Opportunistic Beam Training with Hybrid Analog/Digital Codebooks for mmWave Systems

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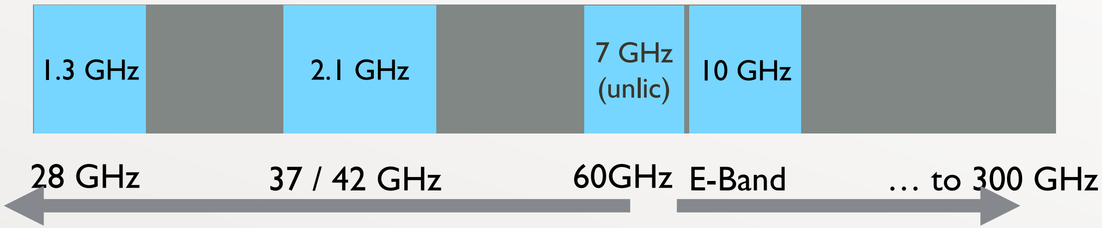
Outline

- Background and motivation
- System model
- Proposed training algorithm
- Proposed codebook design
- Results
- Conclusions

Why MIMO at mmWave?

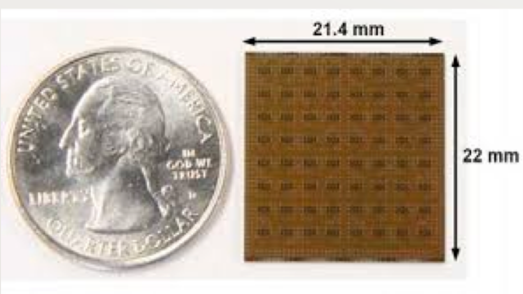
millimeter wave band possible bands used for cellular



Several GHz of spectrum provide an abundance of bandwidth to support Gpbs data rates

Small wavelength enables small-sized arrays with many antenna elements

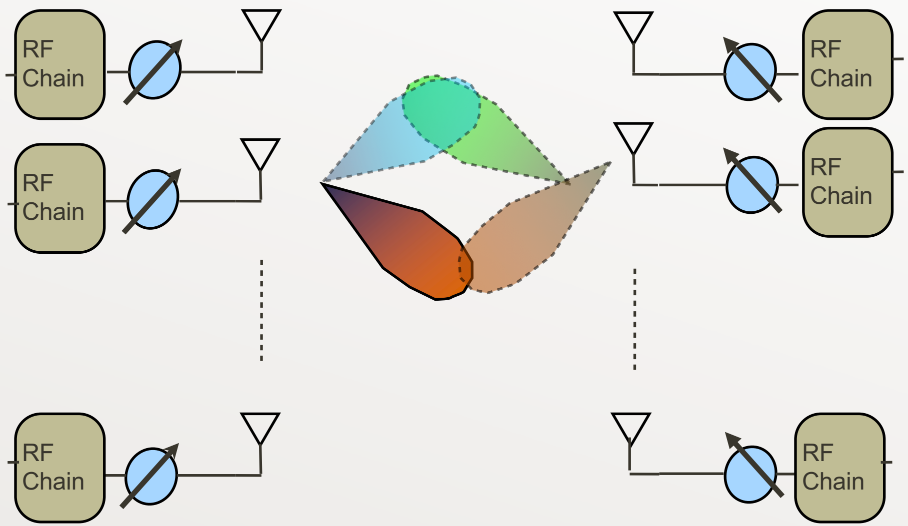
Large arrays provide high directivity to combat path loss and reduce interference



64 element phase array [2]

[1] Shu Sun, T. Rappapport, 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.
[2] S. Zihir, O. Gurbuz, A. Karroy, S. Raman, and G. Rebeiz, "A 60 GHz 64-element wafer-scale phased-array with full-reticle design," in Microwave Symposium (IMS), 2015 IEEE MTT-S International , vol., no., pp.1-3, 17-22 May 2015.

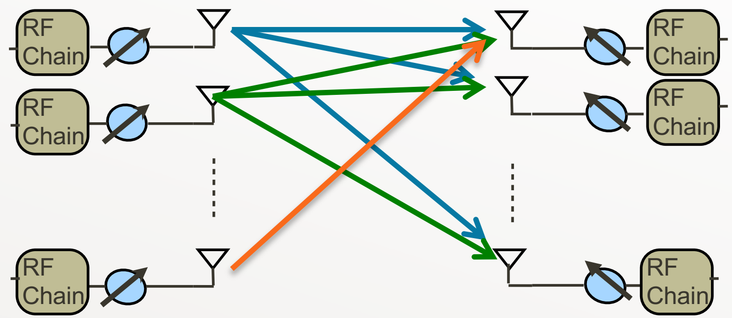
mmWave MIMO: need for channel estimation



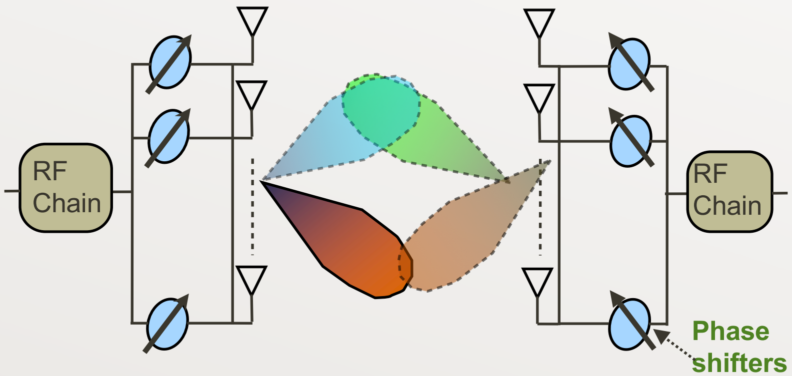
- High directivity is essential at mm-wave to combat large path loss
- Directional precoding requires channel knowledge
- Low SNR before beamforming poses channel estimation challenges

Two main directions for acquiring the channel knowledge

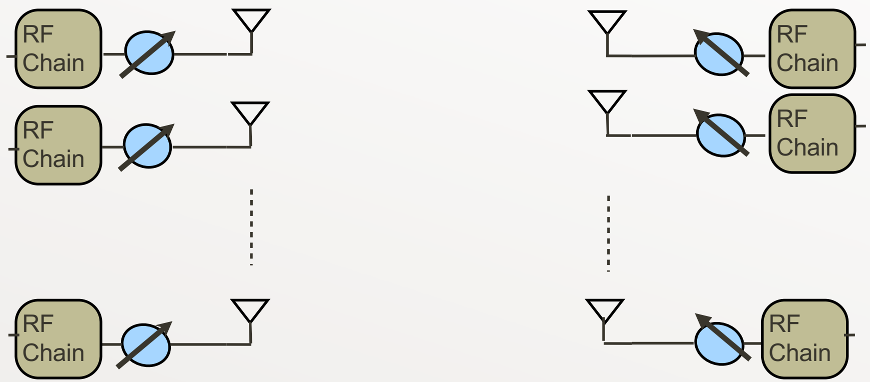
- Explicit channel estimation
  - Typically requires per antenna training
  - Low SNR before beamforming



- Beam training with analog beamforming
  - Look for best beam pair
  - High beamfoming gain
  - High beam training overhead

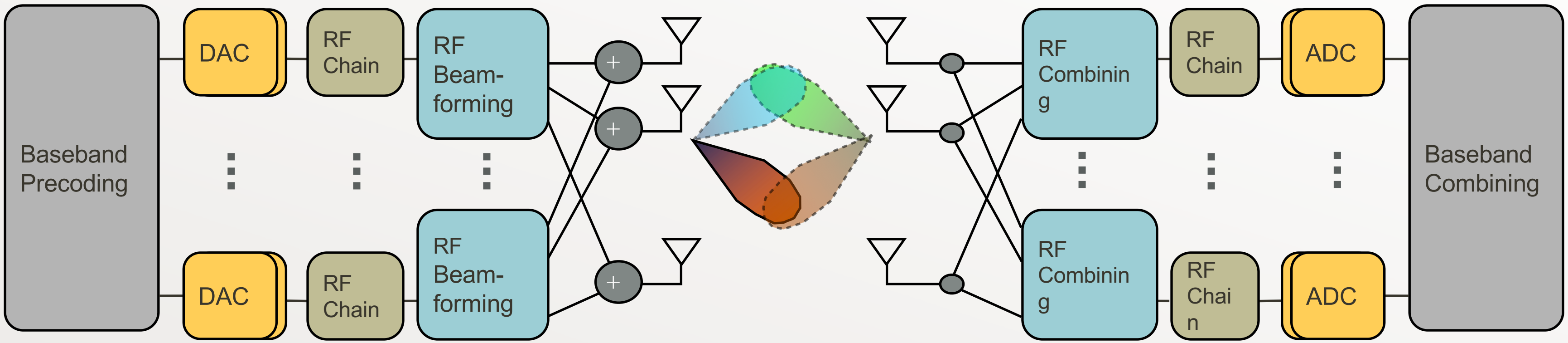


mmWave MIMO challenges



- Additional hardware issues
  - Conventional architectures does not scale
  - Array processing needs complex baseband samples
  - High cost and power consumption
  - Difficult to assign an RF chain for each antenna

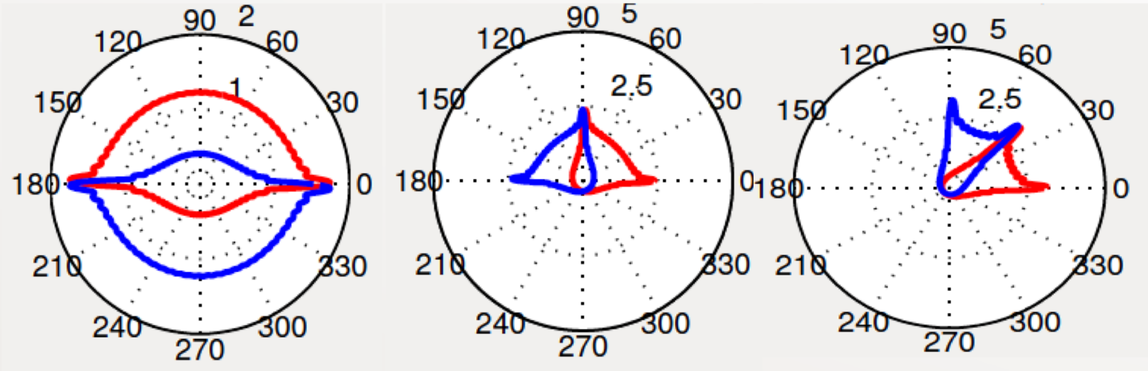
Possible solution: Hybrid Architecture



- Compromise on power consumption & complexity (# ADCs << # Antennas)
- **Problem:** Phase shifters have constraints, e.g., constant gains and quantized shifts
- Digital can correct for analog limitations [1]

[1] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499–1513, March 2014
[2] X. Zhang, A. Molisch, and S. Kung, "Variable-phase-shift-based Rfbaseband codesign for MIMO antenna selection," IEEE Trans. Signal Process., vol. 53, no. 11, pp. 4091-4103, Nov. 2005.

Hierarchical beam training



- Hierarchical beam training
  - Beam training is performed over several stages
  - Directions that maximize the SNR are examined in the next training stages
  - Requires codebook design

Prior work

- Adaptive beam training [1]-[2]
  - Do not exploit BS-MS channel reciprocity
  - Always converge to the highest resolution beams
  - May not be optimal for delay sensitive applications

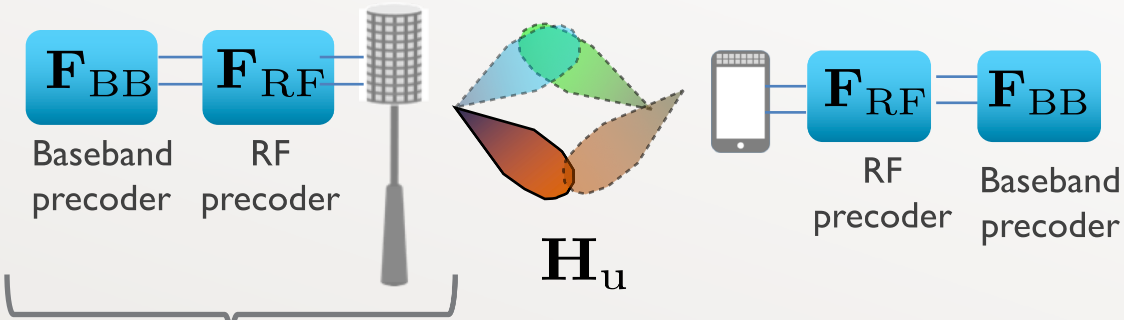
- Beam training codebooks
  - Do not consider RF constraints [1][3]
  - Array size is fixed irrespective of desired beam pattern [1]-[3]
  - Requires large number of RF chains to realize good beam patterns [2]

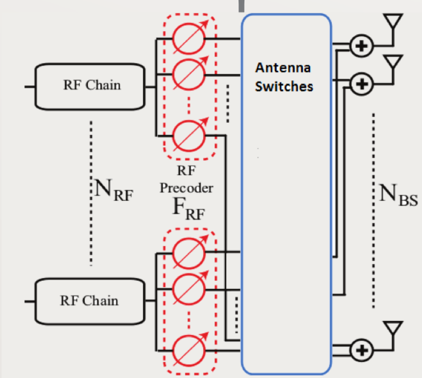
[1] S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," IEEE Trans. Commun., vol. 61, no. 10, pp. 4391-4403, Oct. 2013.
[2] A. Alkhateeb, O. Ayach, G. Leus and R. W. Heath Jr, "Single-sided adaptive estimation of multi-path millimeter wave channels," in the 15th int. Workshop on Sig. Proc. Adv. in Wireless Commun., June 2014, pp. 125-129.
[3] J. Wang, Z. Lan, C. Pyo, T. Baykas, C. Sum, M. Rahman, J. Gao, R. Funada, F. Kojima, H. Harada, "Beam codebook based beam forming protocol for multi-Gbps millimeter-wave WPAN systems," IEEE J. on Selet. Areas in Commun., vol. 27, no. 8, pp. 1390-1399, 2009.

Contributions

- Adaptive beam training
  - Opportunistic: training is terminated once a threshold is satisfied
  - Exploits channel reciprocity
  - No explicit feedback channel is required
- Hybrid codebooks
  - Respect RF constraints
  - Array size is a function of the desired beam pattern

Hybrid mmWave MIMO system model





Assumptions

- BS and MS employ hybrid analog/digital precoders
- Channels are modeled as geometric sparse mmWave channels [1][2]
- Perfect channel estimation at MS and BS

$$\mathbf{H}_u = \sqrt{N_{\mathrm{BS}} N_{\mathrm{MS}}}\,\alpha_u \mathbf{a}_{\mathrm{MS}}\left(\theta_u\right) \mathbf{a}^*_{\mathrm{BS}}\left(\phi_u\right)$$

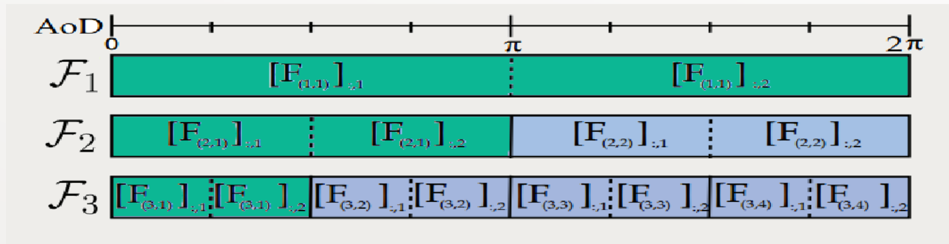
path gain (includes path-loss)

array response vectors

angles of arrival/departure (AoA/AoD)

[1] T. Rappaport, Y. Qiao, J. Tamir, J. Murdock, and E. Ben-Dor, "Cellular broadband millimeter wave propagation and angle of arrival for adaptive beam steering systems," in Radio and Wireless Symposium (RWS), Santa Clara, CA, Jan. 2012, pp. 151-154.
[2] A. Alkhateeb, O. Ayach, G. Leus and R. W. Heath Jr, "Single-sided adaptive estimation of multi-path millimeter wave channels," in the 15th int. Workshop on Sig. Proc. Adv. in Wireless Commun., June 2014, pp. 125-129.

Proposed beam training algorithm



- BS and MS form $S = \log_b K$ codebooks for multistage beam training.
- Using codebooks $F_{s=l}$ and $W_{s=l}$ the BS and MS exchange training packets
- BS and MS estimate channel gain $\Gamma_{s=l}$
- If $\Gamma_{s=l} \geq \gamma$, γ is a QoS threshold, training is terminated
- If $\Gamma_{s=l} < \gamma$, the above steps are repeated with higher codebook levels

Hybrid codebook design

- Step 1
  - Design unconstraint beam pattern as follows

$$\mathbf{f}^{*}_{(s,k,m)}\mathbf{a}(\phi_z) = \begin{cases} C_s & \text{if } z \in \mathcal{I}(s,k,m) \\ 0 & \text{otherwise} \end{cases},$$

digital beamforming vector

array response vector for one quantized angle

range of angles covered by the beam

- Step 2
  - Number of antennas is reduced in initial stages to match number of RF chains
    - Allows digital beamforming in the initial stages
  - Number of required antennas is set as

$$N^{*}_{BS} = 0.891/\sin(\theta_d/2N_{RF})$$

Proposed hierarchical codebook design

- Step 3
  - Approximate ideal pattern by solving the following problem,

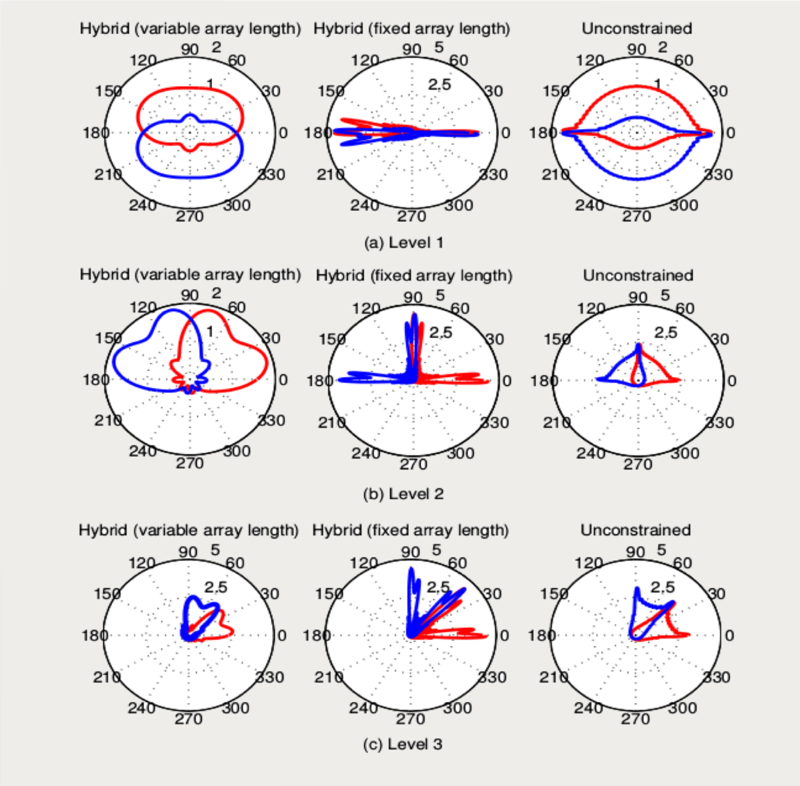
digital beamforming vector

constrained RF beamforming vector

$$
\begin{aligned}
&\{\mathbf{F}^{\star}_{\mathrm{RF},(s,k)}, \mathbf{f}^{\star}_{\mathrm{BB},(s,k,m)}\} = \\
&\arg\min \|\mathbf{f}^{\mathrm{uc}}_{(s,k,m)} - \mathbf{F}_{\mathrm{RF},(s,k)}\mathbf{f}_{\mathrm{BB},(s,k,m)}\|_F, \\
&\text{s.t.} [\mathbf{F}_{\mathrm{RF},(s,k)}]_{:,i} \in \{[\mathbf{A}_{\mathrm{can}}]_{:,\ell} | 1 \leq l \leq N_{\mathrm{can}}\}, i = 1, \cdots, N_{\mathrm{RF}} \\
&\quad \|\mathbf{F}_{\mathrm{RF},(s,k)}\mathbf{f}_{\mathrm{BB},(s,k,m)}\|_F^2 = 1,
\end{aligned}
$$

analog beamforming matrix (due to RF limitations)

Proposed codebook design- An Example



An example of several beam patterns
K = 256, N_{RF} = 4.
N^*_{BS}= 4 in (a), 9 in (b), and 18 in (c),with 6 bit angle quantization.

[1] A. Alkhateeb,O Ayach, G. Leus, and R. W. Heath Jr, "Single-sided adaptive estimation of multi-path millimeter wave channels," in the 15th int. Workshop on Sig. Proc. Adv. in Wireless Commun., June 2014, pp. 125-129.

Performance analysis

- Achievable rate is upper-bounded by

$$R \leq \log_2(1+\gamma_{\text{th}})(1-[1-e^{-\gamma_{\text{th}}/\zeta}]^L) + \int_0^{\gamma_{\text{th}}} \log_2(1+x)\frac{e^{-x/\zeta}}{\zeta L^{-1}}(1-e^{-x/\zeta})^{L-1}\mathrm{d}x$$

QoS threshold

- Training load (number of exchanged training packets) is upper-bounded by
  - For tractability, we assume L=1

$$T \leq T_o \sum_{s=1}^{S}(1-[F_{\gamma(s)}(\gamma_{\text{th}})])\prod_{i=1}^{s-1}[F_{\gamma(i)}(\gamma_{\text{th}})] + [F_{\gamma(s)}(\gamma_{\text{th}})]^s$$

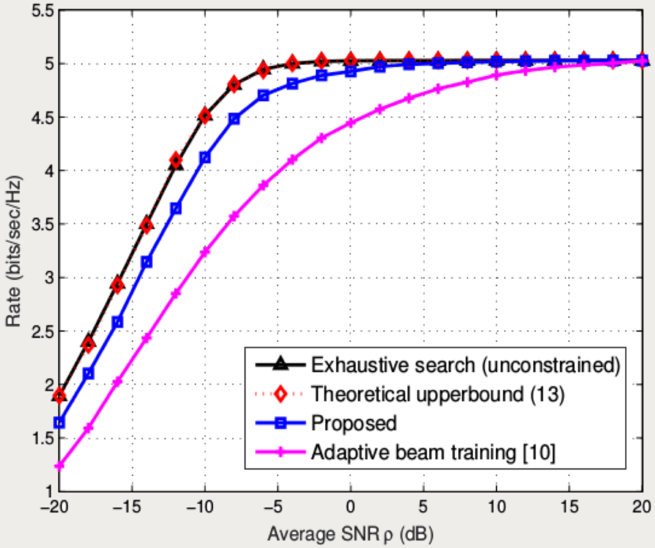
channel gain CDF at level s

maximum training load per level

captures the possibility that at the sth level the receive SNR>γ

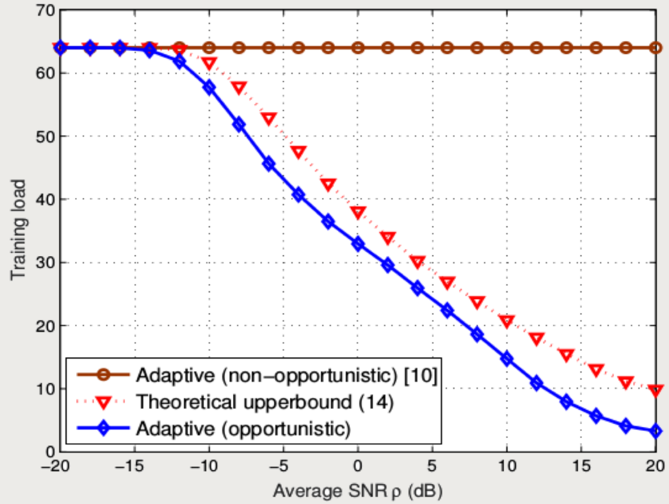
Captures the possibility that the maximum receive SNR <γ at the sth level

Simulation results



Rate versus the average SNR

N_{BS} = 32 antennas
N_{BS} = 16 antennas
N_{RF} = 4 RF chains
Phase-shifter quant. 4 bits
BS-MS link NLOS, L=3
QoS threshold γ=15 dB
AoAs/AoDs are uniformly distributed over 256 angles



Training load versus SNR. Training load for exhaustive search is 256*256

- Near-optimal rate performance compared to exhaustive search techniques
- Low training load at high SNR
- Simple & tight rate and load upper-bounds can be derived

[10] A. Alkhateeb,O Ayach, G. Leus, and R. W. Heath Jr, "Single-sided adaptive estimation of multi-path millimeter wave channels," in the 15th int. Workshop on Sig. Proc. Adv. in Wireless Commun., June 2014, pp. 125-129.

Conclusion

- Proposed an adaptive beam training algorithm for mmWave systems that
  - Exploits channel reciprocity to terminate training when a threshold is satisfied
  - Uses hybrid codebooks with variable array size to improve beam coverage
  - Achieves comparable rates to exhaustive search algorithms, with lower training overhead
- Current hybrid codebooks do not exploit array size in their design
  - Large number of RF chains are required to realize good beam patterns
  - Flexible array size yields better beam patterns with lowers RF chains

Questions?