Antenna Selection for Large-Scale MIMO Receivers with Low-Resolution ADCs

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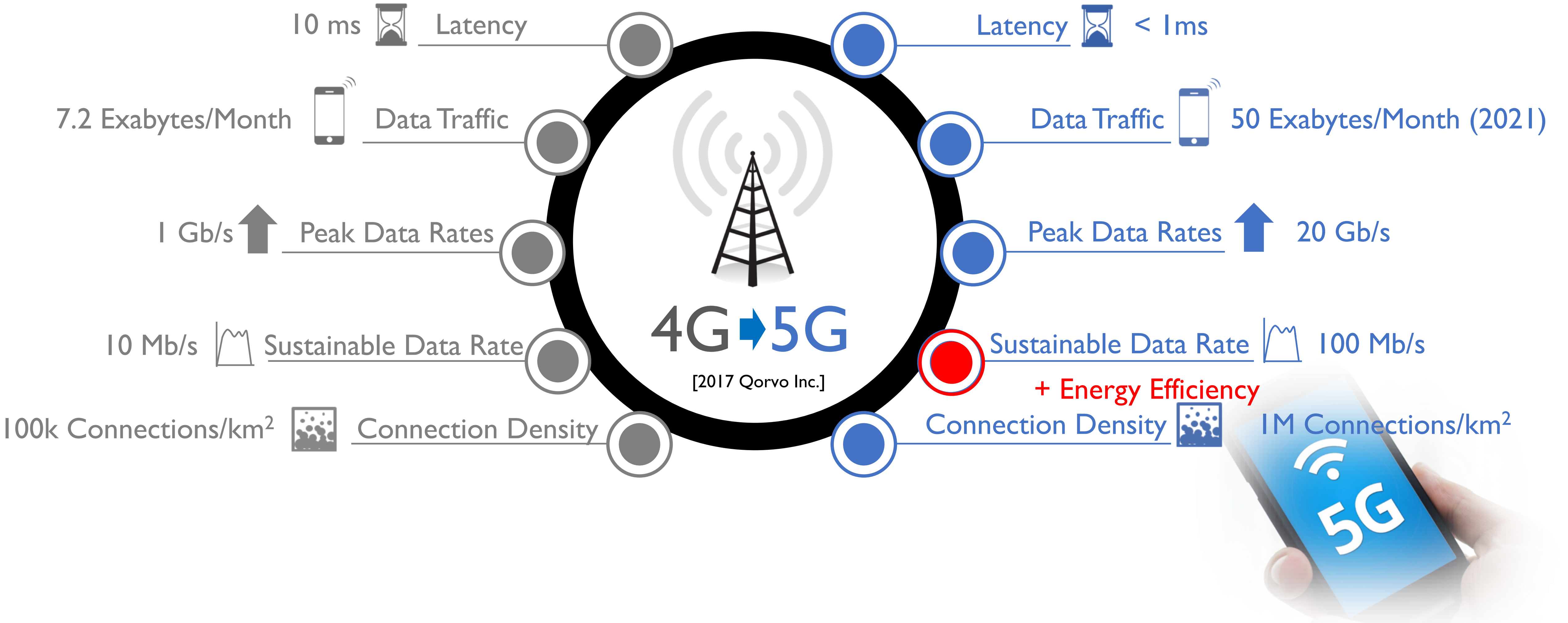
WHAT STARTS HERE CHANGES THE WORLD

Wireless Networking & Communications Group

ESPL

Vision for 5G Communications

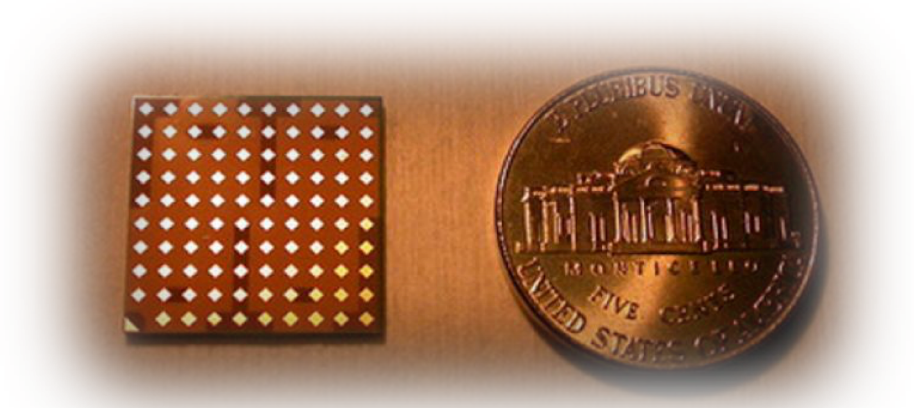


[https://www.qorvo.com/design-hub/blog/getting-to-5g-comparing-4g-and-5g-system-requirements]

Large-Scale Antenna Systems for 5G [Andrews14]

Millimeter wave communications [Pi&Khan11]

- High frequency: 30 – 300 GHz
- Large bandwidth: 100MHz – 1GHz
- Large pathloss / blockage

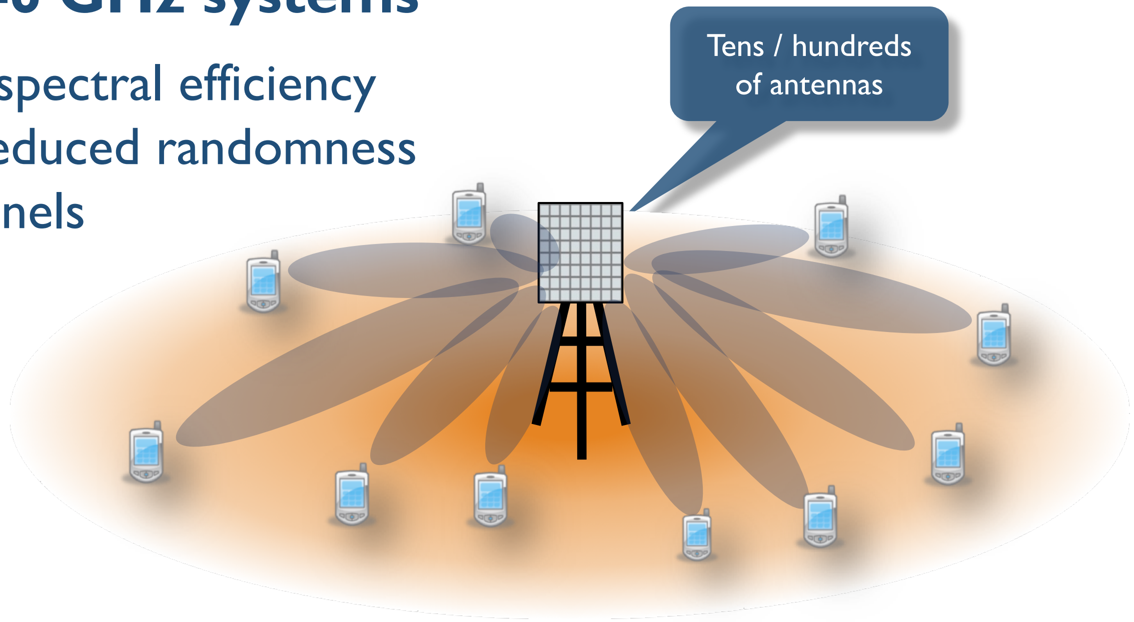


[IBM mmWave antennas]

[Bristol and Lund universities]

Massive MIMO in sub-6 GHz systems [Marzetta10]

- Substantial increase in spectral efficiency
- Channel hardening – reduced randomness
- Quasi-orthogonal channels

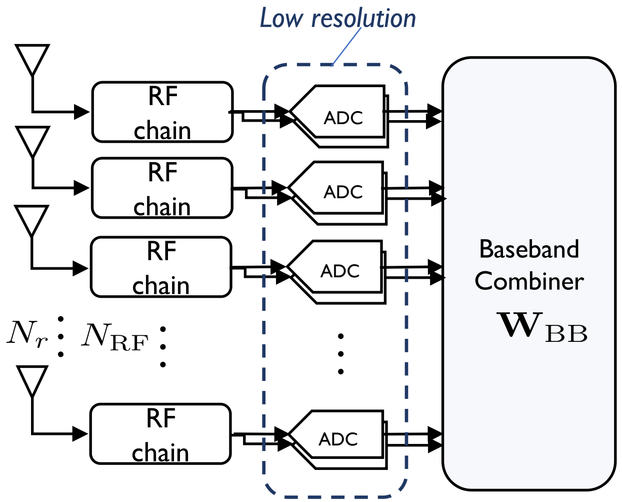


Motivation

- New energy-efficient receiver architecture

Conventional low-power solutions (A, B) | New low-power solution

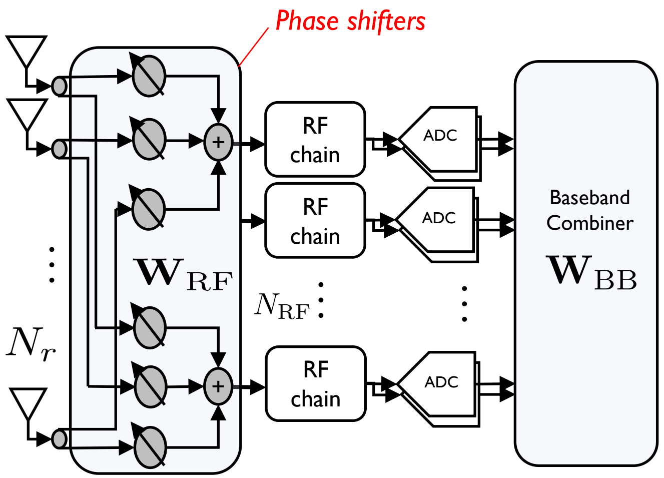
Low-resolution ADC systems



- Fixed low-resolution ADCs (<<12)
- Full RF chains ($N_{RF} = N_r$)

Focus on full RF chains ($N_{RF} = N_r$)

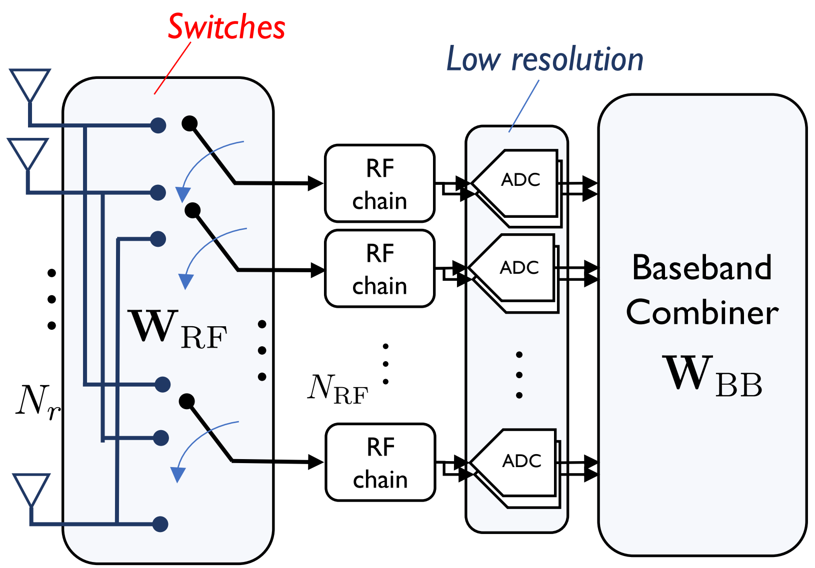
Phase shifter-based hybrid system



- Fewer RF chains ($N_{RF} \ll N_r$)
- Full resolution ADCs

Phase shifters – implementation burden

Switch-based hybrid low-resolution ADC system



Switch-based analog combiner: antenna selection

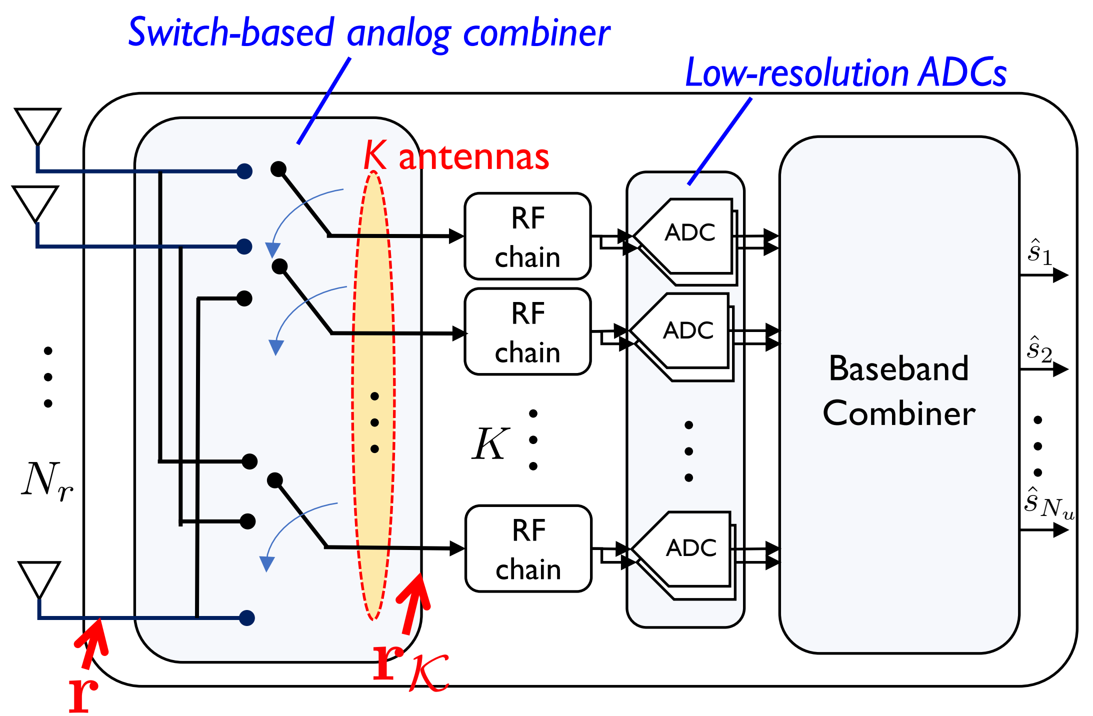
- Previous antenna selection algorithms – ignore quantization error ex. *FAS [Gharavi-Alkhansari04], **ZF-TAS [Lin&Tsai12] [Amadori15]

Develop antenna selection algorithm generalized for different quantization levels

*Fast antenna selection **Zero forcing-transmit antenna selection

System Model

Proposed receiver architecture



K antennas are selected from N_r antennas

- Multi-user MIMO uplink system
  - Single cell environment
  - N_r Rx antennas
  - Select K antennas
  - Serve $N_u \leq K$ users
  - Single-antenna user
- Rx analog baseband signal vector
  - Narrowband channel model

$$\mathbf{r} = \sqrt{\rho}\mathbf{H}\mathbf{s} + \mathbf{n}$$

Average Tx power (ρ); Channel matrix ($\mathbf{H}$); User symbols ($\mathbf{s}$); AWGN vector ($\mathbf{n}$)

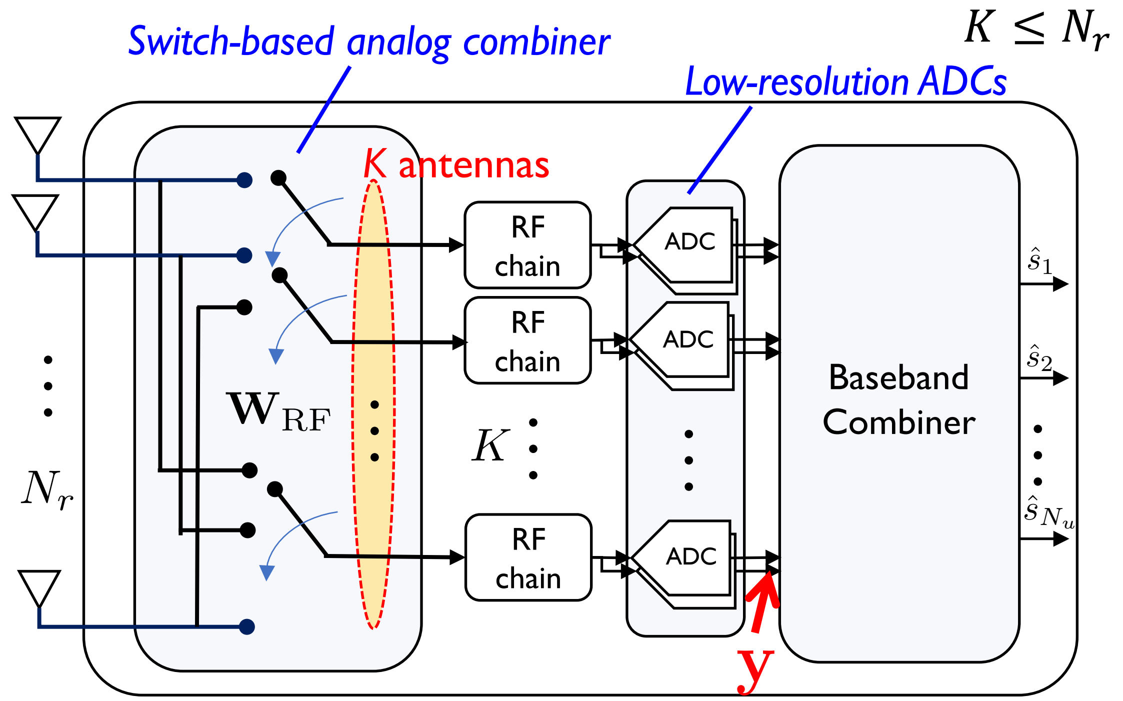
- Rx signal vector after antenna selection

$$\mathbf{r}_{\mathcal{K}} = \sqrt{\rho}\mathbf{H}_{\mathcal{K}}\mathbf{s} + \mathbf{n}_{\mathcal{K}}$$

Index set of selected antennas ($\mathcal{K}$)

System Model

Proposed receiver architecture



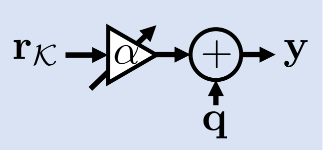
Mutual Information

$$C(\mathbf{H}_{\mathcal{K}}) = \log_2 \left| \mathbf{I}_K + p_u \alpha^2 \left(\alpha^2 \mathbf{I}_K + \mathbf{R}_{\mathbf{qq}} \right)^{-1} \mathbf{H}_{\mathcal{K}} \mathbf{H}_{\mathcal{K}}^H \right|$$

*Quantization noise variance (assumes Gaussian **q**)*

- Quantized signal vector
  - Linear approximation by using AQNM*

$$\mathbf{y} = \mathcal{Q}(\mathrm{Re}\{\mathbf{y}\}) + j\mathcal{Q}(\mathrm{Im}\{\mathbf{y}\})$$
$$= \alpha \sqrt{p_u} \mathbf{H}_{\mathcal{K}} \mathbf{s} + \alpha \mathbf{n}_{\mathcal{K}} + \mathbf{q}$$



Linear quantization gain   *Additive quantization noise*

  - Linear quantization gain

$$\alpha = 1 - \beta \; < 1$$

$$\beta = \frac{\mathbb{E}[|y - y_{\mathrm{q}}|^2]}{\mathbb{E}[|y|^2]} \approx \frac{\pi\sqrt{3}}{2} 2^{-2b}$$

  - Quantization noise covariance

$$\mathbf{R}_{\mathbf{qq}} = \alpha(1-\alpha)\,\mathrm{diag}(\rho \mathbf{H}_{\mathcal{K}} \mathbf{H}_{\mathcal{K}}^H + \mathbf{I})$$

Diagonal matrix

*Additive quantization noise model

Problem Formuation

- Mutual information maximizing antenna selection
  - Select antennas to maximize mutual information

$$C(\mathbf{H}_{\mathcal{K}^\star}) = \max_{\mathcal{K}\subset\{1,\ldots,N_r\}:|\mathcal{K}|=K} C(\mathbf{H}_{\mathcal{K}})$$

  - Approaches

Optimal Approach	Exhaustive search $\binom{N_r}{K}$ Not feasible	vs.	Suboptimal Approach	Greedy search K feasible

  - Mutual information under coarse quantization

$$C(\mathbf{H}_{\mathcal{K}}) = \log_2 \left| \mathbf{I}_K + p_u \alpha^2 (\alpha^2 \mathbf{I}_K + \mathbf{R}_{\mathbf{qq}})^{-1} \mathbf{H}_{\mathcal{K}} \mathbf{H}_{\mathcal{K}}^H \right|$$

Quantization noise variance

$$\mathbf{R}_{\mathbf{qq}} = \alpha(1-\alpha)\,\mathrm{diag}(p_u \mathbf{H}_{\mathcal{K}} \mathbf{H}_{\mathcal{K}}^H + \mathbf{I}_K)$$

Antenna selection measure needs to consider quantization error

Generalized Greedy Selection Measure

- Greedy mutual information maximization solution
  - At (n+1)th antenna selection

$\mathbf{D}_{n+1} = \mathrm{diag}(1 + p_u(1-\alpha)\|\mathbf{f}_{\mathcal{K}(i)}\|^2)$ $\quad$ $\mathbf{f}_i^H$: ith row of $\mathbf{H}$

$$C(\mathbf{H}_{n+1}) = \log_2 \left| \mathbf{I}_K + p_u \alpha \mathbf{D}_{n+1}^{-1} \mathbf{H}_{n+1} \mathbf{H}_{n+1}^H \right|$$

$$= C(\mathbf{H}_n) + \log_2\left(1 + \frac{p_u \alpha}{d_{\mathcal{K}(n+1)}} c_{\mathcal{K}(n+1),n}\right)$$

Function of previous antennas

Functions of (n+1)th antenna

Matrix determinant lemma

$$|\mathbf{A} + \mathbf{u}\mathbf{v}^H| = |\mathbf{A}|(1 + \mathbf{v}^H \mathbf{A}^{-1}\mathbf{u})$$

Mutual information gain		Quantization error penalty		Selection
$c_{\mathcal{K}(n+1),n} = \mathbf{f}_{\mathcal{K}(n+1)}^H \left(\mathbf{I} + p_u \alpha \mathbf{H}_n^H \mathbf{D}_n^{-1} \mathbf{H}_n\right)^{-1} \mathbf{f}_{\mathcal{K}(n+1)}$	vs.	$d_{\mathcal{K}(n+1)} = 1 + p_u(1-\alpha)\|\mathbf{f}_{\mathcal{K}(n+1)}\|^2$	➡	$J = \arg\max_j \frac{c_{j,n}}{d_j}$ Generalized FAS [Gharavi-Alkhansari04]
Mutual information increase from selecting (n+1)th antenna		Quantization error penalty for selecting (n+1)th antenna		Gain vs. Penalty

Quantization-Aware Fast Antenna Selection

Complexity reduction

- Matrix inversion is involved in MI gain

$$c_{j,n} = \mathbf{f}_j^H \left(\mathbf{I} + p_u \alpha \mathbf{H}_n^H \mathbf{D}_n^{-1} \mathbf{H}_n\right)^{-1} \mathbf{f}_j$$

Matrix inversion requires high complexity

- Simplifying MI gain update

$$\mathbf{Q}_{n+1} = \left(\mathbf{I} + p_u \alpha \mathbf{H}_{n+1}^H \mathbf{D}_{n+1}^{-1} \mathbf{H}_{n+1}\right)^{-1} = \mathbf{Q}_n - \mathbf{a}\mathbf{a}^H$$

Matrix inversion lemma

where $\mathbf{a} = \left(c_{J,n} + \frac{d_J}{p_u \alpha}\right)^{-1/2} \mathbf{Q}_n \mathbf{f}_J$ and $\mathbf{Q}_0 = \mathbf{I}_{N_u}$

$$c_{j,n+1} = \mathbf{f}_j^H \mathbf{Q}_{n+1} \mathbf{f}_j = \mathbf{f}_j^H \left(\mathbf{Q}_n - \mathbf{a}\mathbf{a}\right)^H \mathbf{f}_j = c_{j,n} - |\mathbf{f}_j^H \mathbf{a}|^2$$

Matrix inversion lemma
$(A + UCV)^{-1} = A^{-1} - A^{-1}U(C^{-1} + VA^{-1}U)^{-1}VA^{-1}$

Proposed algorithm

Quantization-Aware Fast Antenna Selection (QAFAS)	
1) Initialize: $\mathcal{T} = \{1, \ldots, N_r\}$ and $\mathbf{Q} = \mathbf{I}$.	
2) Initialize antenna gain and compute penalty: $c_j = \|\mathbf{f}_j\|^2$ and $d_j = 1 + \rho(1-\alpha)\|\mathbf{f}_j\|^2$ for $j \in \mathcal{T}$.	
3) Select antenna $J = \mathrm{argmax}_{j \in \mathcal{T}}\, c_j/d_j$.	
4) Update candidate set: $\mathcal{T} = \mathcal{T} \setminus \{J\}$.	
5) Compute: $\mathbf{a} = \left(c_J + \frac{d_J}{\rho\alpha}\right)^{-\frac{1}{2}} \mathbf{Q}\mathbf{f}_J$ and $\mathbf{Q} = \mathbf{Q} - \mathbf{a}\mathbf{a}^H$.	
6) Update $c_j = c_j - |\mathbf{f}_j^H \mathbf{a}|^2$ for $j \in \mathcal{T}$.	
7) Go to step 3 and repeat until select K antennas.	
Complexity	$O(K N_r N_u)$

Rate-Maximization Antenna Selection

Asymptotic complexity analysis

- Complexity for step 5: $O(KN_u^2)$
  - K *iterations x Inner product* $\boldsymbol{Qf}_J$
- Complexity for step 6: $O(KN_rN_u)$
  - K iterations

    x N_r updates

    x Inner product $\boldsymbol{f}_j^H\boldsymbol{a}$
- Large antenna arrays ($N_r \gg N_u$)

Overall complexity becomes O(K Nr Nu)

Proposed algorithm

Quantization-Aware Fast Antenna Selection (QAFAS)	
1) Initialize: $\mathcal{T} = \{1, \ldots, N_r\}$ and $\mathbf{Q} = \mathbf{I}$.	
2) Initialize antenna gain and compute penalty: $c_j = \|\mathbf{f}_j\|^2$ and $d_j = 1 + \rho(1-\alpha)\|\mathbf{f}_j\|^2$ for $j \in \mathcal{T}$.	
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6) Update $c_j = c_j - |\mathbf{f}_j^H\mathbf{a}|^2$ for $j \in \mathcal{T}$.	
7) Go to step 3 and repeat until select K antennas.	
Complexity	O(K Nr Nu)

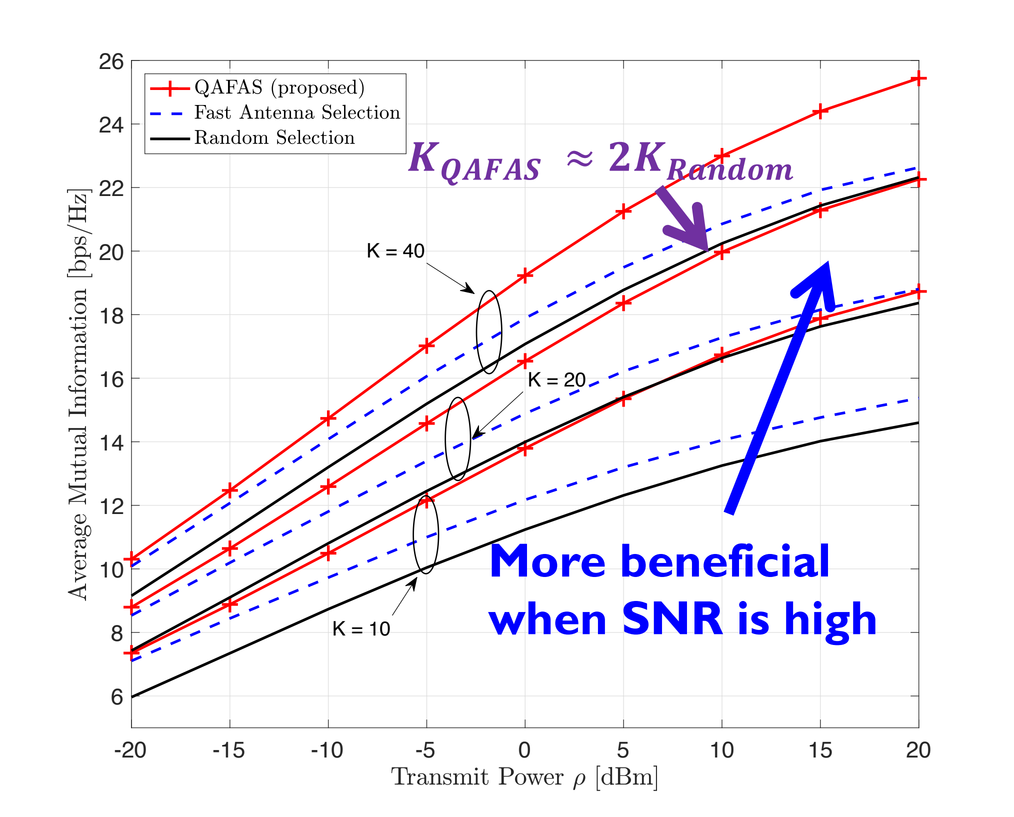
same as FAS [Gharavi-Alkhansari04]

SIMULATION – SUB-6GHz SYSTEM

K: # of selected antennas

Avg. mutual information vs. Transmit power

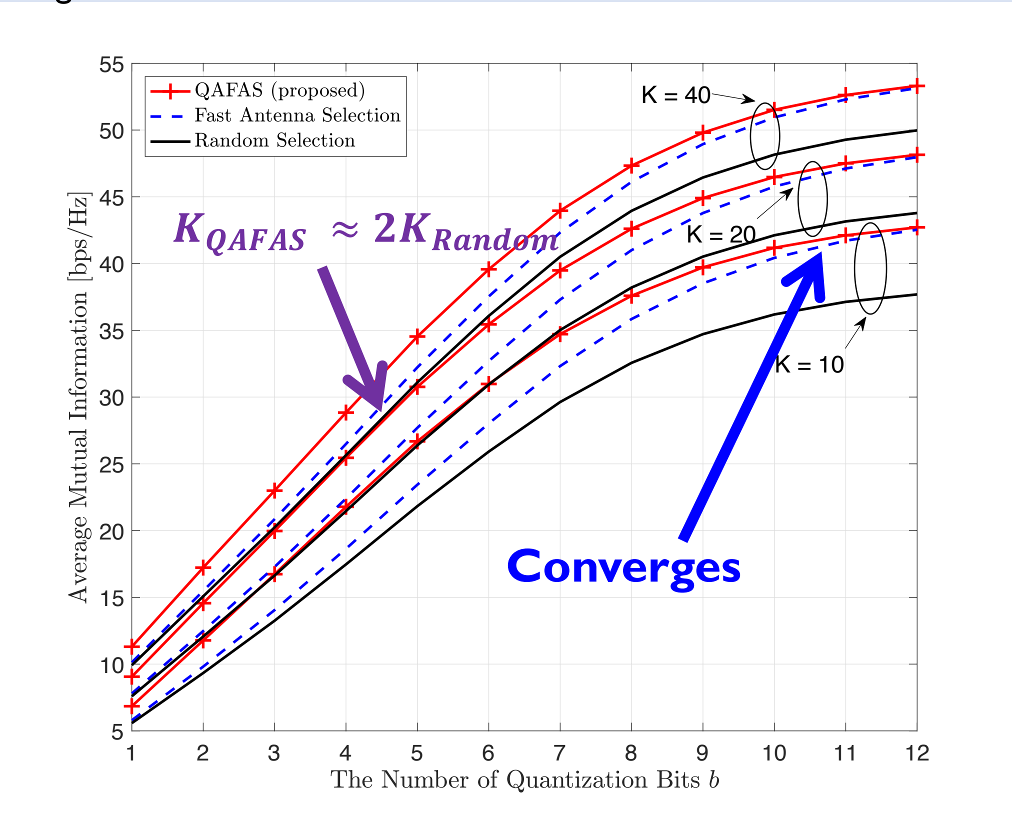
Figure 1 (3 quantization bits)



Why? Quantization error dominates thermal noise
: QAFAS is effective under quantization error

Avg. mutual information vs. # of ADC bits

Figure 2 (5 dBm Tx power)

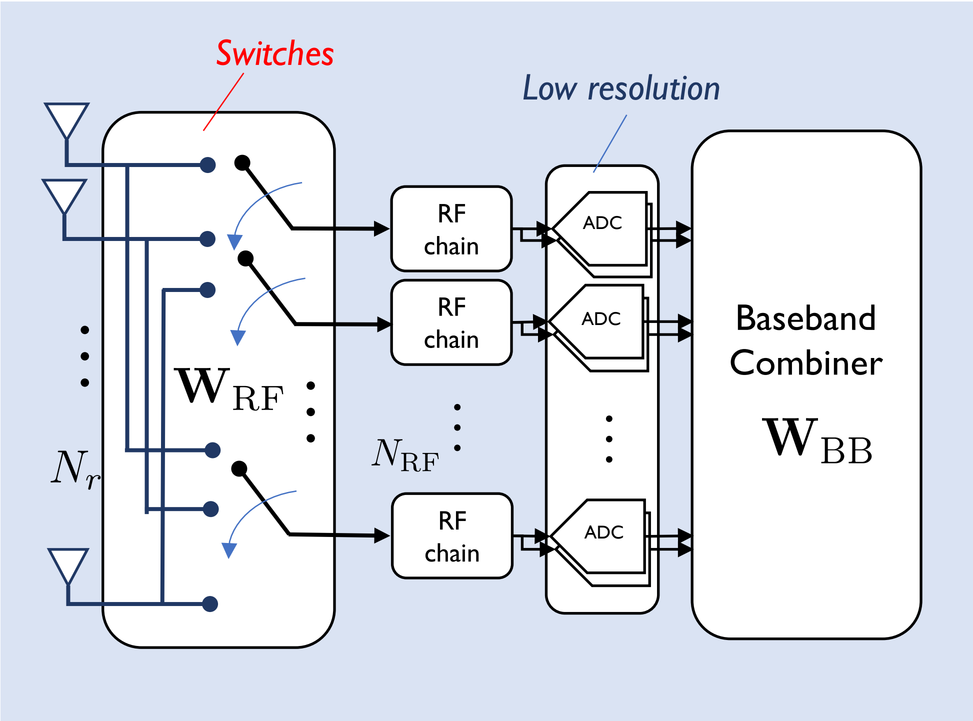


Why? Quantization error becomes negligible
: generalization of FAS algorithm

Settings 128 antennas, 2.4 GHz carrier frequency, 10 MHz bandwidth, 10 users, 2km cell radius, 100m min. user distance to BS

Summary of Contributions

Switch-based hybrid low-res. ADC system



Generalized selection measure

$$J = \arg\max_{j} \frac{c_{j,n}}{d_j}$$

Tradeoff between mutual information gain and quantization penalty

Quantization-aware FAS

1) Initialize: $\mathcal{T} = \{1, \ldots, N_r\}$ and $\mathbf{Q} = \mathbf{I}_{N_u}$.
2) Initialize antenna gain and compute penalty: $c_j = \|\mathbf{f}_j\|^2$ and $d_j = 1 + \rho(1-\alpha)\|\mathbf{f}_j\|^2$ for $j \in \mathcal{T}$.
3) Select antenna : $J = \mathrm{argmax}_{j \in \mathcal{T}}\, c_j / d_j$.
4) Update candidate set: $\mathcal{T} = \mathcal{T} \setminus \{J\}$.
5) Compute: $\mathbf{a} = \left(c_J + \frac{d_J}{\rho\alpha}\right)^{-\frac{1}{2}} \mathbf{Q}\mathbf{f}_J$ and $\mathbf{Q} = \mathbf{Q} - \mathbf{a}\mathbf{a}^H$.
6) Update $c_j = c_j - |\mathbf{f}_j^H \mathbf{a}|^2$ for $j \in \mathcal{T}$.
7) Go to step 3 and repeat until select K antennas.

BACK UP SLIDES

Greedy MI-maximizing Antenna Selection

- Mutual information expression

quantization noise covariance

$\mathbf{R}_{\mathbf{qq}} = \alpha(1-\alpha)\,\mathrm{diag}(\rho \mathbf{H}_{\mathcal{K}}\mathbf{H}_{\mathcal{K}}^H + \mathbf{I})$

- $C(\mathbf{H}_{\mathcal{K}}) = \log_2 \left| \mathbf{I} + \rho\alpha^2 (\alpha^2 \mathbf{I} + \mathbf{R}_{\mathbf{qq}})^{-1} \mathbf{H}_{\mathcal{K}}\mathbf{H}_{\mathcal{K}}^H \right|$

  $= \log_2 \left| \mathbf{I} + \rho\alpha \mathbf{D}_{\mathcal{K}}^{-1} \mathbf{H}_{\mathcal{K}}\mathbf{H}_{\mathcal{K}}^H \right|$ where $\mathbf{D}_{\mathcal{K}} = \mathrm{diag}(1 + \rho(1-\alpha)\|\mathbf{f}_{\mathcal{K}(i)}\|^2)$

- At (n+1)th selection stage

$$
\begin{aligned}
C(\mathbf{H}_{n+1}) &= \log_2 \left| \mathbf{I} + \rho\alpha \mathbf{D}_{n+1}^{-1} \mathbf{H}_{n+1}\mathbf{H}_{n+1}^H \right| \\
&= \log_2 \left| \mathbf{I} + \rho\alpha \mathbf{H}_{n+1}^H \mathbf{D}_{n+1}^{-1} \mathbf{H}_{n+1} \right| \\
&= \log_2 \left| \mathbf{I} + \rho\alpha \left(\mathbf{H}_n^H \mathbf{D}_n^{-1} \mathbf{H}_n + \frac{1}{d_{\mathcal{K}(n+1)}} \mathbf{f}_{\mathcal{K}(n+1)} \mathbf{f}_{\mathcal{K}(n+1)}^H \right) \right| \\
&\overset{(a)}{=} C(\mathbf{H}_n) + \log_2 \left(1 + \frac{\rho\alpha}{d_{\mathcal{K}(n+1)}} c_{\mathcal{K}(n+1),n} \right)
\end{aligned}
$$

(n+1) th row of $\mathbf{H}_{n+1}$

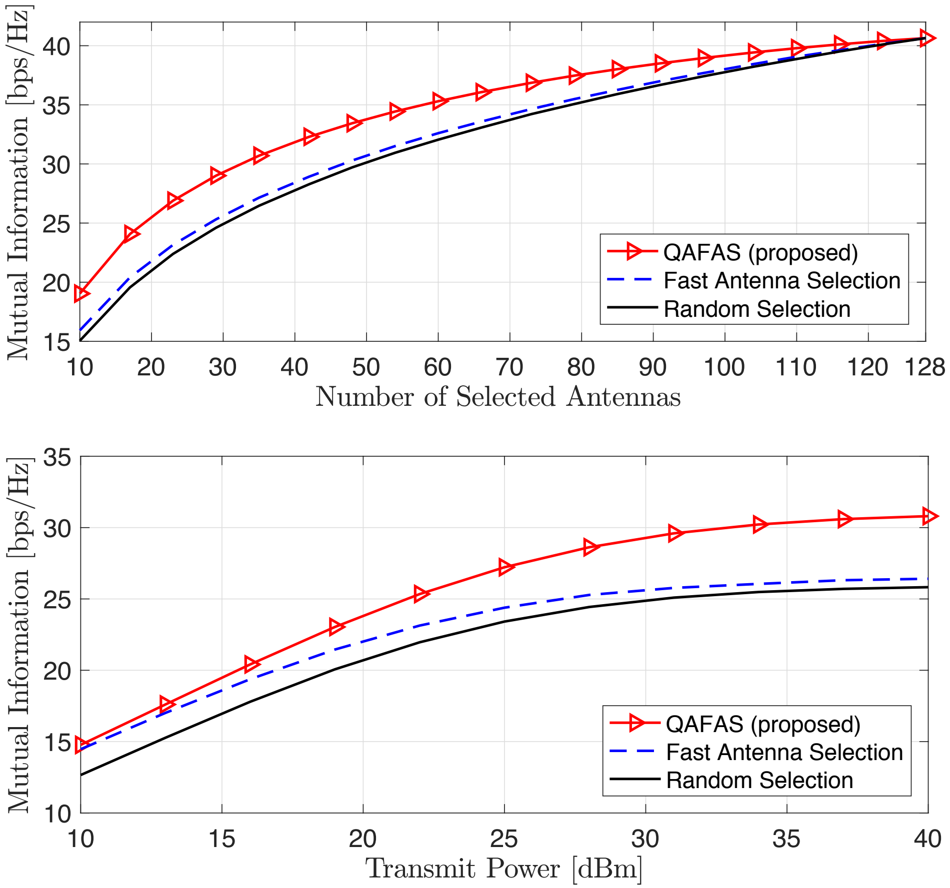
Diagonal entry of $\mathbf{D}$ corresponding to $\mathbf{f}_{\mathcal{K}(n+1)}$

where $c_{\mathcal{K}(n+1),n} = \mathbf{f}_{\mathcal{K}(n+1)}^H \left(\mathbf{I} + \rho\alpha \mathbf{H}_n^H \mathbf{D}_n^{-1} \mathbf{H}_n \right)^{-1} \mathbf{f}_{\mathcal{K}(n+1)}$

where (a) comes from matrix determinant lemma $|\mathbf{A} + \mathbf{u}\mathbf{v}^H| = |\mathbf{A}|(1 + \mathbf{v}^H \mathbf{A}^{-1} \mathbf{u})$

SIMULATION – MILLIMETER WAVE SYSTEM

MmWave Channel



Settings

256 antennas

52 selected antennas

3 channel paths

8 users

28 GHz carrier freq.

200 MHz BW

200m cell radius,

20m min. user distance

3 ADC bits