ADC Bit Optimization for Spectrum- and Energy-Efficient Millimeter Wave Communications

Jinseok Choi, Junmo Sung, Brian Evans, and Alan Gatherer*

Electrical and Computer Engineering, The University of Texas at Austin

**Huawei Technologies*

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Motivation

Millimeter Wave Massive MIMO

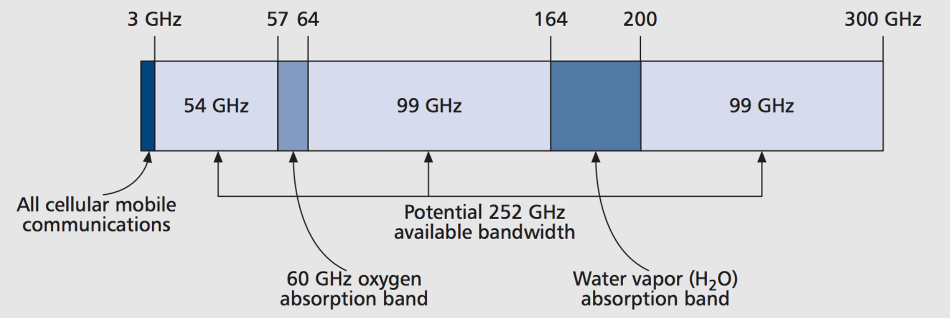
- Large bandwidth to achieve multi-gigabit data rates
- Small antenna sizes due to high carrier frequency
- **Large antenna arrays** to compensate large pathloss

Goal

- Reduce uplink power consumption at base station
  ➡ Need to reduce power consumption at ADCs

Approach

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

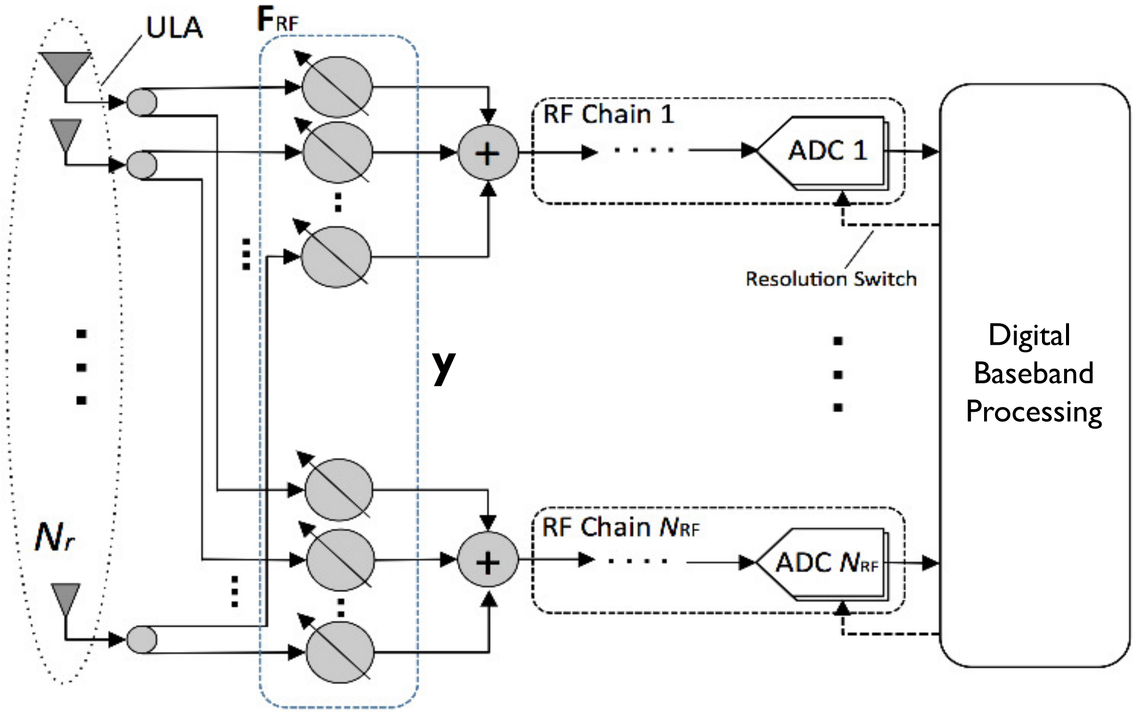


Millimeter Wave Spectrum [Pi & Khan, 11]

System Model

Multiuser Massive MIMO Uplink

- N_u users, each with single antenna
- N_r ULA* antennas at base station ($N_r >> N_u$)
- Narrowband channel $\mathbf{H}$
- Known channel state information at receivers
- Received signals after analog combining



Hybrid receiver with adaptive-resolution ADCs

Analog combiner : DFT** matrix

AWGN

$$\mathbf{y} = \sqrt{p_u}\mathbf{F}_{\mathrm{RF}}^H\mathbf{H}\mathbf{s} + \mathbf{F}_{\mathrm{RF}}^H\tilde{\mathbf{n}}$$

Tx power

User symbols

*Uniform Linear Array
**Discrete Fourier Transform

System Model

Millimeter Wave Channel

- *L* major propagation paths

Array response vector

$$\mathbf{h}_k = \sqrt{\gamma_k}\sum_{\ell=1}^{L}\omega_\ell^k \mathbf{a}(\theta_\ell^k) \in \mathbb{C}^{N_r}$$

Pathloss
Complex path gain

- Array response vector under ULA

Angle of arrival

$$\mathbf{a}(\theta) = \frac{1}{\sqrt{N_r}}\left[1, e^{-j2\pi\vartheta}, e^{-j4\pi\vartheta}, \dots, e^{-j2(N_r-1)\pi\vartheta}\right]^{\mathsf{T}}$$

where $\vartheta = \frac{d}{\lambda}\sin(\theta)$

Quantization Model [Fletcher et al., 07]

- Linear gain plus noise model
- Variable number of quantization bits

Quantization gain matrix
Quantization noise

$$\mathbf{y}_{\mathrm{q}} = \mathcal{Q}(\mathbf{y}) = \mathbf{W}_\alpha \mathbf{y} + \mathbf{n}_{\mathrm{q}}$$
$$= \sqrt{p_u}\mathbf{W}_\alpha \mathbf{H}_{\mathrm{b}}\mathbf{s} + \mathbf{W}_\alpha \mathbf{n} + \mathbf{n}_{\mathrm{q}}$$

Beamspace channel $\mathbf{F}_{\mathrm{RF}}^H\mathbf{H}$
$\mathbf{F}_{\mathrm{RF}}^H\tilde{\mathbf{n}}$

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

variance of $\mathbf{n}_{\mathrm{q}}$: $\mathbf{R}_{\mathrm{qq}} = \mathbf{W}_\alpha(\mathbf{I} - \mathbf{W}_\alpha)\mathrm{diag}(p_u\mathbf{H}_{\mathrm{b}}\mathbf{H}_{\mathrm{b}}^H + \mathbf{I})$

Problem Formulation

Minimum Mean Squared Quantization Error (MMSQE)

MSQE: $\mathbb{E}\left[|x_i - x_{\mathrm{q}i}|^2\right] = \frac{\pi\sqrt{3}}{2}\sigma_{x_i}^2\, 2^{-2b_i}$ where $\sigma_{x_i}^2 = \|[\mathbf{H}_\mathrm{b}]_{i,:}\|^2$

$$\mathbf{b}^\star = \mathrm{argmin}_{\mathbf{b}\in\mathbb{Z}_+^{N_\mathrm{RF}}} \sum_{i=1}^{N_\mathrm{RF}} \mathcal{E}_i(b_i) \quad \text{s.t.} \quad P_\mathrm{tot} \le p$$

[Choi, Evans & Gatherer, 17]
Resolution switching power consumption
$P_\mathrm{SW}(b) = c_\mathrm{sw}\left|2^b - 2^{b^\mathrm{prev}}\right|$

where $P_\mathrm{tot} = N_r P_\mathrm{LNA} + N_\mathrm{act}(N_r P_\mathrm{PS} + P_\mathrm{RFchain}) + 2\sum_{i=1}^{N_\mathrm{RF}}\left(P_\mathrm{ADC}(b_i) + P_\mathrm{SW}(b_i)\right) + P_\mathrm{BB}$

# of active RF chains $\sum_{i=1}^{N_r} \mathbf{1}_{b_i\neq 0}$

ADC power consumption $cf_s 2^b$

Challenges

N_act
$P_\mathrm{SW}(b_i)$
$P_\mathrm{ADC}(b_i)$

functions of quantization bits (N_act, P_SW involves nonlinearity)

General Approach

Offline processing ($P_{\mathrm{SW}}(b_i)$)

Step 0. Estimate switching power $P_{\mathrm{SW}}(b_i)$ as a function of power constraint *p*, $P_{\mathrm{SW}}(b) \to P_{\mathrm{SW}}(p)$

➡ Switching power becomes fixed value for given power constraint

Joint search ($N_{\mathrm{act}}, \mathbf{b}^\star$)

Step 1. Sort aggregated channel gain $\sigma^2_{x_i}$ to be $\sigma^2_{x_1} \geq \sigma^2_{x_2} \geq \cdots \geq \sigma^2_{x_{N_{\mathrm{RF}}}}$

➡ To consider RF chains with larger channel gains first

Step 2. Derive a MMSQE solution $\mathbf{b}^\star_M$ assuming first *M* RF chains used $(N_{\mathrm{act}} = M)$

➡ Closed form bit allocation solution for given *M* active RF chains

Step 3. Find optimal $M^\star \in \{1, 2, \ldots, N_{\mathrm{RF}}\}$ that provides smallest quantization error $\sum_i \mathcal{E}_i(b^\star_{M,i})$

➡ Through binary search $O(N_r) \to O(\log N_r)$

Step 4. Final solution: $\mathbf{b}^\star_{M^\star}$

➡ Closed form bit allocation solution for *M** active RF chains

Joint Binary Search

Bit allocation solution at binary search stage *s*

Convex optimization problem

# of activated RF chains at stage s

$p - P_{\mathrm{total}\backslash\mathrm{ADC}}$: Fixed value

$$\mathbf{b}^{\mathrm{s}} = \mathrm{argmin}_{\mathbf{b} \in \mathbb{R}^{M_s}} \sum_{i=1}^{M_s} \mathcal{E}_i(b_i) \quad \text{s.t.} \quad 2\sum_{i=1}^{M_s} P_{\mathrm{ADC}}(b_i) \leq \tilde{p}$$

Real number relaxation

KKT* condition

Closed-form optimal solution

$$b_i^{\mathrm{s}} = \log_2 \frac{\tilde{p}}{2c\, f_s} + \log_2 \left(\frac{\|[\mathbf{H}_{\mathrm{b}}]_{i,:}\|^{2/3}}{\sum_{j=1}^{M_s} \|[\mathbf{H}_{\mathrm{b}}]_{j,:}\|^{2/3}} \right), \quad i = 1, \cdots, M_s.$$

: function of channel gains

* Karush–Kuhn–Tucker conditions

Bit Optimization Algorithm

1) Set power constraint p ← determines P_{SW}
2) Sort channel gains to be $\sigma_{x_1}^2 \geq \sigma_{x_2}^2 \geq \cdots \geq \sigma_{x_{N_{\mathrm{RF}}}}^2$
3) Compute $M_{\max}$

$$M_{\max} = \min\left(\left\lfloor \frac{p - N_r P_{\mathrm{LNA}} - 2N_{\mathrm{RF}} P_{\mathrm{SW}}(p) - P_{\mathrm{BB}}}{N_r P_{\mathrm{PS}} + P_{\mathrm{RFchain}}} \right\rfloor, \sum_{i=1}^{N_{\mathrm{RF}}} 1_{\{h_i \neq 0\}}\right).$$

4) Set $\mathbb{S} = \{1, 2, \ldots, M_{\max}\}$
5) $\boxed{\text{Binary Search}}$ at stage s with $M_s \in \mathbb{S}$
   a) $M_s^{\mathrm{L}} = \max(1, M_s - 1),\ M_s^{\mathrm{R}} = \min(M_{\max}, M_s + 1)$
   b) For $M_s^{\mathrm{L}},\ M_s,\ M_s^{\mathrm{R}}$ $\quad b_i^{\mathrm{s}} = \log_2 \frac{\tilde{p}}{2c\, f_s} + \log_2\left(\frac{\|[\mathbf{H}_{\mathrm{b}}]_{i,:}\|^{2/3}}{\sum_{j=1}^{M_s} \|[\mathbf{H}_{\mathrm{b}}]_{j,:}\|^{2/3}}\right)$
      i. $\boxed{\text{compute } \mathbf{b}^{\mathrm{s}}}$
      Enforce positivity & append zeros
      ii. compute $\hat{\mathbf{b}}^{\mathsf{T}} = \left[\max(\mathbf{b}^{\mathrm{s}}, \mathbf{0})^{\mathsf{T}}, \mathbf{0}^{\mathsf{T}}\right] \in \mathbb{R}^{1 \times N_{\mathrm{RF}}}$
   c) compare total quantization error for $M_s^{\mathrm{L}},\ M_s,\ M_s^{\mathrm{R}}$
   d) **If** M_s has minimum total quantization error
      i. map $\hat{\mathbf{b}}$ of M_s to nearest integer, then
      ii. **return** $\hat{\mathbf{b}}$
   e) **else** go to smaller half

Joint binary search

Offline Average Switching Power Modeling

Resolution switching power estimation

: estimate average switching power as a function of total power constraint *p*

- **Training for given power constraint *p***

Step 1. Set estimated average switching power $\bar{P}_{\text{est}}$

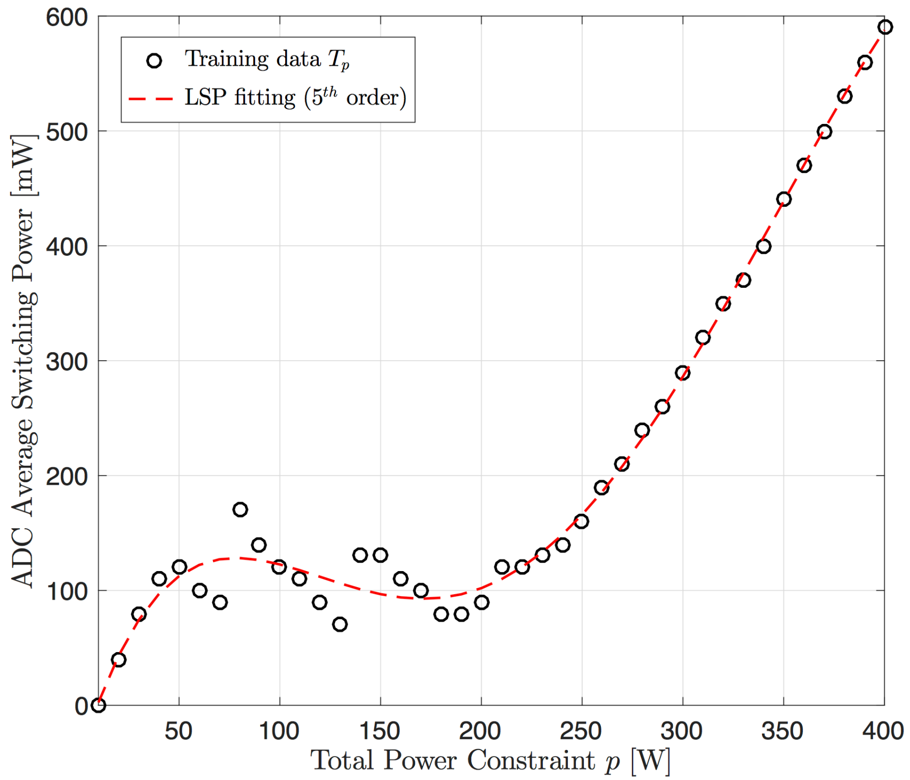
Step 2. Perform Algorithm over different channel realizations and calculate actual switching power $\bar{P}_{\text{act}}$

Step 3. Repeat Step 1 and 2 for different $\bar{P}_{\text{est}}$

Step 4. Find best estimate of average switching power

$$\bar{P}^{\star}_{\text{est}} = \text{argmin}_{\bar{P}_{\text{est}}(i)} |\bar{P}_{\text{act}}(i) - \bar{P}_{\text{est}}(i)|$$

Step 5. Set $T_p = \bar{P}^{\star}_{\text{est}}$ (training data for power constraint *p*)



- **Modeling trained data T_p**

Use least-squares polynomial to model average switching power using training data T_p

Simulation

Environment

System Parameters	
Cell radius	200 m
Min dist.	30 m
Noise fig.	5 dB
Carrier freq. f_c	28 GHz
Bandwidth	1 GHz
# Rx ant.	256
# RF chains	128
# users	10
# paths	13
Tx Power	20 dBm

Setting

- **Proposed bit allocation (BA) algorithm**
- Infinite resolution ADCs ($b_\infty = 12$)
- Fixed ADCs ($\bar{b}$-bit ADCs)
- revMMSQE-BA* [Choi, Evans & Gatherer, 17]

: Solves MMSQE subject to total ADC power constraint

Total ADC power (not receiver power)

$$\hat{\mathbf{b}} = \text{argmin}_{\mathbf{b}} \sum_{i=1}^{N_{\mathrm{RF}}} \mathcal{E}_{x_i}(b_i) \quad \text{s.t.} \quad \sum_{i=1}^{N_{\mathrm{RF}}} P_{\mathrm{ADC}}(b_i) \leq N_{\mathrm{RF}} P_{\mathrm{ADC}}(\bar{b})$$

Fixed ADC bits

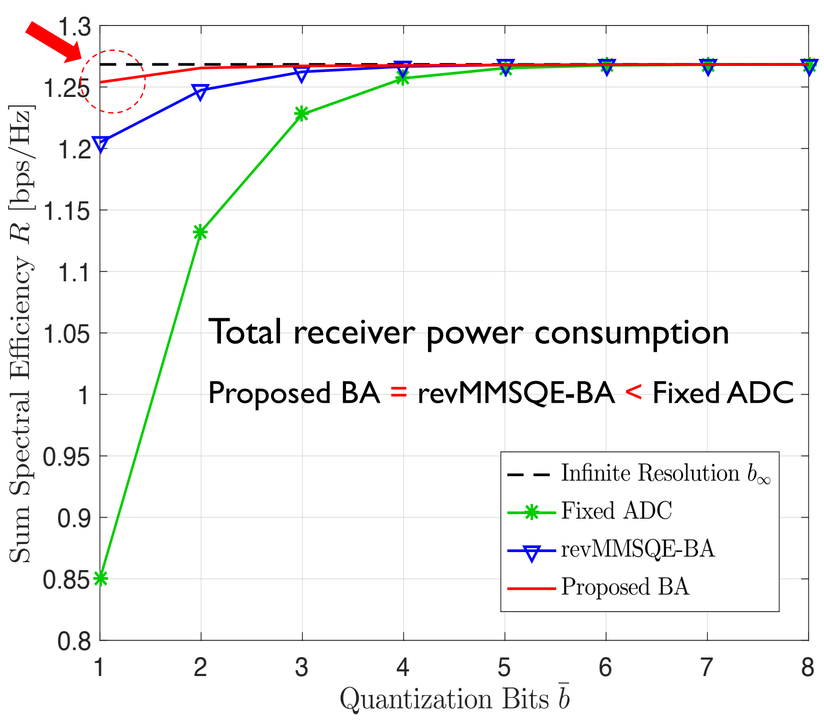
Resulting total receiver power from revMMSQE-BA

➡ Power constraint for proposed BA algorithm

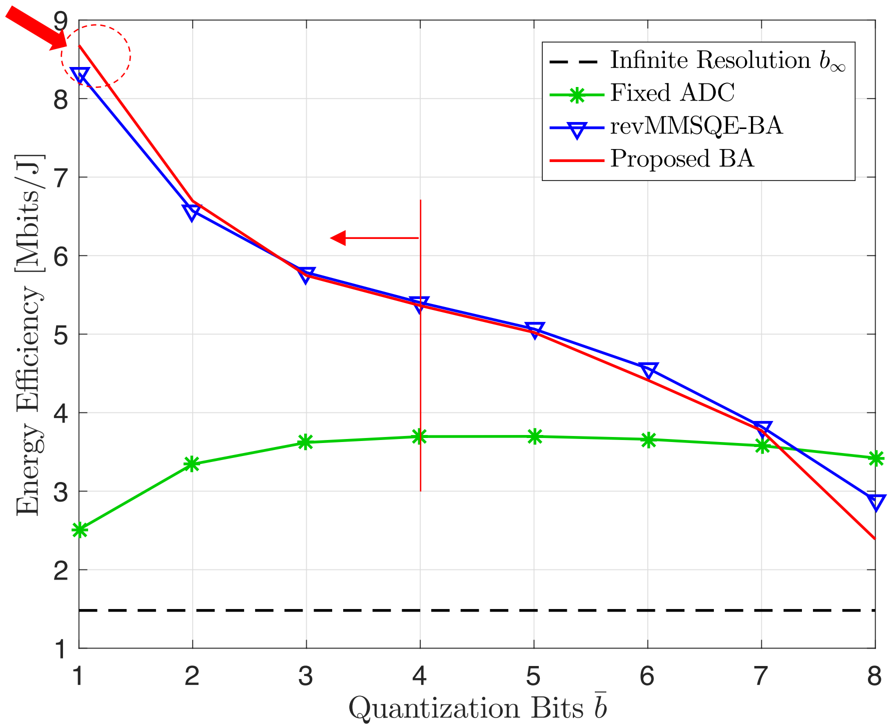
*Bit Allocation

Simulation

Spectral Efficiency with MRC



Energy Efficiency $\eta_{\text{EE}} = \frac{RW}{P_{\text{tot}}}$ bits/Joule



Proposed Method

- Highest spectral efficiency
- Comparable to infinite-resolution at $\bar{b} = 1$
- Almost no quantization distortion at $\bar{b} = 1$

- Highest energy efficiency
- $\bar{b} < 4$ is effective region (already comparable to infinite bits)

Conclusion

Contributions

- Proposes bit optimization algorithm that solves MMSQE problem:

$$\hat{\mathbf{b}} = \operatorname{argmin}_{\mathbf{b}\in\mathbb{Z}_+^{N_{\mathrm{RF}}}} \sum_{i=1}^{N_{\mathrm{RF}}} \mathcal{E}_i(b_i) \quad \text{s.t.} \quad P_{\mathrm{tot}} \leq p$$

- Achieves **highest spectral/energy efficiency for low-resolution ADCs**
- Eliminates most of quantization distortion with **small power consumption**
- Enables **existing state-of-the-art digital combiners** to be employed
- Allows more power **for downlink communication**

Thank you

References

[1] Pi, Zhouyue, and Khan, Farooq. "An introduction to millimeter-wave mobile broadband systems." *IEEE communications magazine* 49.6 (2011).

[2] Fletcher, Alyson K., et al. "Robust predictive quantization: Analysis and design via convex optimization." *IEEE Journal of selected topics in signal processing* 1.4 (2007): 618-632.

[3] J. Choi, B. L. Evans and A. Gatherer, "Resolution-Adaptive Hybrid MIMO Architectures for Millimeter Wave Communications," in *IEEE Transactions on Signal Processing*, vol. 65, no. 23, pp. 6201-6216, Dec.1, 1 2017.