# ADC Bit Allocation under a Power Constraint for MmWave Massive MIMO Communication Receivers

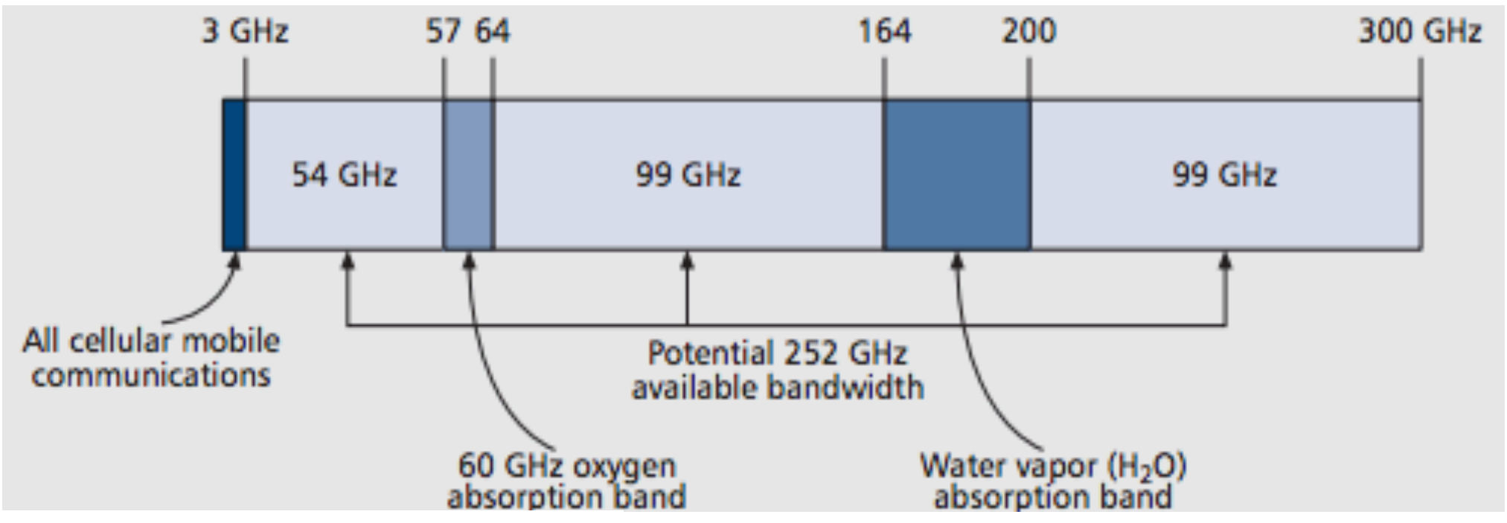
Jinseok Choi, Brian L. Evans and *Alan Gatherer
Wireless Networking and Communications Group, The University of Texas at Austin
*Huawei Technologies, Plano, Texas

## Millimeter Wave Massive MIMO

I

### Overview

- Large bandwidth to achieve multi-gigabit data rates
- Small antenna sizes due to high carrier frequency
- Large antenna arrays to compensate large pathloss



Millimeter Wave Spectrum [Pi11]

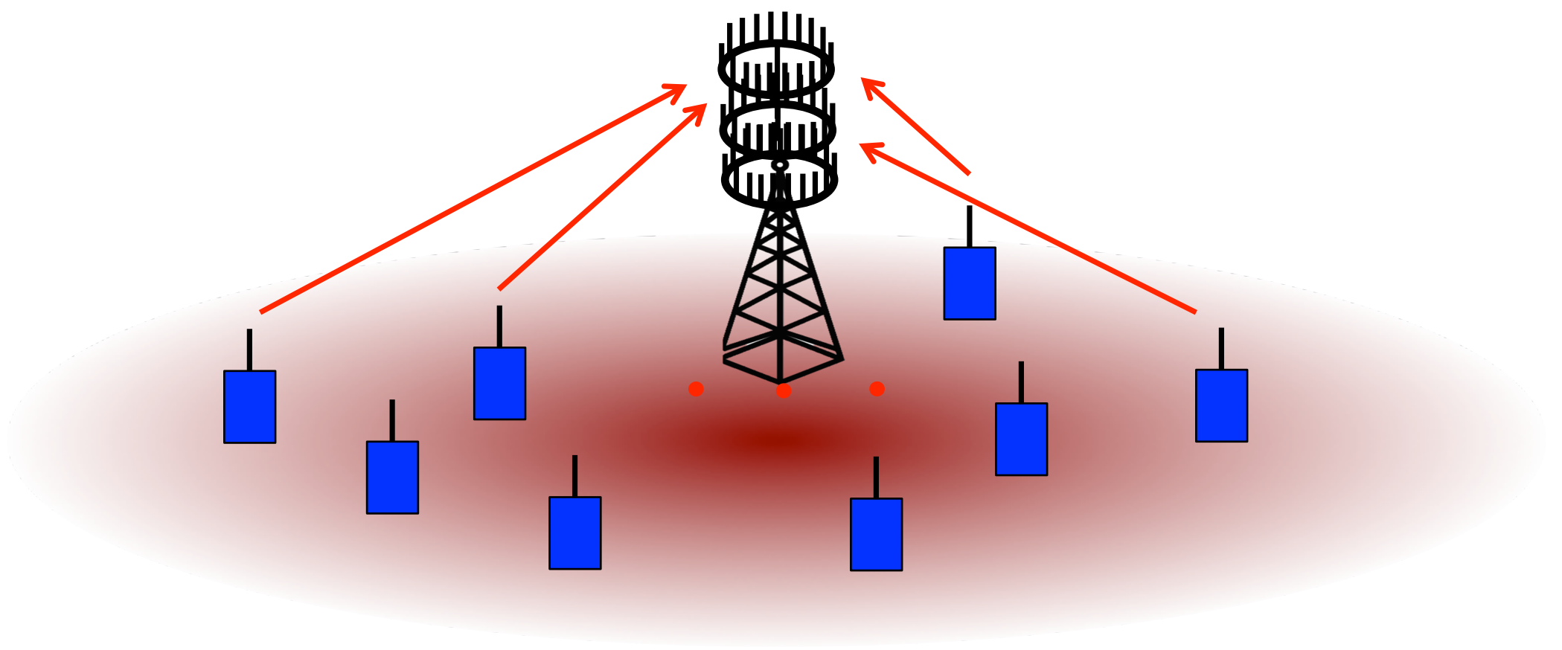
### Goal

- Reduce uplink power consumption at base station

➡ Need to reduce power consumption at ADCs

### Approach

- Exploit beamspace sparsity in mmWave MIMO channels
- Apply ADCs after analog beamforming (preprocessing)
- ADC bit allocation subject to a total power constraint
  - Some ADCs will be turned off to save power
  - Other ADCs will have a variable number of bits



Massive MIMO Communications

## Models & Assumptions

II

### Multiuser massive MIMO uplink

- *M* users, each having a single Tx antenna
- Narrowband channel
- Base station has *N* Rx antennas (*N* >> *M*) and knows channel state information $\mathbf{H}$
- Received signals in vector form

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad \text{with} \quad \mathbf{n} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_N)$$

$$\mathbb{E}[x_i] = 0 \ \text{ and } \ \mathbb{E}[|x_i|^2] = 1$$

### Millimeter wave channel

- *p* major scattering paths (limited scattering)
- Virtual channel representation under ULA*

$$\mathbf{H} = \sqrt{N/p}\,[\mathbf{a}(\theta_1), \cdots, \mathbf{a}(\theta_N)][\mathbf{h}_{\mathrm{b}1}, \cdots, \mathbf{h}_{\mathrm{b}M}]$$

$$= \sqrt{N/p}\,\mathbf{A}\mathbf{H}_{\mathrm{b}} = \mathbf{A}\mathbf{G}$$

where

$\mathbf{a}(\theta_i)$ : array response vector with $\theta_i \in [0, 2\pi]$

$\mathbf{h}_{\mathrm{b}i}$ : beamspace channel vector of *i*-th user (*p* major elements + *N-p* minor elements)

### Additive quantization noise model

- Optimal scalar minimum mean square error quantizer
- Variable number of quantization bits for each ADC

$$\mathbf{y}_{\mathrm{q}} = Q(\mathbf{y}) = \mathbf{W}_\alpha \mathbf{y} + \mathbf{n}_{\mathrm{q}}$$

$$= \mathbf{W}_\alpha \mathbf{H}\mathbf{x} + \mathbf{W}_\alpha \mathbf{n} + \mathbf{n}_{\mathrm{q}}$$

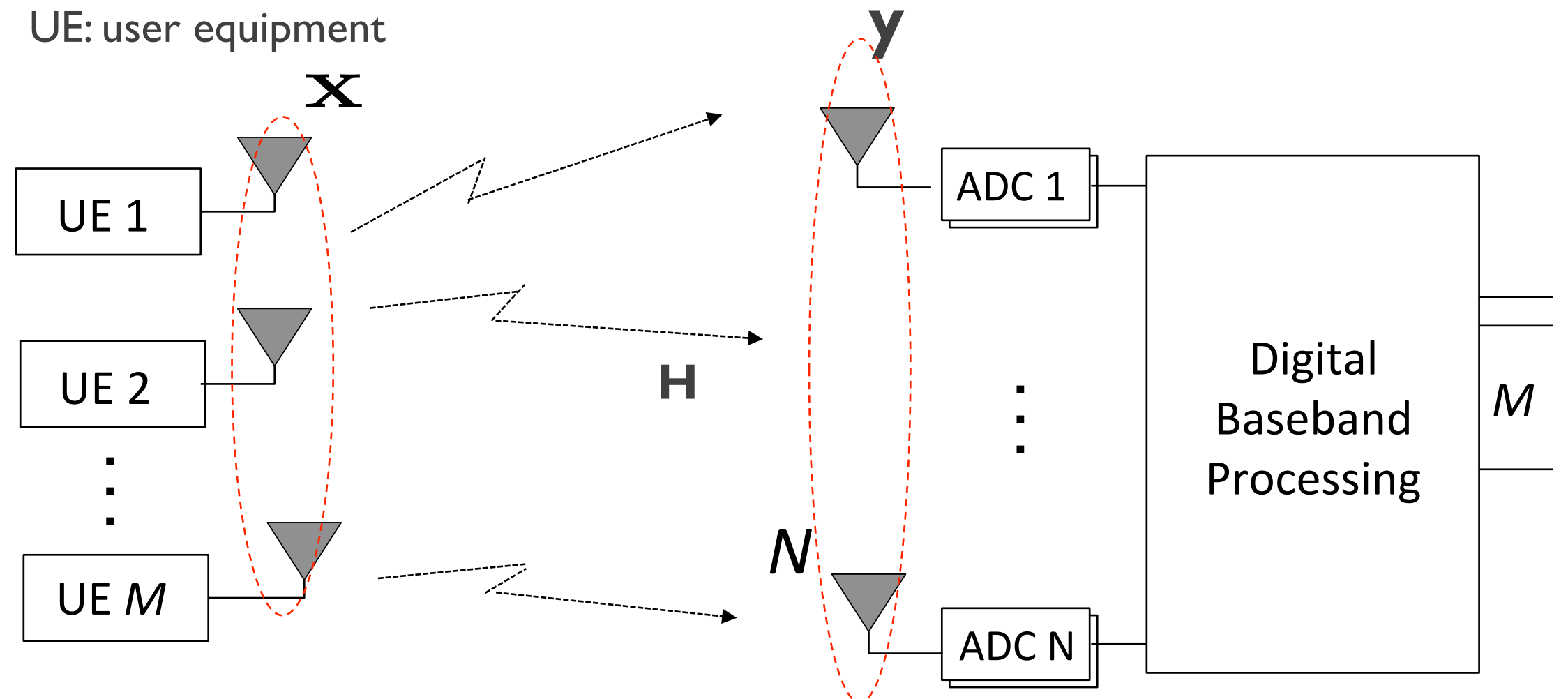
where

$\mathbf{W}_\alpha = \mathrm{diag}(\alpha_1, \cdots, \alpha_N)$

$\alpha_i = 1 - \beta_i$ : quantization gain with $\beta_i = \frac{\mathbb{E}[|y_i - y_{\mathrm{q}i}|^2]}{\mathbb{E}[|y_i|^2]}$

$\mathbf{n}_{\mathrm{q}}$: quantization noise

UE: user equipment



Multi-user massive MIMO uplink communication

* ULA: Uniform linear array

## Power Constrained ADC Bit Allocation

III

### RF Preprocessing: Beamspace projection

- Exploits the mmWave channel sparsity
- Uses an analog combiner ***F****RF* (***F****RF* = **A**; FT matrix)

$$\tilde{\mathbf{y}} = \mathbf{F}_{\mathrm{RF}}^H\,\mathbf{y} = \mathbf{F}_{\mathrm{RF}}^H\,\mathbf{H}\mathbf{x} + \mathbf{F}_{\mathrm{RF}}^H\,\mathbf{n}$$

- Applies quantization after the projection

$$\tilde{\mathbf{y}}_{\mathrm{q}} = \mathbf{W}_\alpha \mathbf{G}\mathbf{x} + \mathbf{W}_\alpha \tilde{\mathbf{n}} + \mathbf{n}_{\mathrm{q}}$$

### Relaxed MSQE* minimization problem

Includes negativity

- Relaxes (i) $\mathbf{b} \in \mathbb{Z}_+^N$ ➡ $\mathbf{b} \in \mathbb{R}^N$ (ii) $P_{\mathrm{ADC}}(b) = cW2^b$ for $\boxed{b \in \mathbb{R}}$

Convex optimization

$$\boxed{\begin{aligned} \hat{\mathbf{b}} = &\underset{\mathbf{b}=[b_1,\cdots,b_N]^\intercal}{\mathrm{argmin}} \sum_{i=1}^{N} D_i(b_i) \\ \text{s.t.} \quad &\sum_{i=1}^{N} P_{\mathrm{ADC}}(b_i) \le N P_{\mathrm{ADC}}(\bar{b}),\ \mathbf{b} \in \mathbb{R}^N. \end{aligned}}$$

with

Quantization bits for *i*-th ADC

$$D_i(\boxed{b_i}) = \mathbb{E}[|\tilde{y}_i - \tilde{y}_{\mathrm{q}i}|^2] = \frac{\pi\sqrt{3}}{2}\sigma_{\tilde{y}_i}^2\, 2^{-2b_i}$$

- Power Constraint: total power of *N* $\bar{b}$*-bit* ADCs

- Solution using Karush-Kuhn-Tucker conditions:

Global optimal

$$\boxed{\hat{b}_i = \bar{b} - \log_2\left(\frac{1}{N}\sum_{j=1}^{N}\left\{\frac{1+\mathrm{SNR}_j^{\mathrm{RF}}}{1+\mathrm{SNR}_i^{\mathrm{RF}}}\right\}^{\frac{1}{3}}\right)}$$

with

$$\mathrm{SNR}_j^{\mathrm{RF}} = \frac{[\mathbf{G}]_{j,:}[\mathbf{G}]_{j,:}^H}{N_0}$$

* MSQE: Mean square quantization error

### Map solution to non-negative integers

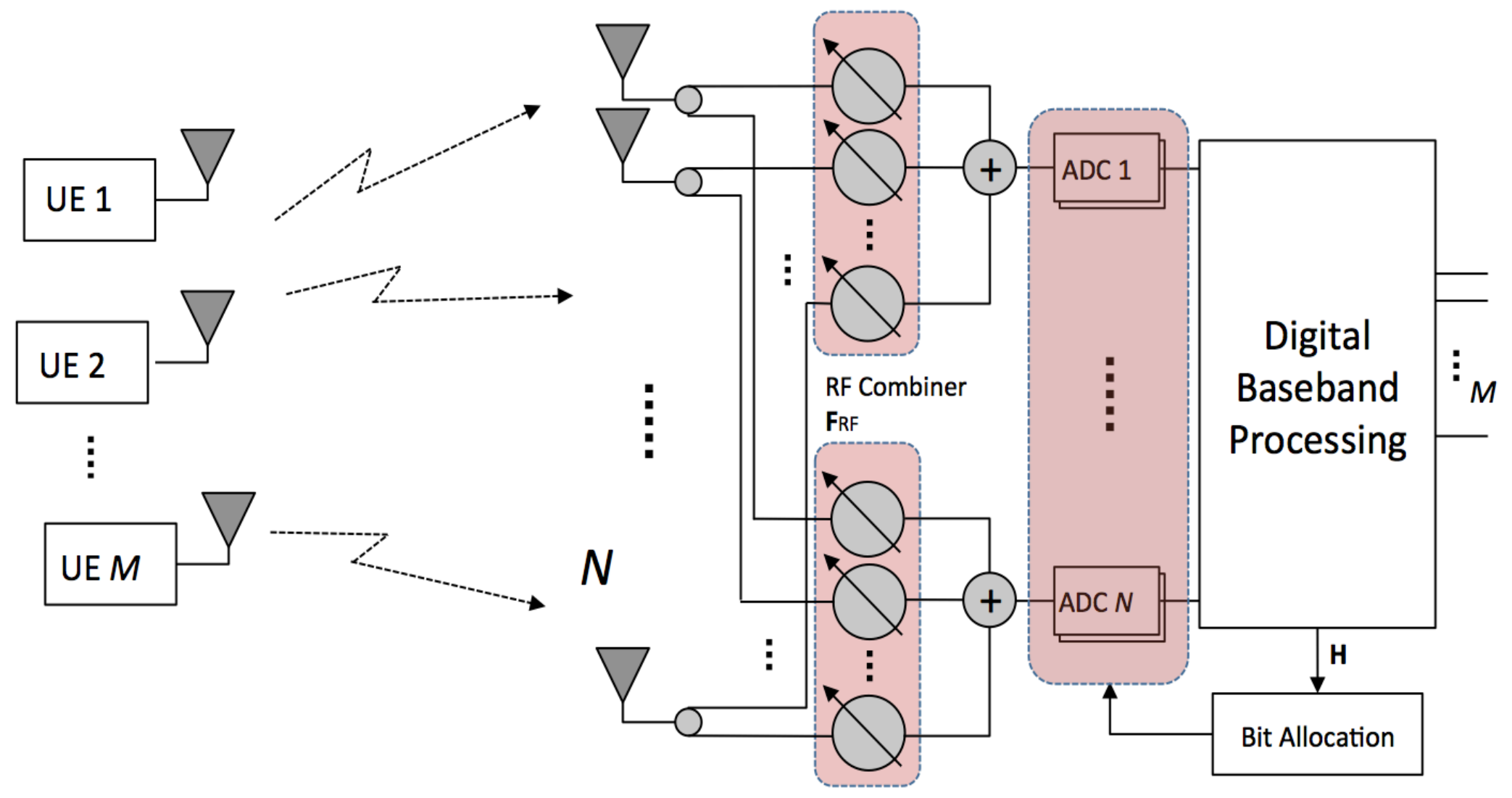
(i) *bi ≤ 0*: map to 0 because $P_{\mathrm{ADC}}(b) = 0$ for $b \le 0$

(ii) *bi > 0*: map using either floor or ceiling

- Achieve best trade-off in *MSQE vs. Power Consumption*

$$T(i) = \left|\frac{\Delta D_i(\hat{b}_i)}{\Delta P_{\mathrm{ADC}}(\hat{b}_i)}\right| = \left|\frac{D_i(\hat{b}_i) - D_i(\lfloor \hat{b}_i \rfloor)}{P_{\mathrm{ADC}}(\hat{b}_i) - P_{\mathrm{ADC}}(\lfloor \hat{b}_i \rfloor)}\right|.$$

- *T(i):* MSQE increase/unit power savings after $b_i \to \lfloor b_i \rfloor$



Proposed system diagram (RF preprocessing + ADC bit allocator)

## Validation & Contributions

IV

### Performance measure

- Error vector magnitude (EVM) for all users

$$\mathrm{EVM}\ (\%) = \frac{\|\mathbf{x} - \hat{\mathbf{x}}\|}{\|\mathbf{x}\|} \times 100\,(\%)$$

- Signal-to-noise ratio (SNR) for each user at Rx input

$$\text{SNR} = \frac{\mathbb{E}[|x_i|^2]}{N_0} = \frac{1}{N_0}$$

### Tx/Rx Settings

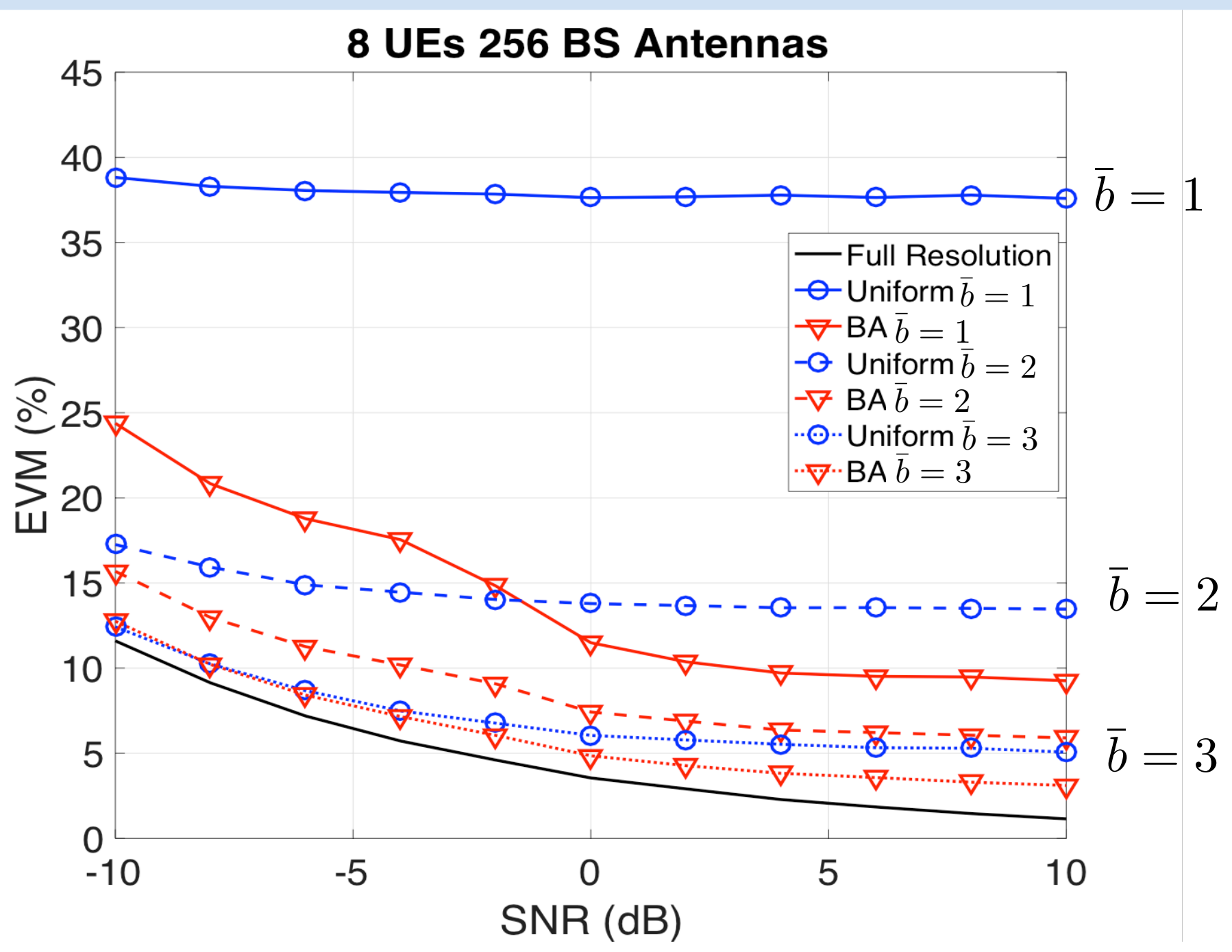
- QPSK modulation
- *M* = {8, 16} users
- *N* = 256 Rx antennas

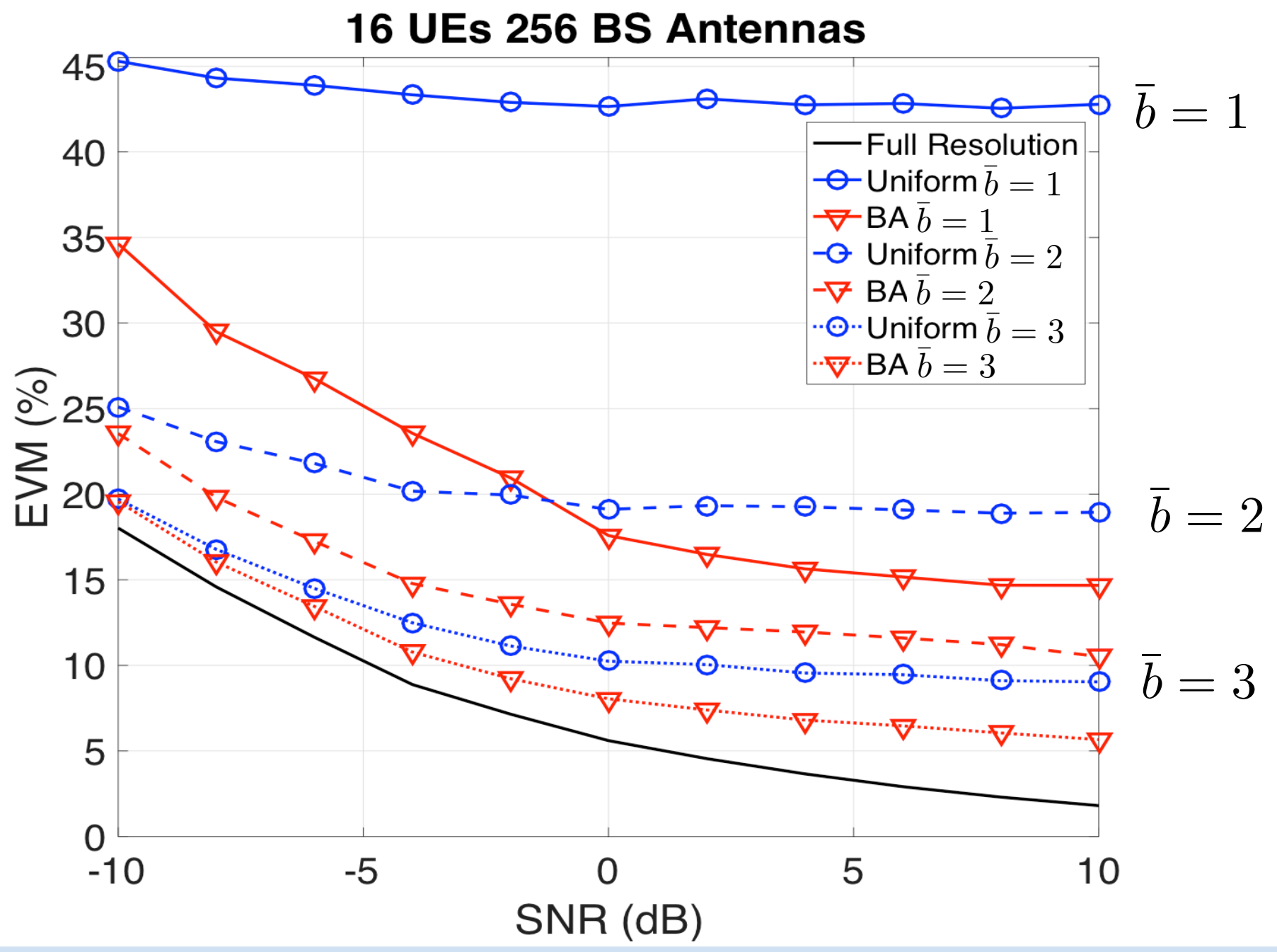
### Channel Settings [Thomas14]

- Channel: 1 cluster & 4 subpaths
- Transmission band 72-74 GHz
- Antenna spacing $\lambda/4$

### Contributions

- Low-complexity near-optimal ADC bit allocation technique
  - Consumes lower or equal power vs. all ADCs use $\bar{b}$ bits
- Simulations show EVM reduction at all Rx input SNR values
  - 50% reduction in EVM at high SNR





https://sites.google.com/site/jinseokchoi89/

The University of Texas at Austin
Electrical and Computer Engineering
Cockrell School of Engineering

Wireless Networking & Communications Group