A Hybrid Beamforming Receiver with Two-Stage Analog Combiner and Low-Resolution ADCs

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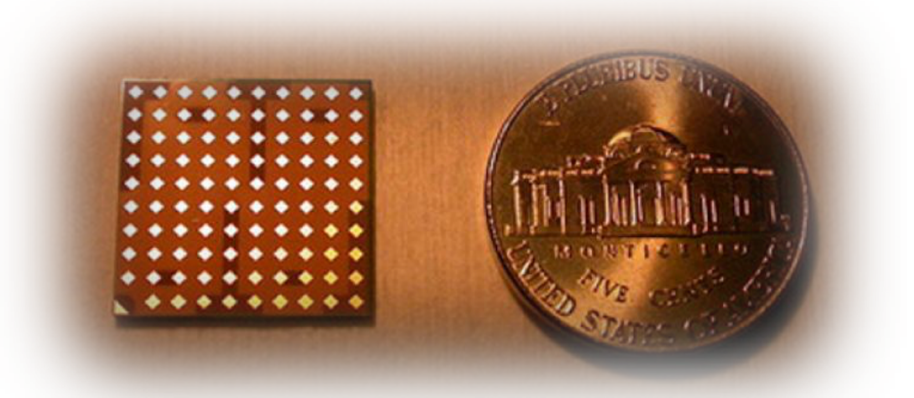
MILLIMETER WAVE COMMUNICATIONS FOR 5G [Pi&Khan11]

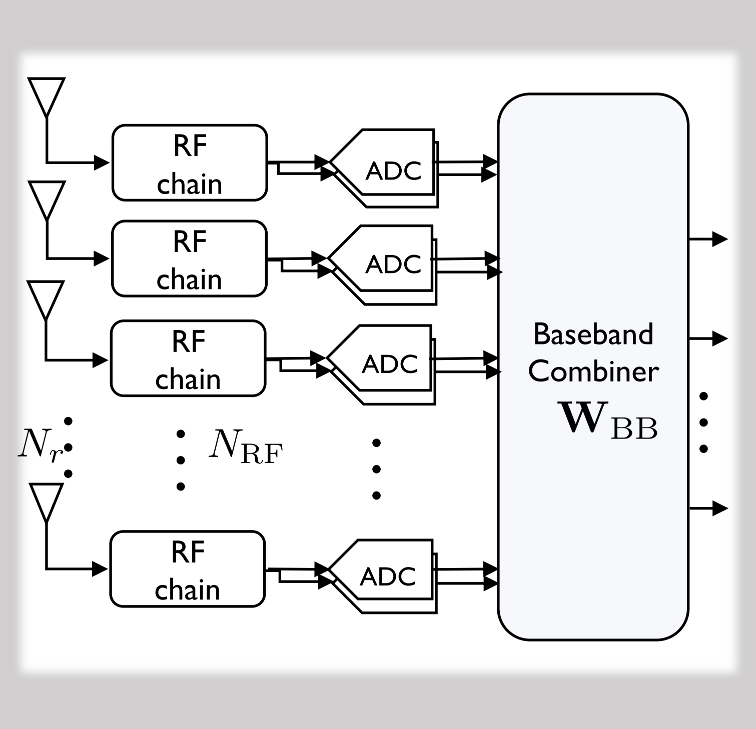
- **Key Properties**
  - High frequency: 30 – 300 GHz
  - Large bandwidth: 100MHz – 1GHz
  - Large pathloss / blockage



[IBM mmWave antennas]

- **Excessive power consumption**
  - large number of antennas and radio frequency chains
  - high sampling rate

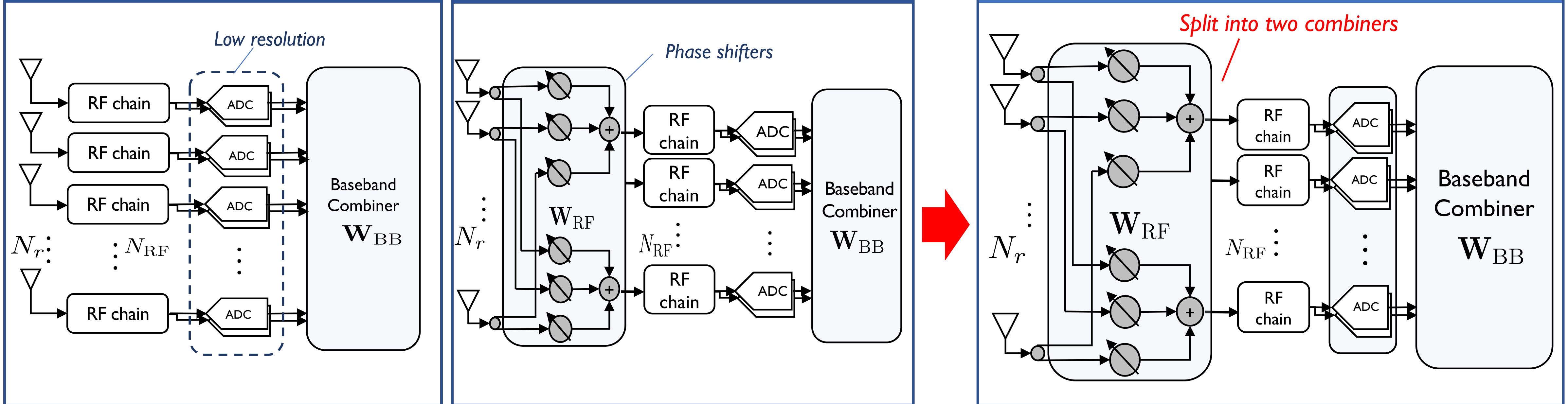
Conventional MIMO Receiver



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

Goal

- Design new analog combining to incorporate quantization error



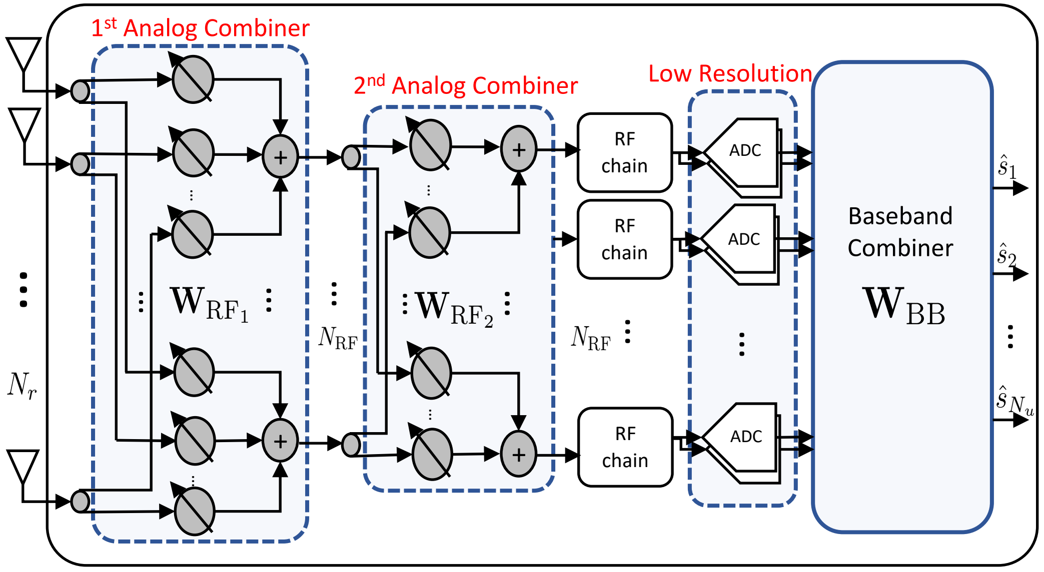
Low-resolution ADC system	Hybrid beamforming system	Hybrid + Low-resolution ADCs
Reduced number of ADC bits, BUT full RF chains ($N_{RF} = N_r$)	Reduced number of RF chains, BUT full-resolution ADCs ($b \geq 12$)	(1) Reduces number of RF chains (2) Low-resolution ADCs

Key Idea: 1st AC*: aggregates channel gain + 2nd AC: spread gains

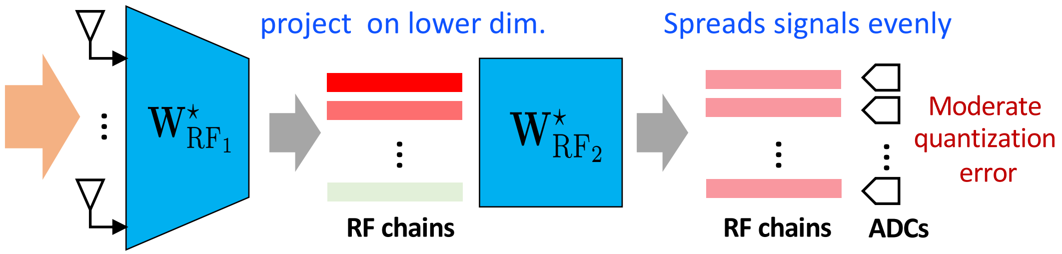
*AC: Analog combiner

System Model

Two-Stage Analog Combining



Two-stage solution



- Multi-user MIMO uplink system
  - Single cell environment
  - Serve $N_u \le N_{RF}$ users w. single antenna
- Millimeter wave channel

[Akdeniz&Rappaport14]

Large scale fading gain — Small scale path gain — Angle of arrival — Array response vector

$$\mathbf{h}_{\gamma,k} = \frac{1}{\sqrt{\gamma_k}}\mathbf{h}_k = \sqrt{\frac{N_r}{\gamma_k L_k}}\sum_{\ell=1}^{L_k} g_{\ell,k}\mathbf{a}(\theta_{\ell,k})$$

*ARV for uniform linear array (ULA)

$$\mathbf{a}(\theta) = \frac{1}{\sqrt{N_r}}\left[1, e^{-j\pi\vartheta}, \ldots, e^{-j(N_r-1)\pi\vartheta}\right]^{\mathsf{T}} \text{ and } \vartheta = \frac{2d}{\lambda}\sin\theta$$

- Received signal after power control

$$\mathbf{r} = \mathbf{H}_{\gamma}\mathbf{x} + \mathbf{n} = \mathbf{HBPs} + \mathbf{n} = \sqrt{\rho}\mathbf{Hs} + \mathbf{n}$$

$$\mathbf{B} = \mathrm{diag}\{\sqrt{1/\gamma_1}, \ldots, \sqrt{1/\gamma_{N_u}}\}$$
$$\mathbf{P} = \mathrm{diag}\{\sqrt{\rho\,\gamma_1}, \ldots, \sqrt{\rho\,\gamma_{N_u}}\}$$
$$\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_{N_r})$$

*ARV: Array response vector

Problem Formulation

- Maximizing mutual information
  - Maximum MI problem: $\mathcal{C}(\mathbf{W}_{\mathrm{RF}}) \triangleq \mathrm{I}(\mathbf{s};\mathbf{y}_{\mathrm{q}})$
    - Assume semi-unitary constraint: $\mathbf{W}_{\mathrm{RF}}^{H}\mathbf{W}_{\mathrm{RF}} = \mathbf{I}_{N_{\mathrm{RF}}}$
    - No constant modulus constraint on analog combiner

$$\mathcal{P}1: \ \mathbf{W}_{\mathrm{RF}}^{\mathrm{opt}} = \arg\max_{\mathbf{W}_{\mathrm{RF}}} \ \mathcal{C}(\mathbf{W}_{\mathrm{RF}}), \ \text{s.t.} \ \mathbf{W}_{\mathrm{RF}}^{H}\mathbf{W}_{\mathrm{RF}} = \mathbf{I}.$$

- Optimal scaling law with respect to number of RF chains N_{RF}

Theorem 1: Optimal scaling law

Optimal solution to $\mathcal{P}1$ achieves following scaling law with respect to number of RF chains:

$$\mathcal{C}(\mathbf{W}_{\mathrm{RF}}^{\mathrm{opt}}) \sim N_u \log_2 N_{\mathrm{RF}}$$

It can be also achieved by using following two-stage combiners:

(i) $\mathbf{W}_{\mathrm{RF}_1}^{\star} = [\mathbf{U}_{1:N_u}\mathbf{U}_{\perp}]$: matrix of left singular vectors : conventional optimal solution for perfect quantization systems

(ii) $\mathbf{W}_{\mathrm{RF}_2}^{\star}$: any N_{RF} x N_{RF} unitary matrix with constant modulus

OPTIMAL SCALING LAW (cont'd)

- Optimal scaling law with respect to number of RF chains N_{RF}

Corollary 1: Upper bound for conventional solution

Conventional optimal solution $\mathbf{W}_{\mathrm{RF}}^{\mathrm{cv}} = [\mathbf{U}_{1:N_u} \mathbf{U}_{\perp}]$ for perfect quantization systems cannot achieve optimal scaling law in coarse quantization systems. It is upper bounded by

quantization gain < 1

$$\mathcal{C}\left(\mathbf{W}_{\mathrm{RF}}^{\mathrm{cv}}\right) < \mathcal{C}_{\mathrm{svd}}^{\mathrm{ub}} = N_u \log_2\left(1 + \frac{\alpha_b}{1-\alpha_b}\right)$$

Captures channel gains:
N_u largest singular values

vs.

Increases quantization noise:
Large gains on a few ADCs

Second analog combiner $\mathbf{W}_{\mathrm{RF2}}$ in Theorem 1 resolves quantization noise enhancement

Optimal Mutual Infomation

- Optimal MI for special case : Homogeneous channel singular values

Theorem 2: Maximum Mutual Information

For homogeneous channel singular value case, two-stage analog combining solution in Theorem 1, $\mathbf{W}_{\mathrm{RF}}^{\star} = \mathbf{W}_{\mathrm{RF}_1}^{\star}\mathbf{W}_{\mathrm{RF}_2}^{\star}$, maximizes MI:

$$\mathbf{W}_{\mathrm{RF}}^{\star} = \arg\max_{\mathbf{W}_{\mathrm{RF}}} \mathcal{C}(\mathbf{W}_{\mathrm{RF}})$$

$$\text{s.t. } \mathbf{W}_{\mathrm{RF}}^{H}\mathbf{W}_{\mathrm{RF}} = \mathbf{I}_{N_{\mathrm{RF}}} \text{ and } \lambda_1 = \cdots = \lambda_{N_u} = \lambda$$

Optimal mutual information:

$$\mathcal{C}_{\mathrm{opt}} \triangleq \mathcal{C}(\mathbf{W}_{\mathrm{RF}}^{\star}) = N_u \log_2\left(1 + \frac{\alpha_b \lambda N_{\mathrm{RF}}}{\lambda N_u(1-\alpha_b) + N_{\mathrm{RF}}/\rho}\right)$$

Proposed two-stage analog combining achieves optimal MI for homogeneous massive MIMO

Two-Stage Analog Combining Algorithm (cont'd)

- Two-stage analog combiner under practical constraints
  - Array response vector-based two-stage analog combining

Algorithm 1: ARV-based TSAC

1 **Initialization**: set $\mathbf{W}_{\mathrm{RF}_1}$ = empty matrix, $\mathbf{H}_{\mathrm{rm}} = \mathbf{H}$, and $\mathcal{V} = \{\vartheta_1, \ldots, \vartheta_{|\mathcal{V}|}\}$ where $\vartheta_n = \frac{2n}{|\mathcal{V}|} - 1$:AoA codebook

1st analog combiner

2 **for** $i = 1 : N_{\mathrm{RF}}$ **do**

3 Maximum channel gain aggregation

(a) $\mathbf{a}(\vartheta^\star) = \mathrm{argmax}_{\vartheta \in \mathcal{V}} \|\mathbf{a}(\vartheta)^H \mathbf{H}_{\mathrm{rm}}\|^2$: capture max channel gain

(b) $\mathbf{W}_{\mathrm{RF}_1} = [\ \mathbf{W}_{\mathrm{RF}_1} \mid \mathbf{a}(\vartheta^\star)\ ]$

(c) $\mathbf{H}_{\mathrm{rm}} = \mathcal{P}^{\perp}_{\mathbf{a}(\vartheta^\star)} \mathbf{H}_{\mathrm{rm}}$, where $\mathcal{P}^{\perp}_{\mathbf{a}(\vartheta)} = \mathbf{I} - \mathbf{a}(\vartheta)\mathbf{a}(\vartheta)^H$: null space projection (for orthogonality)

(d) $\mathcal{V} = \mathcal{V} \setminus \{\vartheta^\star\}$

4 **end**

5 Set $\mathbf{W}_{\mathrm{RF}_2} = \mathbf{W}_{\mathrm{DFT}}$ where $\mathbf{W}_{\mathrm{DFT}}$ is a normalized $N_{\mathrm{RF}} \times N_{\mathrm{RF}}$ DFT matrix. 2nd analog combiner

6 **return** $\mathbf{W}_{\mathrm{RF}_1}$ and $\mathbf{W}_{\mathrm{RF}_2}$;

SIMULATION RESULTS

- Millimeter wave channels
  - Simulation cases

1) **ARV-TSAC**: proposed two-stage analog combining

2) **ARV**: one-stage analog combining
with $\mathbf{W}_{\mathrm{RF}} = \mathbf{W}_{\mathrm{RF}_1}$ designed from ARV-TSAC

Infeasible to implement

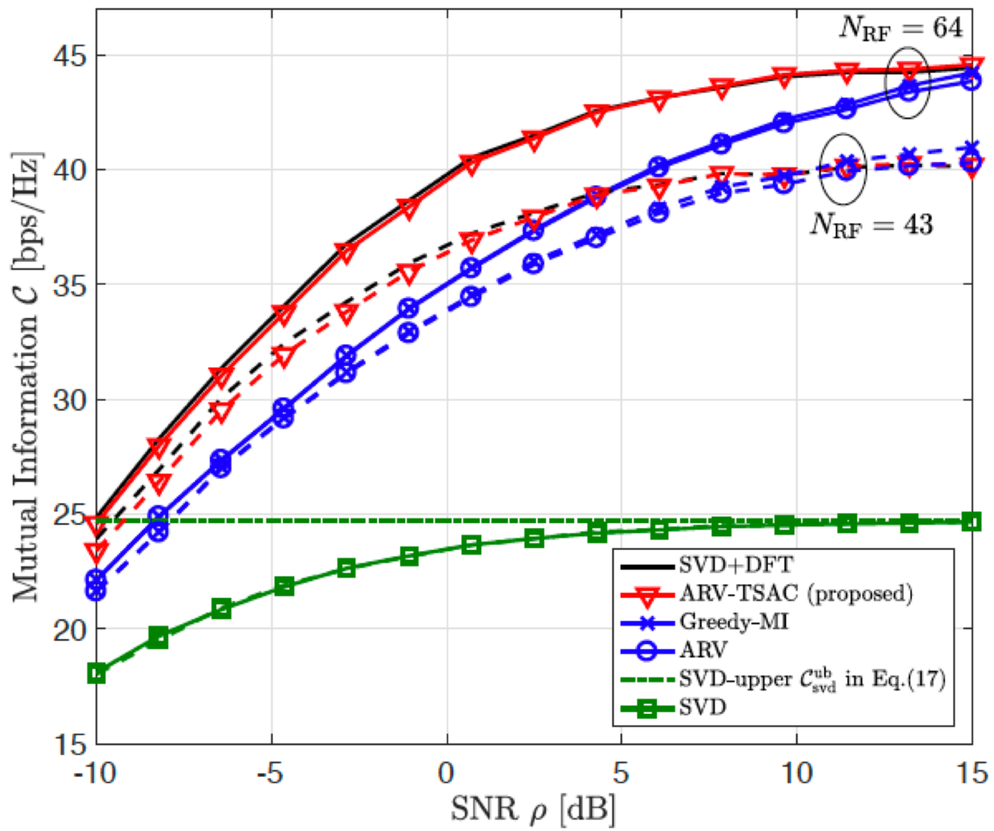
3) **SVD+DFT**: two-stage analog combining in Theorem 1
with $\mathbf{W}_{\mathrm{RF}_1} = \mathbf{U}_{1:N_{\mathrm{RF}}}$,$\mathbf{W}_{\mathrm{RF}_2} = \mathbf{W}_{\mathrm{DFT}}$

4) **SVD**: one-stage analog combing with $\mathbf{W}_{\mathrm{RF}} = \mathbf{U}_{1:N_{\mathrm{RF}}}$.

5) **Greedy-MI**: one-stage analog combining
with greedy-based MI maximization

MI vs. SNR

Figure 5

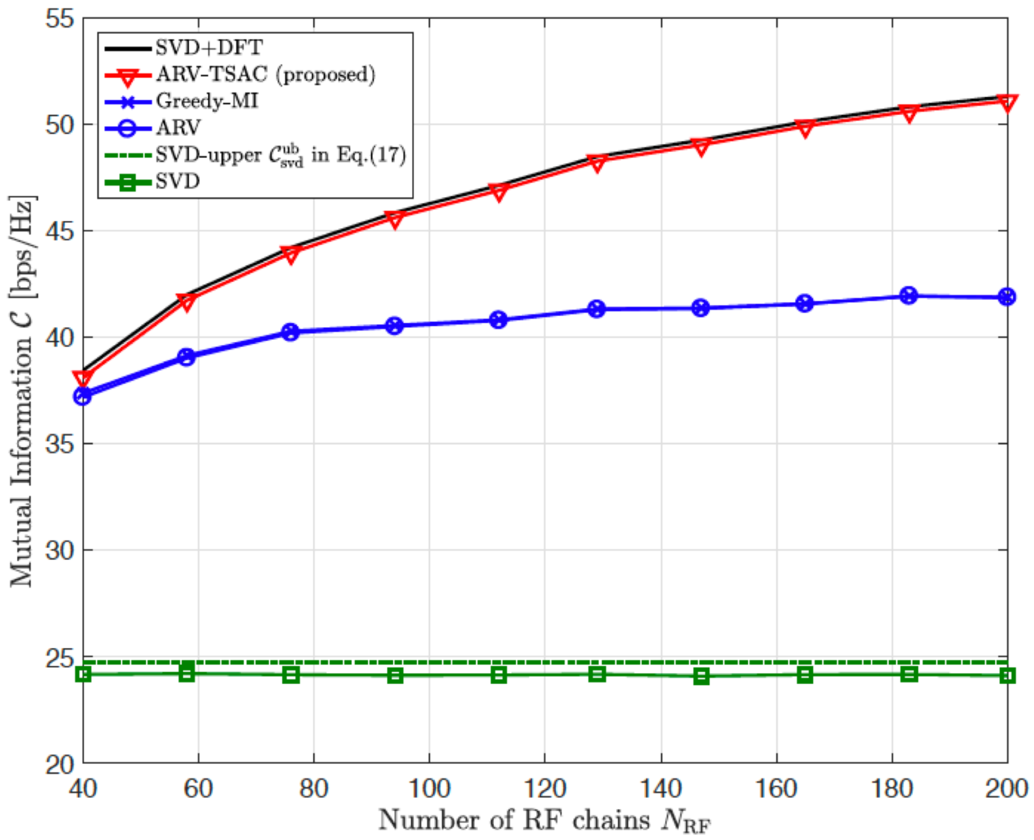


(N_r = 128 , N_u = 8, b = 2, channel paths = 3)

SIMULATION RESULTS (cont'd)

MI vs. N_{RF} (Fixed N_r)

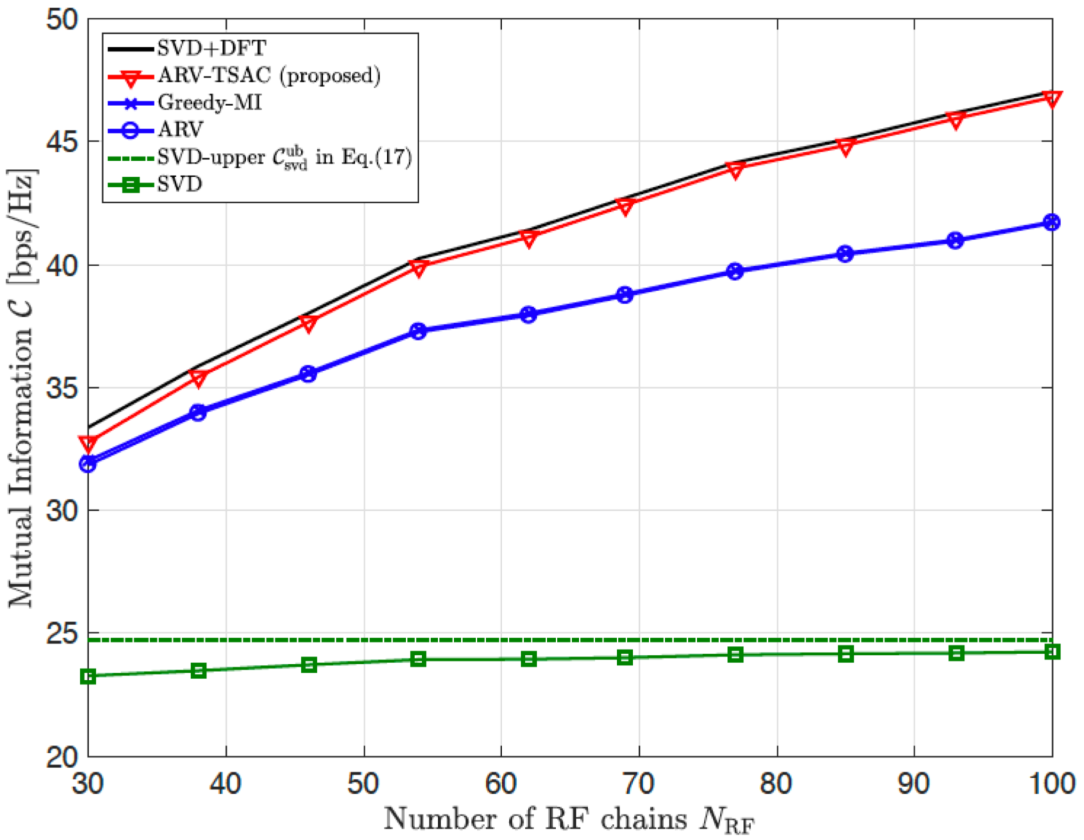
Figure 2



(SNR = 0 dB, N_r = 256, N_u = 8, b = 2, paths = 4)

MI vs. N_{RF} (Fixed $k = N_{RF}/N_r$)

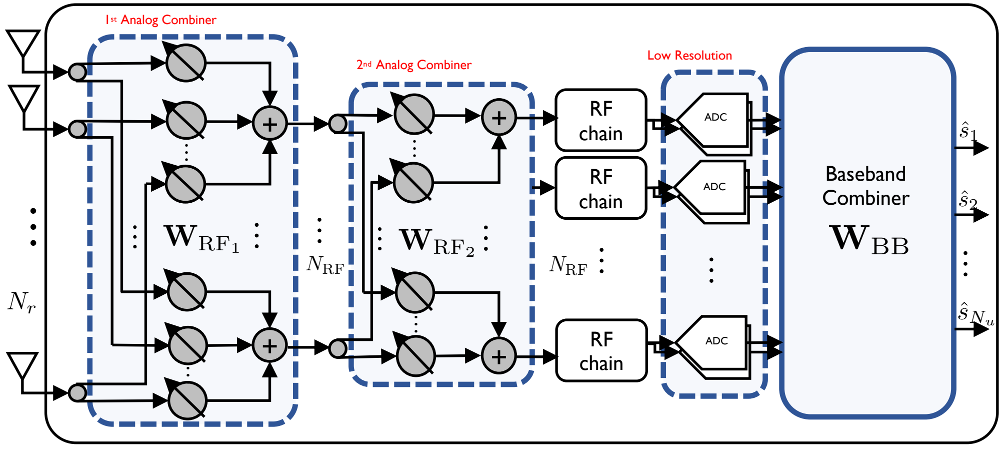
Figure 3



(SNR = 0 dB, $k = N_{RF}/N_r$ = 1/3, N_u = 8, b = 2, paths = 4)

SUMMARY

Proposed receiver architecture



Two-stage analog combining hybrid receiver

Optimality

Optimal scaling law

$$\mathcal{C}(\mathbf{W}_{\mathrm{RF}}^{\mathrm{opt}}) \sim N_u \log_2 N_{\mathrm{RF}}$$

Optimal mutual information

$$\mathcal{C}_{\mathrm{opt}} \triangleq \mathcal{C}(\mathbf{W}_{\mathrm{RF}}^{\star}) = N_u \log_2 \left(1 + \frac{\alpha_b \lambda N_{\mathrm{RF}}}{\lambda N_u (1-\alpha_b) + N_{\mathrm{RF}}/\rho}\right)$$

Algorithm

ARV-TSAC algorithm

$$\tilde{\mathbf{W}}_{\mathrm{RF}}^{\star} = \mathbf{W}_{\mathrm{AoA}} \mathbf{W}_{\mathrm{DFT}}$$

Related Articles

Conference paper

Jinseok Choi, Gilwon Lee, and Brian L. Evans, "A Hybrid Beamforming Receiver with Two-Stage Analog Combiner and Low-Resolution ADCs", *IEEE Int. Conf. on Communications*, 2019, accepted for publication.

Journal article

Jinseok Choi, Gilwon Lee, and Brian L. Evans, "Two-Stage Analog Combining in Hybrid Beamforming Systems with Low-Resolution ADCs", *IEEE Transactions on Signal Processing*, vol. 67, no. 9, pp. 2410-2425, May 1, 2019.

Thank you