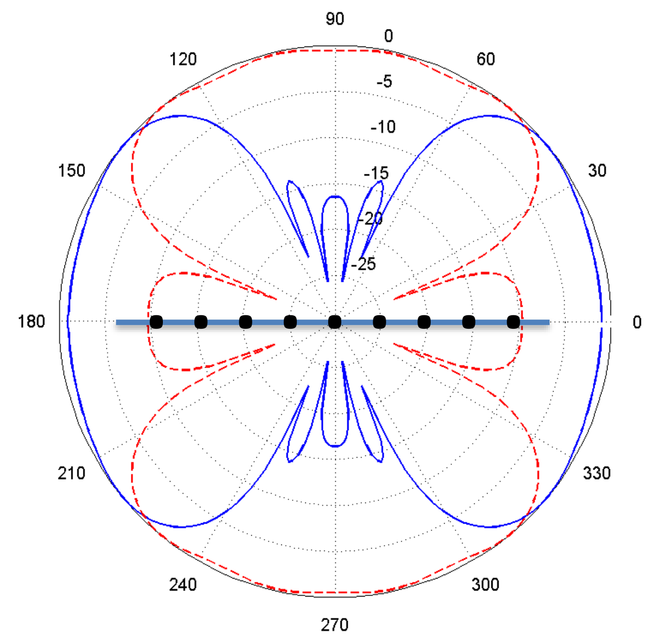
Backup Slides: Beam Patterns

Zadoff-Chu



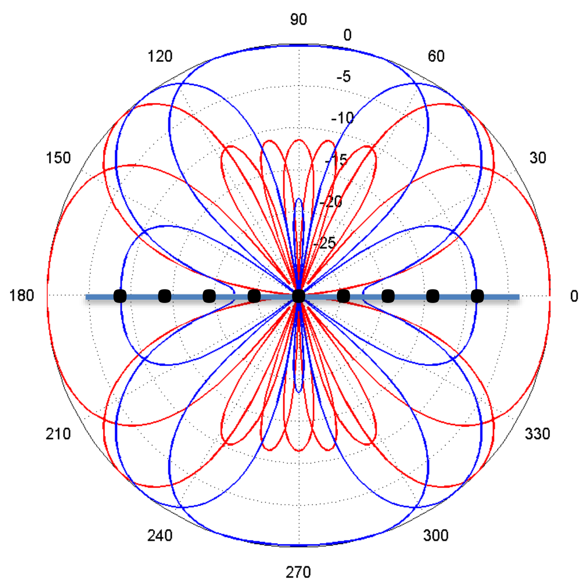
½ Omni



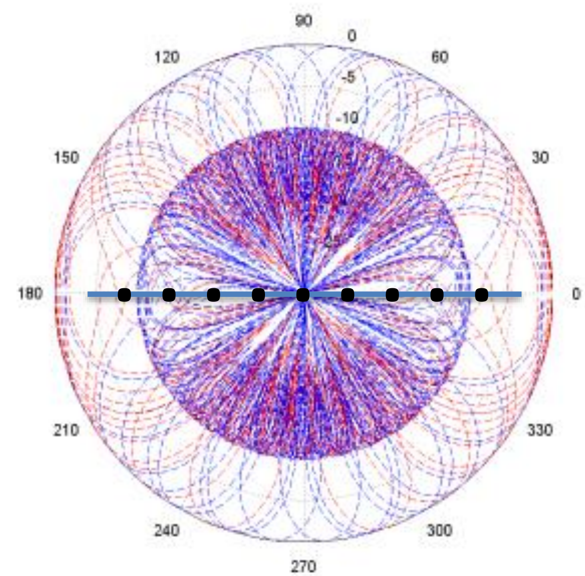
$$zc[m+1] = e^{-\frac{j\pi R m(m+1)}{N}}, for\ m = 0, \ldots, N-1$$

Backup Slides: Beam Patterns

Sector



Beam



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