User Scheduling for Millimeter Wave MIMO Communications with Low-Resolution ADCs

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ICC May 23, 2018

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WHAT STARTS HERE CHANGES THE WORLD

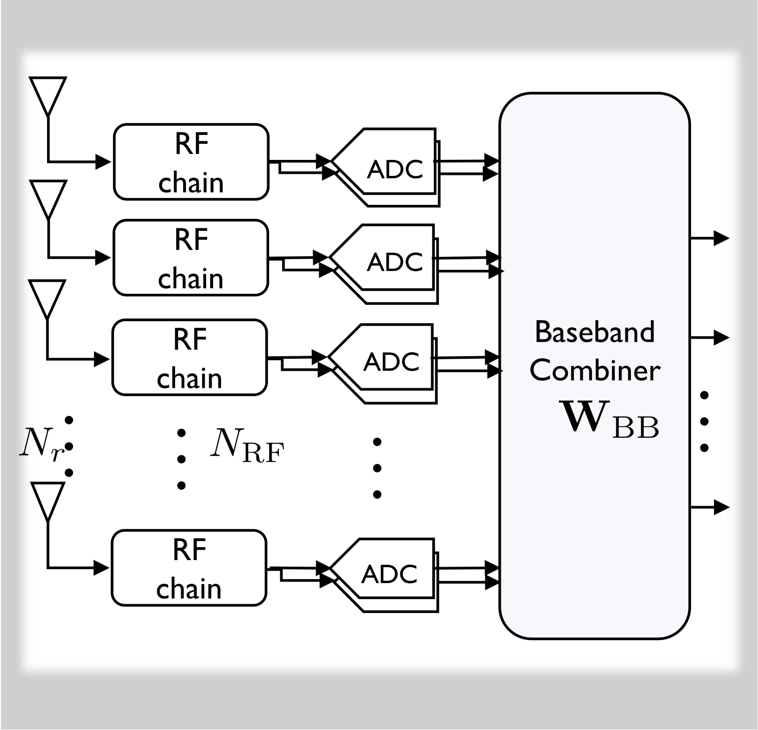
Wireless Networking & Communications Group

ESPL

EXCESSIVE POWER CONSUMPTION

Millimeter wave communications “large number of antennas” + “high sampling rate”

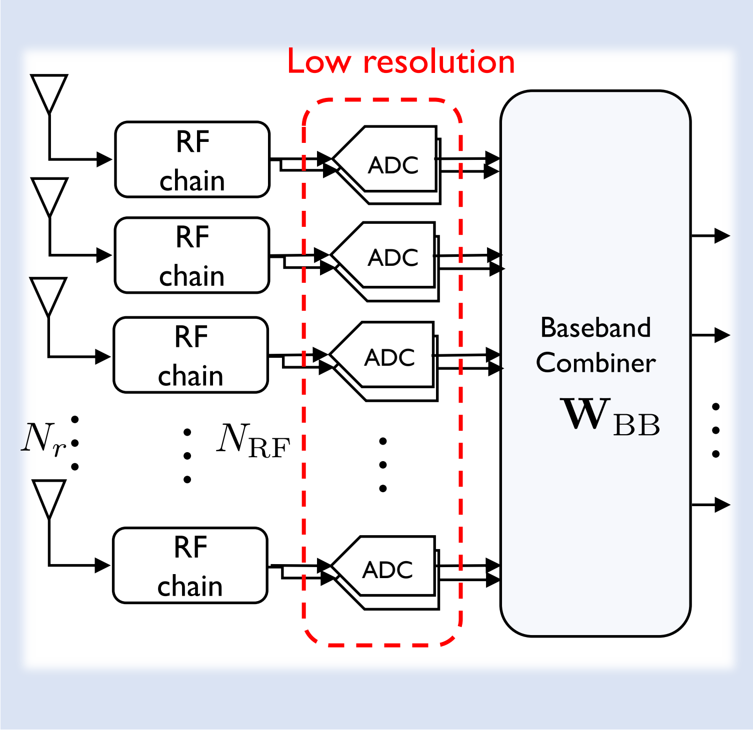
Conventional MIMO Receiver



- Full-resolution ADC (12 – 16 bits)
- Full RF chains ($N_{RF} = N_r$)

Conventional Solution A

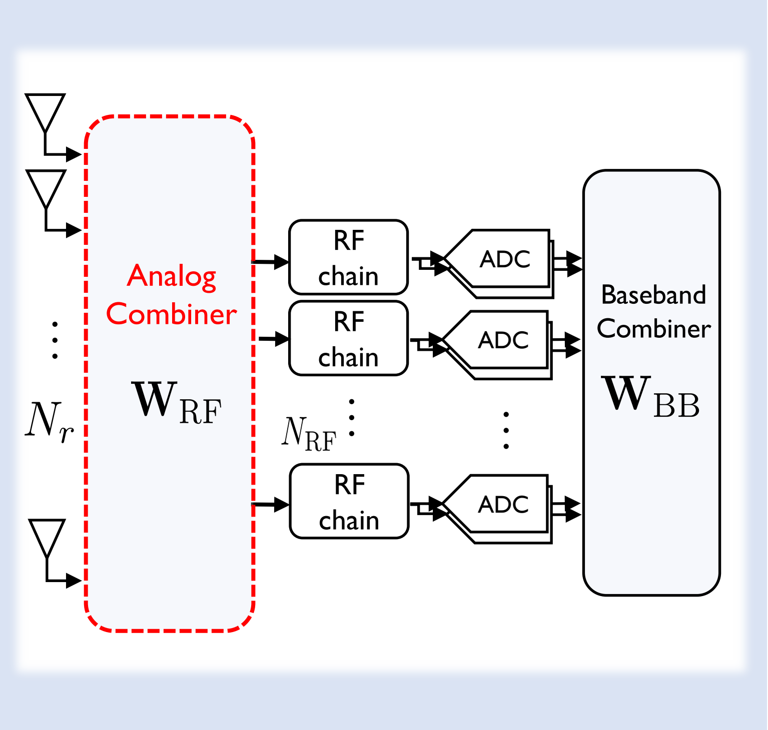
Low-resolution ADC receiver



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

Conventional Solution B

Hybrid beamforming receiver



- Full-resolution ADC (12 – 16 bits)
- Fewer RF chains ($N_{RF} << N_r$)

USER SCHEDULING

☐ Scheduling gain in single-cell environment

- Performance gains by *increasing channel gains* while *decreasing inter-user interference* (IUI)
- Previous scheduling algorithms
  - Random beamforming (RBF) [Sharif&Hassibi05]
  - Semi-orthogonal user scheduling (SUS) [Yoo&Goldsmith06]
  - Millimeter wave beam aggregation scheduling (mBAS) [Lee&Sung16]

Perfect quantization

Channel orthogonality

Channel magnitude

☐ Non-negligible quantization error

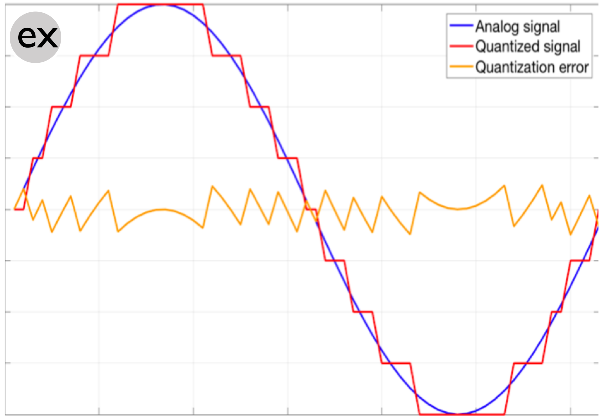
- Change in SINR computation:

$$\text{SINR} = \frac{\text{SIGNAL}}{\text{AWGN+IUI+QN}}$$

Prop. to channel gain *h*

Inv. prop to quantization bits *b*

$$\propto h2^{-2b}$$

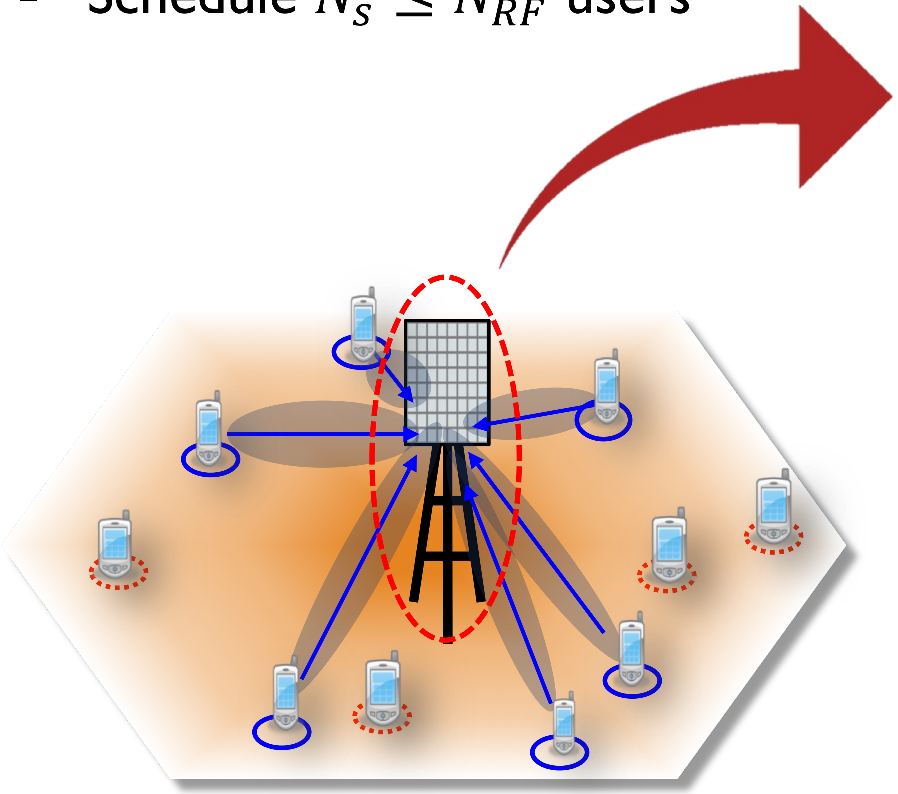


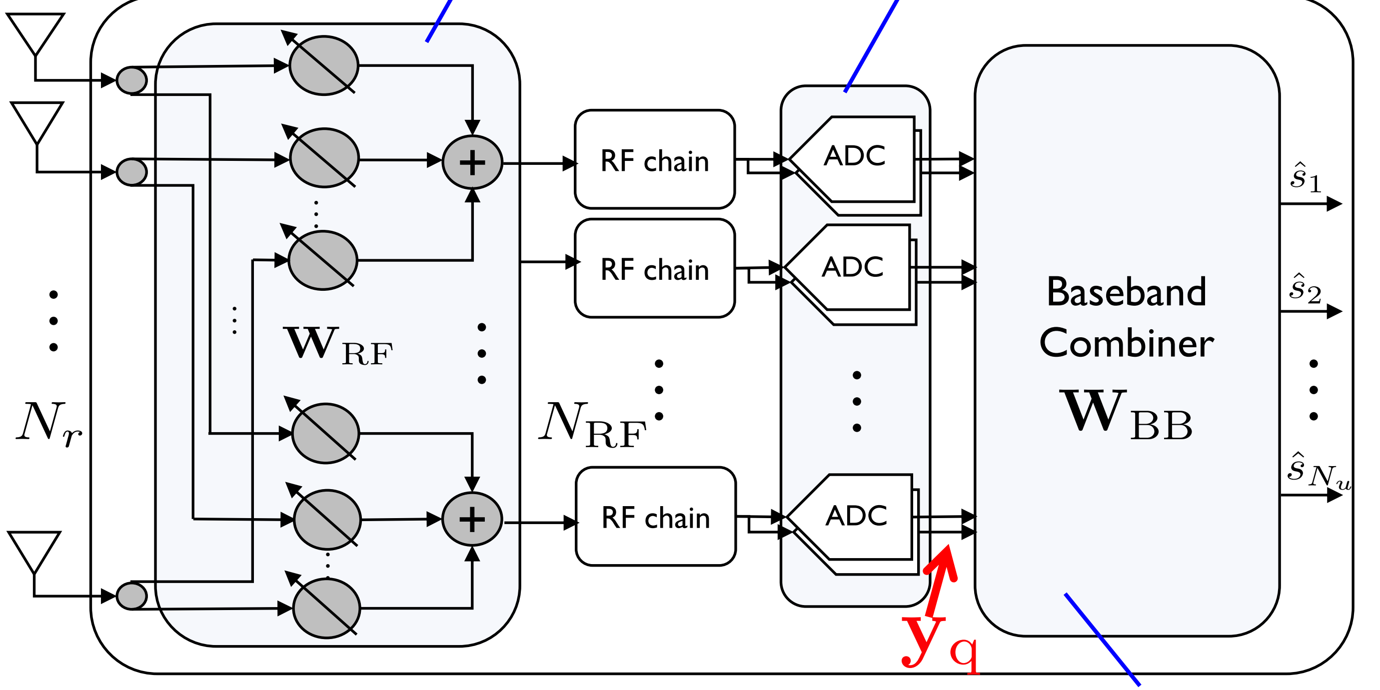
QN needs to be considered to maximize SINR with scheduling

*QN: Quantization Noise

SYSTEM MODEL

- ❑ Multi-user MIMO uplink system
  - Single cell environment
  - N_u users in single cell
  - Single-antenna user
  - Schedule $N_s \leq N_{RF}$ users





Submatrix of *DFT matrix

Low-resolution ADCs

Zero-forcing combiner

[Fletcher&Rangan07]

- ❑ Quantized signal vector (linear approx.)

$$\mathbf{y}_{\mathrm{q}} = \mathcal{Q}\big(\mathrm{Re}\{\mathbf{y}\}\big) + j\mathcal{Q}\big(\mathrm{Im}\{\mathbf{y}\}\big)$$
$$= \alpha\sqrt{\rho}\underbrace{\boxed{\mathbf{H}_{\mathrm{b}}}}_{\textit{Beam domain channel matrix}}\mathbf{s} + \alpha\boldsymbol{\eta} + \underbrace{\boxed{\mathbf{q}}}_{\textit{Additive quantization noise}}$$

*Discrete Fourier transform

PROBLEM FORMULATION

- ☐ Maximum sum rate scheduling
  - Schedule users to maximize sum rate

$$\mathcal{P}1: \quad \mathcal{R}(\mathbf{H}_{\mathrm{b}}(\mathcal{S}^{\star})) = \max_{\mathcal{S}\subset\{1,\ldots,N_u\}:|\mathcal{S}|\leq N_s} \sum_{k\in\mathcal{S}} \mathcal{R}_k(\mathbf{H}_{\mathrm{b}}(\mathcal{S}))$$

$\mathcal{S}$: scheduled user set $\quad \mathbf{H}_{\mathrm{b}}(\mathcal{S})$: $\mathbf{H}_{\mathrm{b}}$ of users in $\mathcal{S}$

  - Achievable rate of user *k*

$$\mathcal{R}_k(\mathbf{H}_{\mathrm{b}}) = \log_2\left(1 + \frac{\alpha^2 p_u}{\alpha^2 \underbrace{\|\mathbf{w}_{\mathrm{zf},k}\|^2}_{\text{AWGN}} + \mathbf{w}_{\mathrm{zf},k}^H \underbrace{\mathbf{R}_{\mathbf{qq}}(\mathbf{H}_{\mathrm{b}})}_{\text{QN}} \mathbf{w}_{\mathrm{zf},k}}\right)$$

minimize

minimize

Previous scheduling condition

(1) $\mathbf{h}_{\mathrm{b},k} \perp \mathbf{h}_{\mathrm{b},k'}, \quad k \neq k'$

(2) $\text{maximize } \|\mathbf{h}_{\mathrm{b},k}\|^2$

Additional condition

$$\mathbf{R}_{\mathbf{qq}}(\mathbf{H}_{\mathrm{b}}) = \alpha\beta\,\mathrm{diag}(p_u \boxed{\mathbf{H}_{\mathrm{b}}\mathbf{H}_{\mathrm{b}}^H} + \mathbf{I}_{N_{\mathrm{RF}}})$$

(3) $\text{minimize } \|[\mathbf{H}_{\mathrm{b}}]_{i,:}\|^2$

: minimize quantization error

PROBLEM RE-FORMULATION

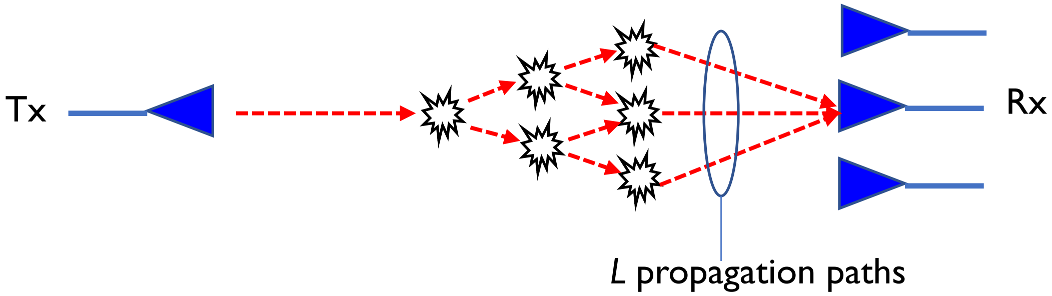
☐ Optimal channel design problem

- Characterize channel matrix that maximizes uplink sum rate

$$\mathcal{P}2: \quad \mathcal{R}(\mathbf{H}_{\mathrm{b}}^{\star}) = \max_{\mathbf{H}_{\mathrm{b}} \in \mathbb{C}^{N_{\mathrm{RF}} \times N_u}} \sum_{k=1}^{N_u} \mathcal{R}_k(\mathbf{H}_{\mathrm{b}}), \quad \text{s.t. } \|\mathbf{h}_{\mathrm{b},k}\| = \sqrt{\gamma_k} \;\; \forall k.$$

- Virtual channel representation [Sayeed02]
  - provides *geographical interpretation* for analysis

$\mathbf{h}_{\mathrm{b}}$: *L*-sparse vector (*L* nonzero complex gains for propagation paths)



NEW USER SCHEDULING CRITERIA

- Solution of $\mathcal{P}2$: structural scheduling criteria
  - For total # of channel paths $\leq N_{RF}$

$\mathcal{L}_k$: index set of nonzero elements

Theorem 1

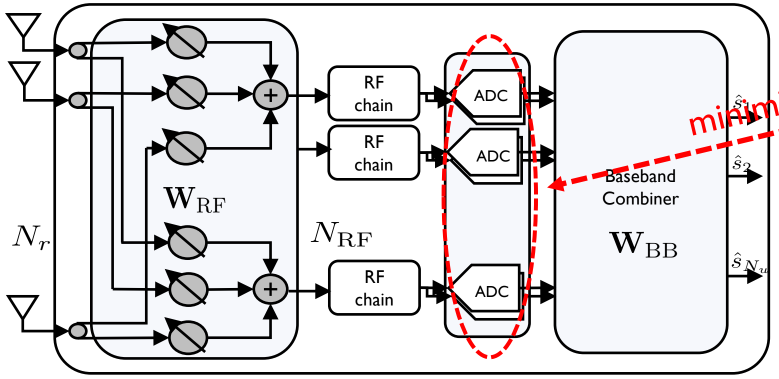
I. Unique *AoAs at receiver for channel paths of each scheduled user:

$$\mathcal{L}_{\mathcal{S}(k)} \cap \mathcal{L}_{\mathcal{S}(k')} = \emptyset \text{ if } k \neq k'.$$

II. Equal power spread across beamspace complex gains within each channel:

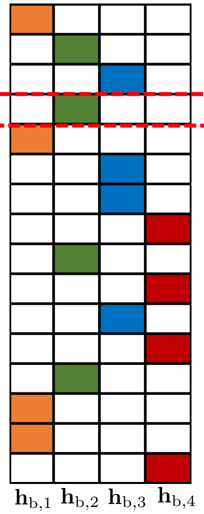
$$|h_{\mathrm{b},i,\mathcal{S}(k)}| = \sqrt{\gamma_{\mathcal{S}(k)}/L_{\mathcal{S}(k)}} \text{ for } i \in \mathcal{L}_{\mathcal{S}(k)}.$$

*Angle of arrivals



minimize error here

Channel $\mathbf{H}_{\mathrm{b}}$



$\mathbf{h}_{\mathrm{b},1}$	$\mathbf{h}_{\mathrm{b},2}$	$\mathbf{h}_{\mathrm{b},3}$	$\mathbf{h}_{\mathrm{b},4}$
🟧			
	🟩		
		🟦	
	🟩		
🟧			
		🟦	
		🟦	
			🟥
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🟧			
🟧			
			🟥

Aggregated channel gain at ADC

- Unique AoAs
- Equal power spread

$\text{minimize } \|[\mathbf{H}_{\mathrm{b}}]_{i,:}\|^2$

USER SCHEDULING CRITERIA

❑ User scheduling criteria under coarse quantization

Previous criteria

(A) Orthogonality among scheduled users $\mathbf{h}_{\mathrm{b},k} \perp \mathbf{h}_{\mathrm{b},k'}, \ \ k \neq k'$

(B) Large channel gain for each user $\|\mathbf{h}_{\mathrm{b},k}\|^2$

Additional criteria

(C) Unique angle of arrivals for each user $\mathcal{L}_{\mathcal{S}(k)} \cap \mathcal{L}_{\mathcal{S}(k')} = \phi$ if $k \neq k'$

(D) Equal power spread within each user channel $|h_{\mathrm{b},i,\mathcal{S}(k)}| = \sqrt{\gamma_{\mathcal{S}(k)}/L_{\mathcal{S}(k)}}$ for $i \in \mathcal{L}_{\mathcal{S}(k)}$

: structural scheduling criteria

- Previous algorithms only consider (A) and (B)

New scheduling algorithm satisfying (A - D) is necessary

PROPOSED ALGORITHM I

- ☐ Channel structure-based scheduling (CSS)

Step1. Set filtering: modified semi-orthogonality filtering

Cond. A $\mathbf{h}_{\mathrm{b},k} \perp \mathbf{h}_{\mathrm{b},k'}$	Semi-orthogonality $\frac{\lvert \mathbf{f}_{\mathcal{S}(i)}^H \mathbf{h}_{\mathrm{b},k} \rvert}{\lVert \mathbf{f}_{\mathcal{S}(i)} \rVert \lVert \mathbf{h}_{\mathrm{b},k} \rVert} < \epsilon$	$\mathbf{f}_{\mathcal{S}(i)}$: component of $\mathbf{h}_{\mathrm{b},\mathcal{S}(i)}$ such that $\mathbf{f}_{\mathcal{S}(i)} \perp \mathrm{span}\{\mathbf{f}_{\mathcal{S}(1)}, \ldots, \mathbf{f}_{\mathcal{S}(i-1)}\}$
Cond. C $\mathcal{L}_k \cap \mathcal{L}_{k'} = \phi$	Spatial orthogonality $\lvert \mathcal{B}_{\mathcal{S}(i)} \cap \mathcal{B}_k \rvert \le N_{\mathrm{OL}}$	$\mathcal{B}_k$: index set of dominant beamspace gains

: remaining users become semi-orthogonal to scheduled users

Step2. Selection: maximum approximated SINR

Cond. B
$\max \lVert \mathbf{h}_{\mathrm{b},k} \rVert$

Cond. D
$\lvert h_{\mathrm{b},i,\mathcal{S}(k)} \rvert = \sqrt{\frac{\gamma_{\mathcal{S}(k)}}{L_{\mathcal{S}(k)}}}$

$$\mathrm{SINR}_k\big(\mathbf{H}_{\mathrm{b}}(\mathcal{S} \cup \{k\})\big) \approx \frac{\alpha p_u \boxed{\lVert \mathbf{h}_{\mathrm{b},k} \rVert^4}}{(1-\alpha)\boxed{\mathbf{h}_{\mathrm{b},k}^H \mathbf{D}\big(\mathbf{H}_{\mathrm{b}}(\mathcal{S} \cup \{k\})\big) \mathbf{h}_{\mathrm{b},k}}}$$

Tradeoff

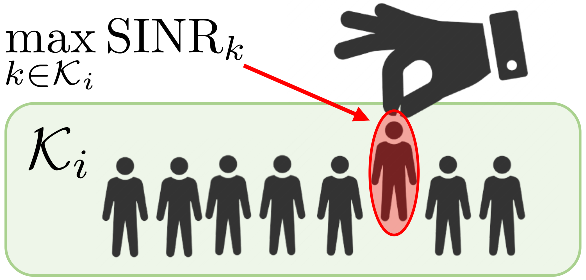
semi-orthogonality filtering

$\mathbf{w}_{\mathrm{zf},k} \approx \mathbf{h}_{\mathrm{b},k} / \lVert \mathbf{h}_{\mathrm{b},k} \rVert^2$

where $\mathbf{D}(\mathbf{H}_{\mathrm{b}}) = \mathrm{diag}(\rho \mathbf{H}_{\mathrm{b}} \mathbf{H}_{\mathrm{b}}^H + \frac{1}{1-\alpha} \mathbf{I}_{N_{\mathrm{RF}}})$

Maximum SINR scheduling

$\max_{k \in \mathcal{K}_i} \mathrm{SINR}_k$

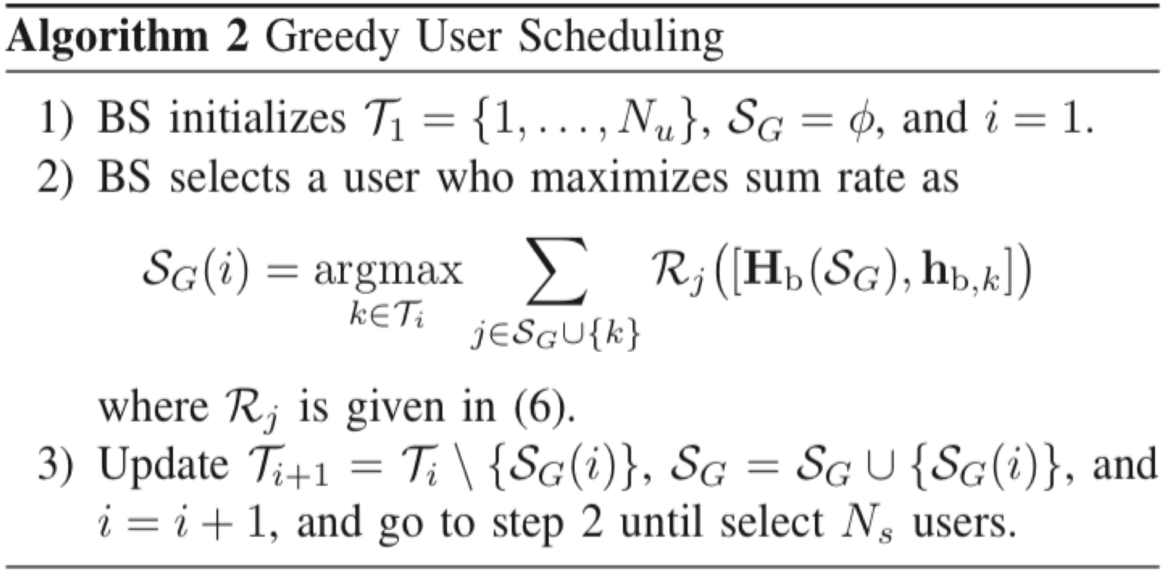


Repeat step1 and 2

PROPOSED ALGORITHM 2

❑ Greedy User Scheduling

- Schedules user who provides max. sum rate
- Provides sub-optimal performance
- Requires prohibitively high complexity



Algorithm 2 Greedy User Scheduling

1) BS initializes $\mathcal{T}_1 = \{1, \ldots, N_u\}$, $\mathcal{S}_G = \phi$, and $i = 1$.
2) BS selects a user who maximizes sum rate as

$$\mathcal{S}_G(i) = \operatorname*{argmax}_{k \in \mathcal{T}_i} \sum_{j \in \mathcal{S}_G \cup \{k\}} \mathcal{R}_j\left([\mathbf{H}_\mathrm{b}(\mathcal{S}_G), \mathbf{h}_{\mathrm{b},k}]\right)$$

where $\mathcal{R}_j$ is given in (6).

3) Update $\mathcal{T}_{i+1} = \mathcal{T}_i \setminus \{\mathcal{S}_G(i)\}$, $\mathcal{S}_G = \mathcal{S}_G \cup \{\mathcal{S}_G(i)\}$, and $i = i + 1$, and go to step 2 until select N_s users.

❑ At *i* th scheduling stage (iteration)

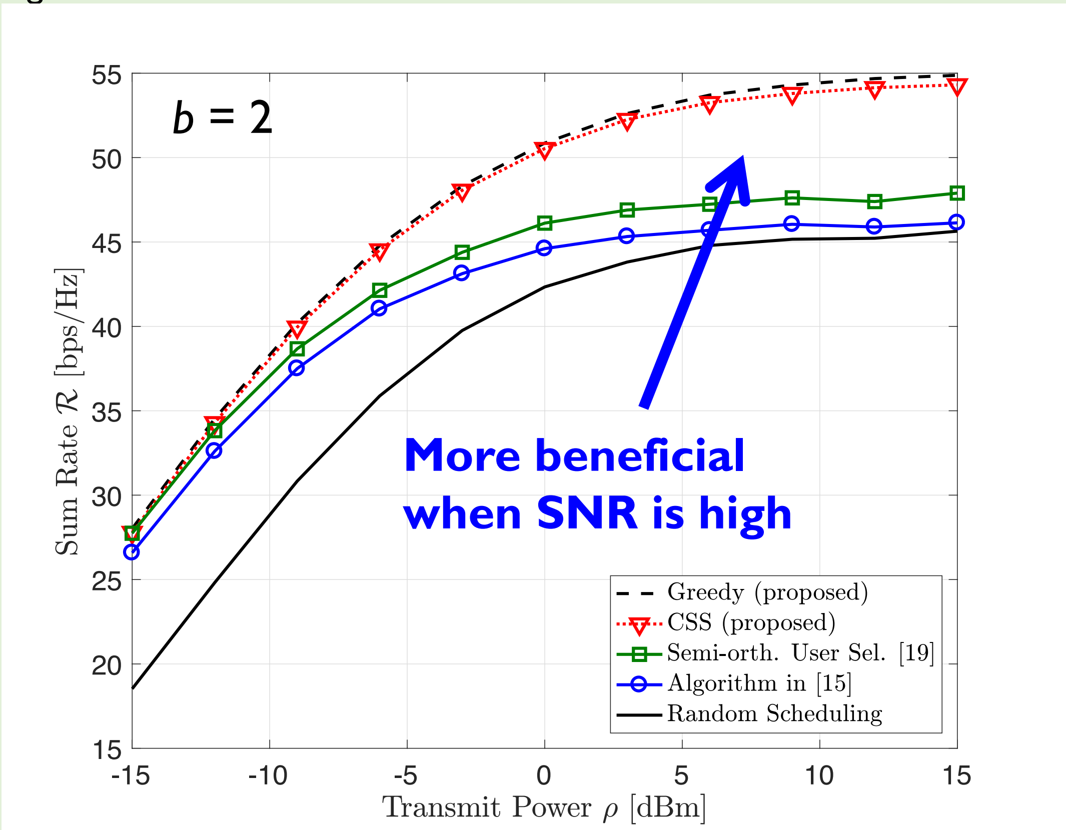
Greedy		**CSS**
Compute $\mathcal{R}_j$ $\lvert\mathcal{T}_i\rvert \times i$	vs.	Approx. SINR $\lvert\mathcal{K}_i\rvert$
Matrix inversion involved in $\mathcal{R}_j$	vs.	No inversion in SINR
No set filtering $\lvert\mathcal{T}_i\rvert \gg \lvert\mathcal{K}_i\rvert$	vs.	Set filtering $\lvert\mathcal{T}_i\rvert \gg \lvert\mathcal{K}_i\rvert$
High complexity		Low complexity

SIMULATION RESULTS

[19] Yoo&Goldsmith06
[15] Lee&Sung16

Sum Rate vs. Transmit power

Figure 1

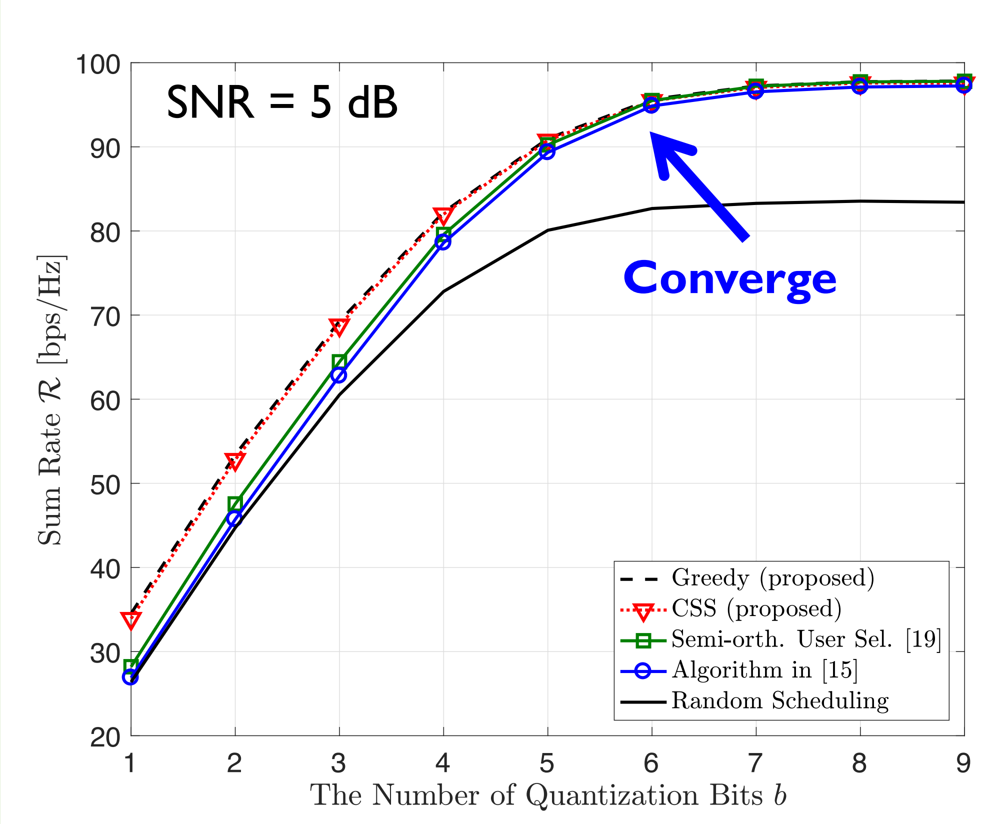


More beneficial when SNR is high

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

Sum Rate vs. # of ADC bits

Figure 2



Converge

Why? Quantization error becomes negligible
: CSS is also effective under perfect quantization

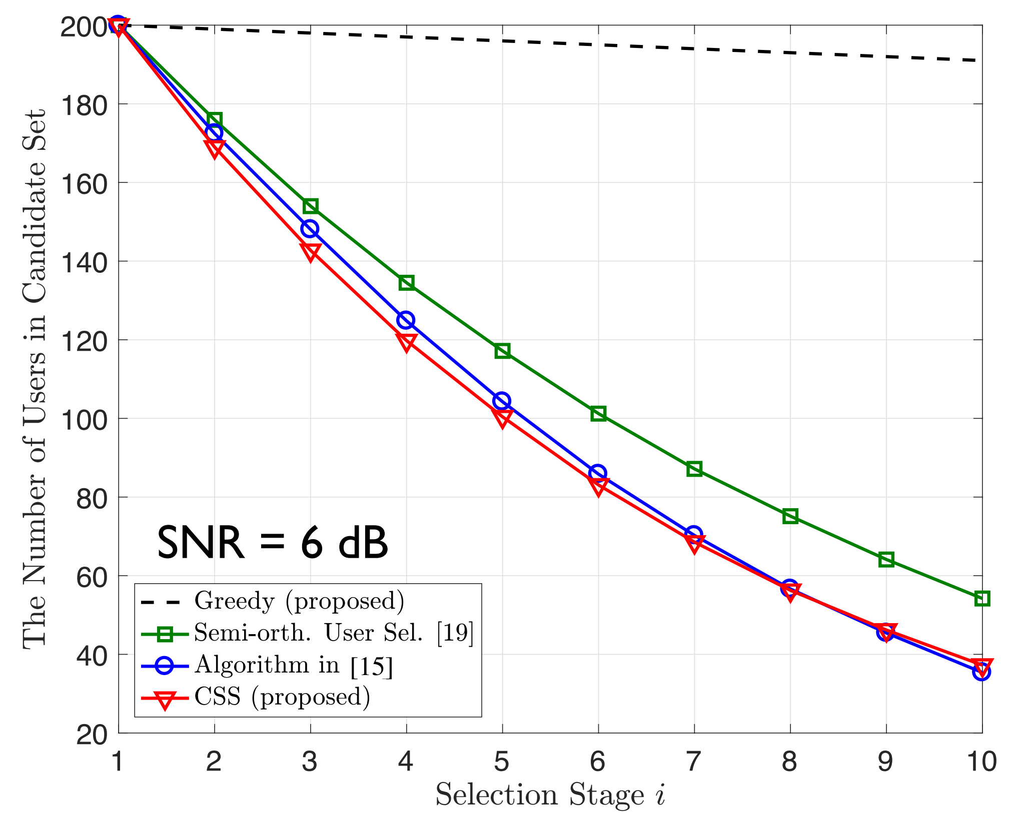
Settings 128 antennas, 128 RF chains, 200 candidate users, 10 scheduled users, 4 channel paths / user

SIMULATION RESULTS

[19] Yoo&Goldsmith06
[15] Lee&Sung16

of Users in Set vs. Selection Stage

Figure 3



- CSS has **smallest candidate user sets** over most of stages
- CSS becomes **more efficient** than Greedy as more users are scheduled
- CSS becomes **more efficient** than Greedy as total candidate user increases

Settings	128 antennas, 128 RF chains, 200 candidate users, 10 scheduled users, 4 channel paths / user

CONCLUSION

❑ Contributions

- ✦ Provided optimal channel structure analysis

  : offers channel structural scheduling criteria

- ✦ Proposed efficient user scheduling algorithm in low-resolution ADC systems

  : achieves sub-optimal sum rate performance with low complexity

❑ Future work

- ✦ Develop efficient user scheduling algorithm that jointly optimizes RF chain

Thank you

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