Sum-Rates for Wyner-type C-RAN Uplink with Inter-Connected Oblivious Radio Units

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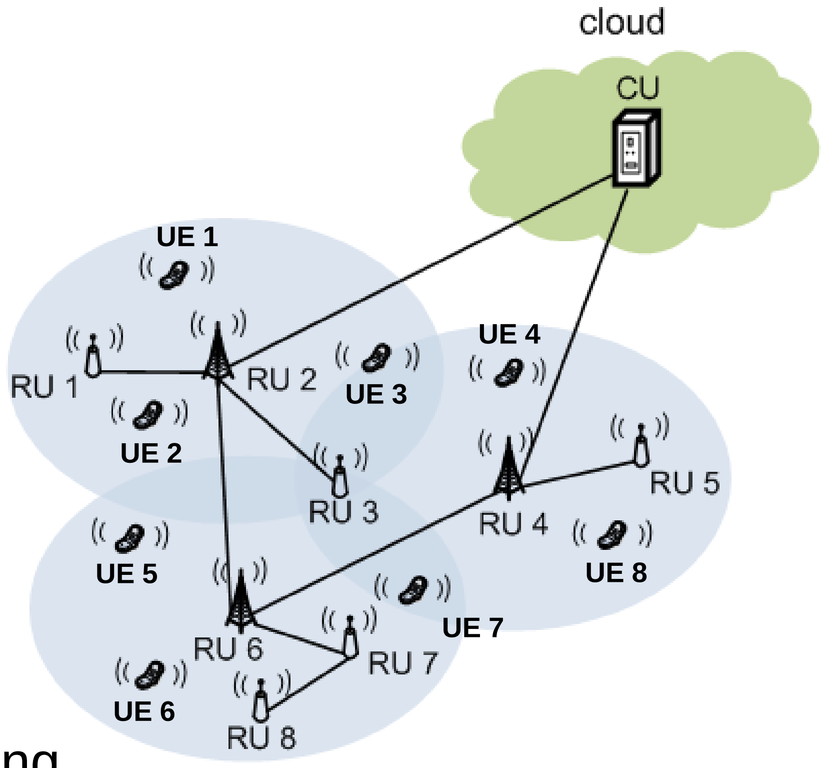
Outline

- **Introduction**
- System Model
- Point-to-Point Compression
- Leveraging Side Information
- Joint Decompression and Decoding
- Concluding Remarks

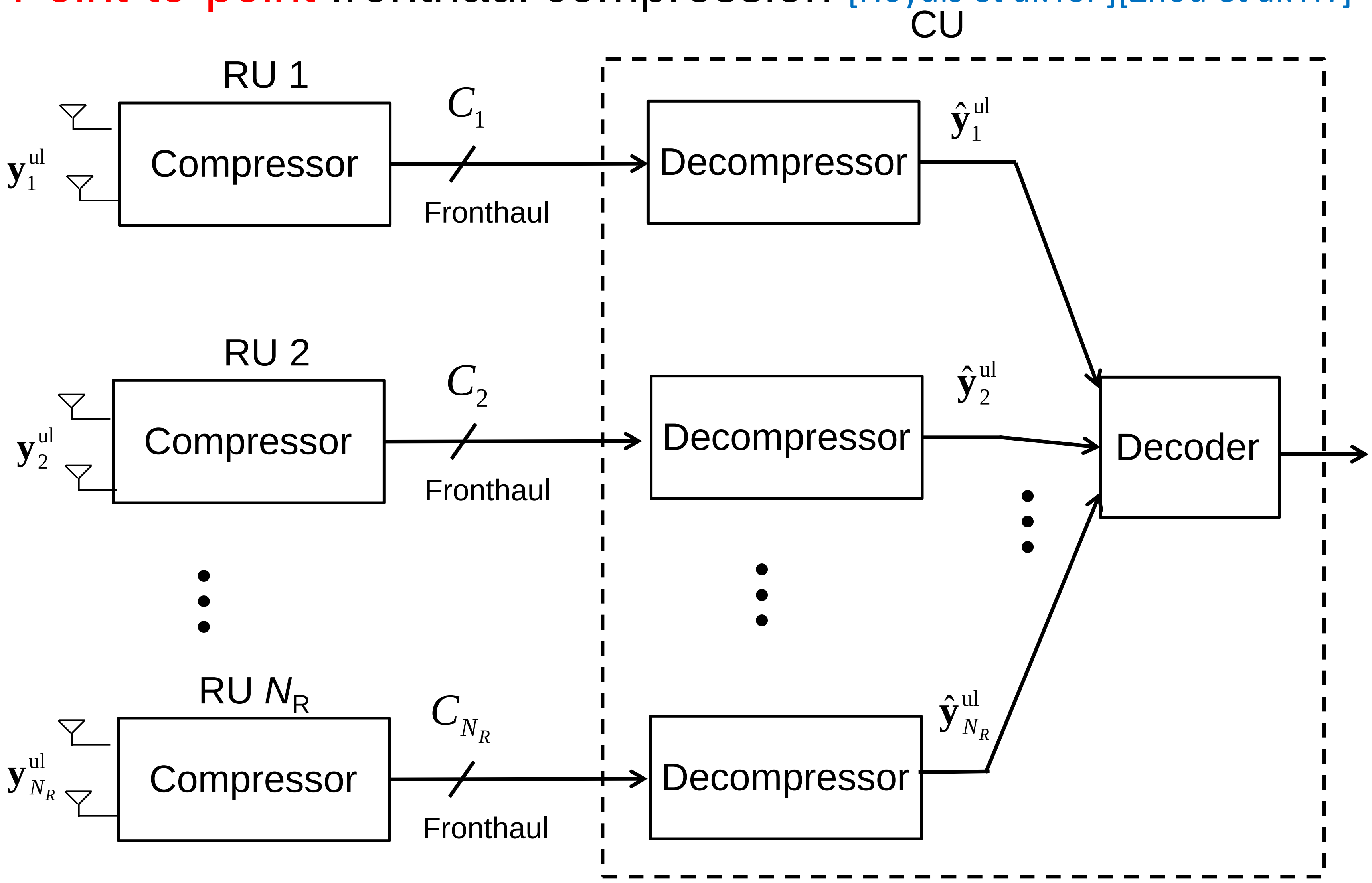
Cloud Radio Access Network (C-RAN)

- Base Stations (BSs) operate as radio units (RUs) [China][Simeone et al:JCN].
- Baseband processing takes place in the "cloud".
- Fronthaul links carry complex (IQ) baseband signals [CPRI][IDC][Andrews et al:JSAC].
- Advantages
  - Low-cost deployment of BSs [China][Segel-Weldon]
  - Effective interference mitigation via joint baseband processing [Shamai et al:JWCC][Somekh et al:TIT]



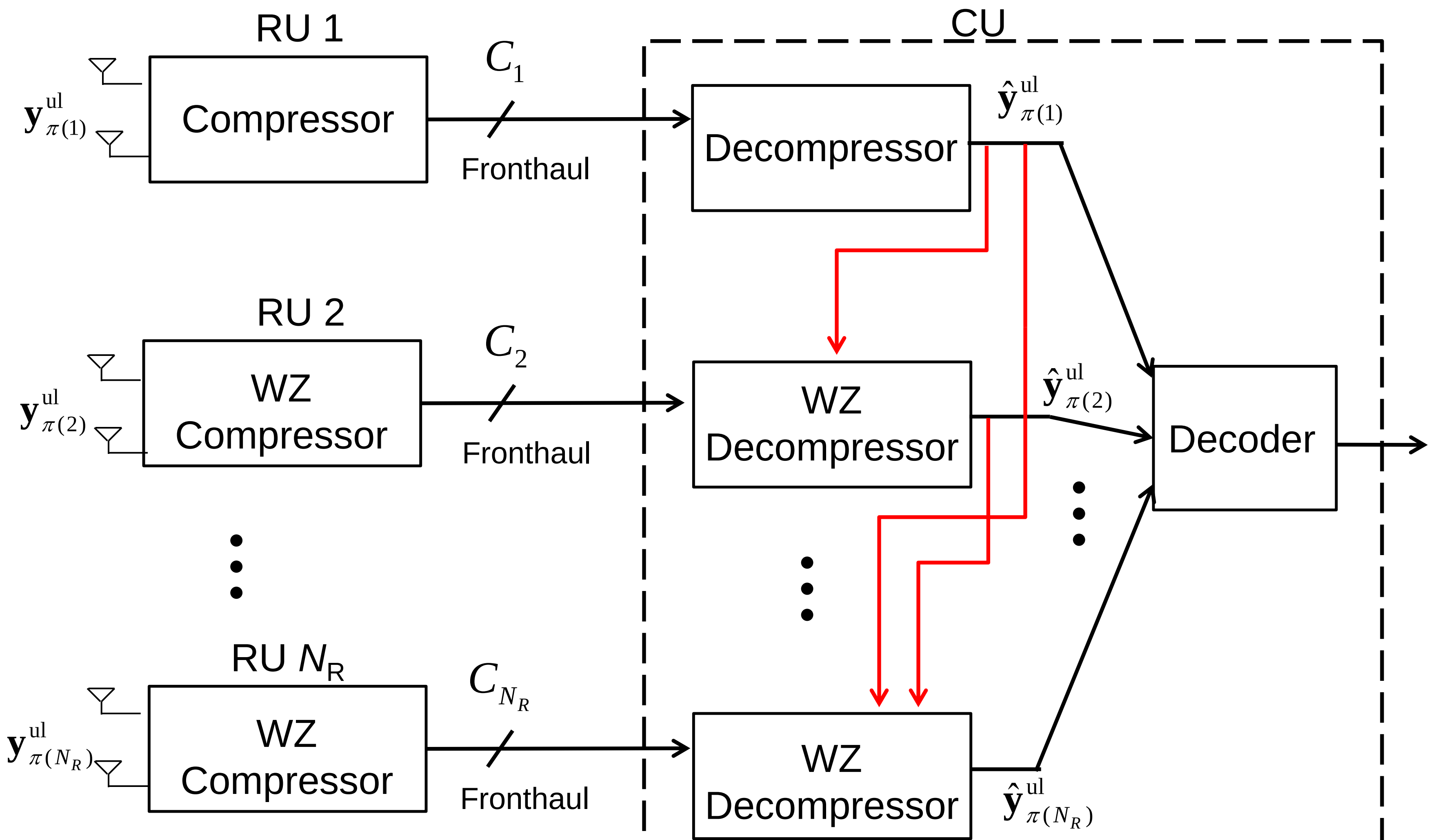
State-of-the-Art

- Point-to-point fronthaul compression [Hoydis et al:TSP][Zhou et al:TIT]



State-of-the-Art

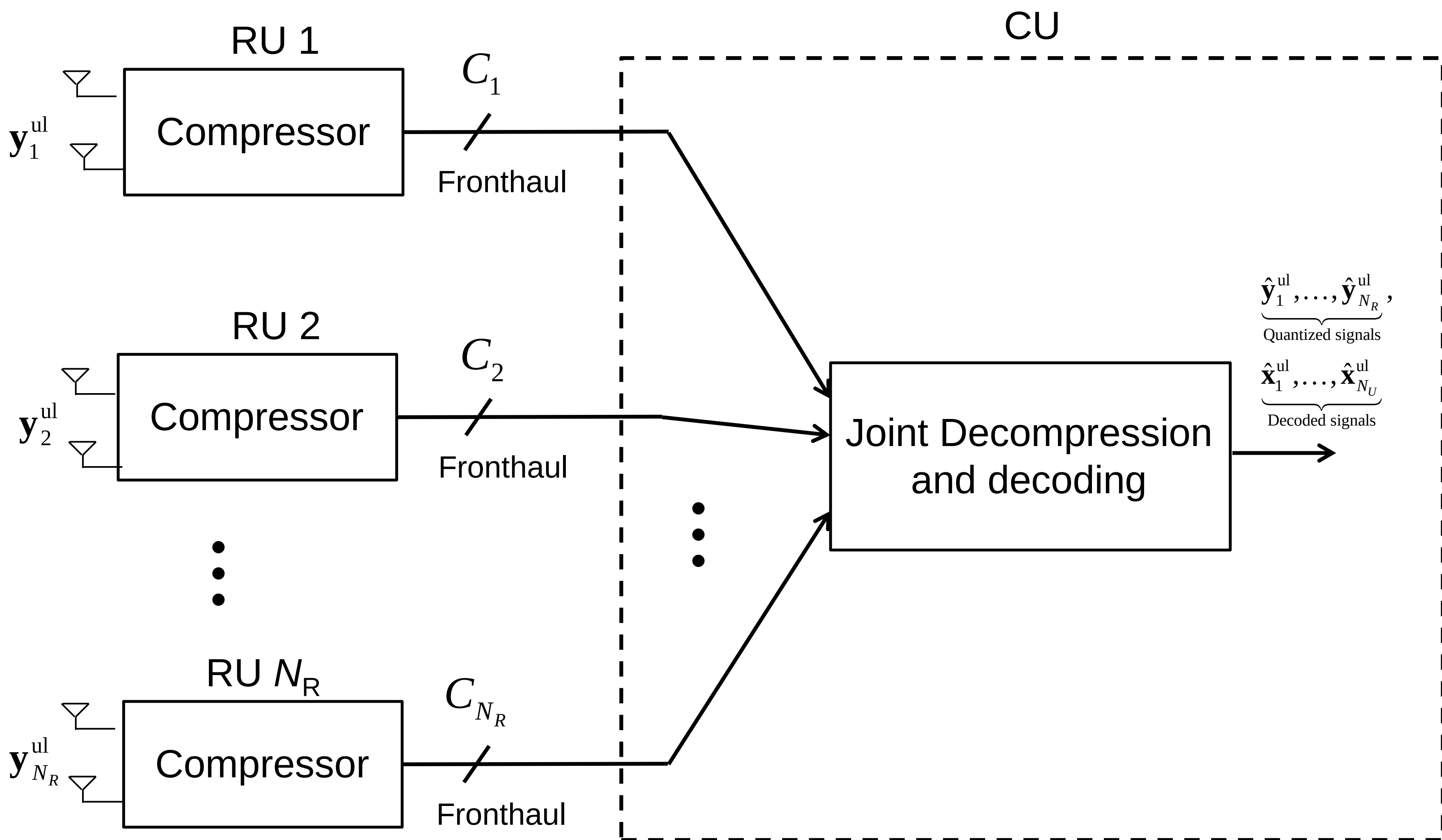
- Distributed fronthaul compression
  [Sanderovich et al:TIT][dCoso-Simosens][Zhou-Yu:JSAC][Park et al:SPM][Zhou et al:TIT]



π denotes a permutation of RUs' indexes.

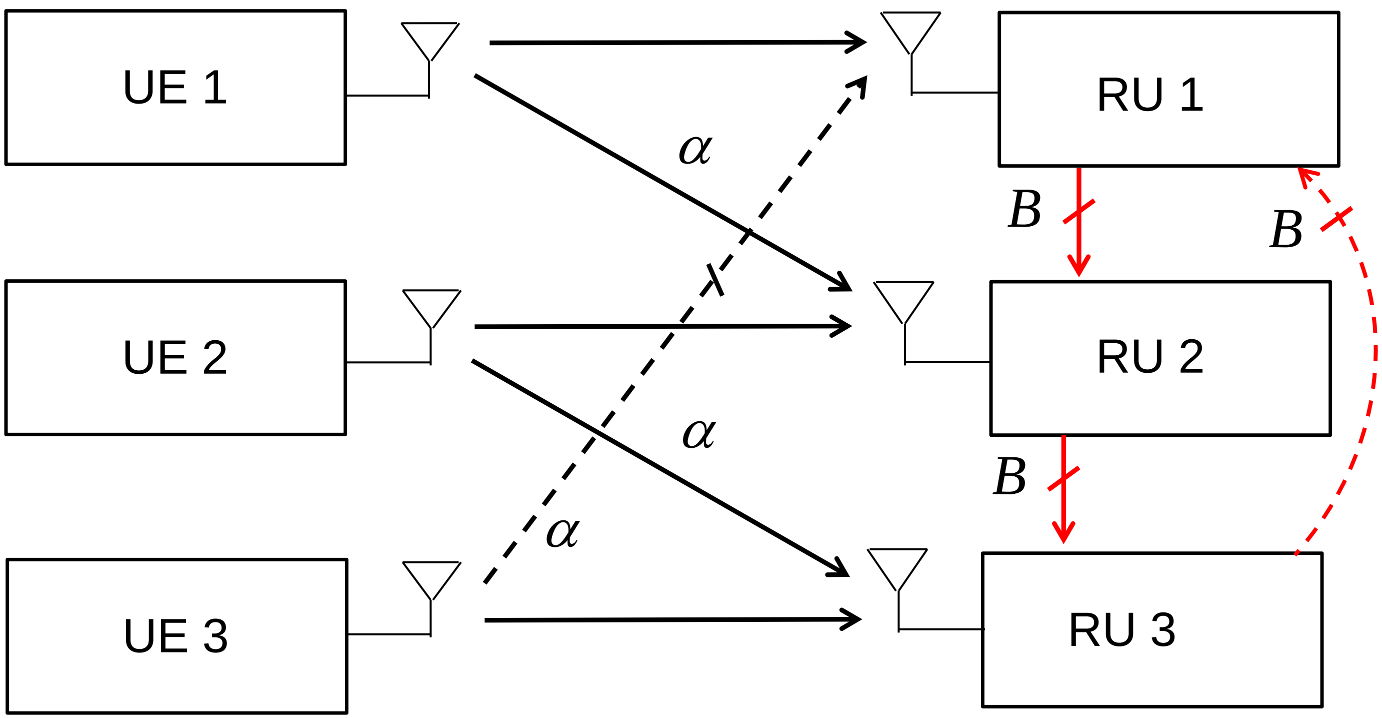
State-of-the-Art

- Joint decompression and decoding (JDD)
  [Sanderovich et al:TIT][Lim et al:TIT][Park et al:SPL][Zhou et al:TIT]



State-of-the-Art

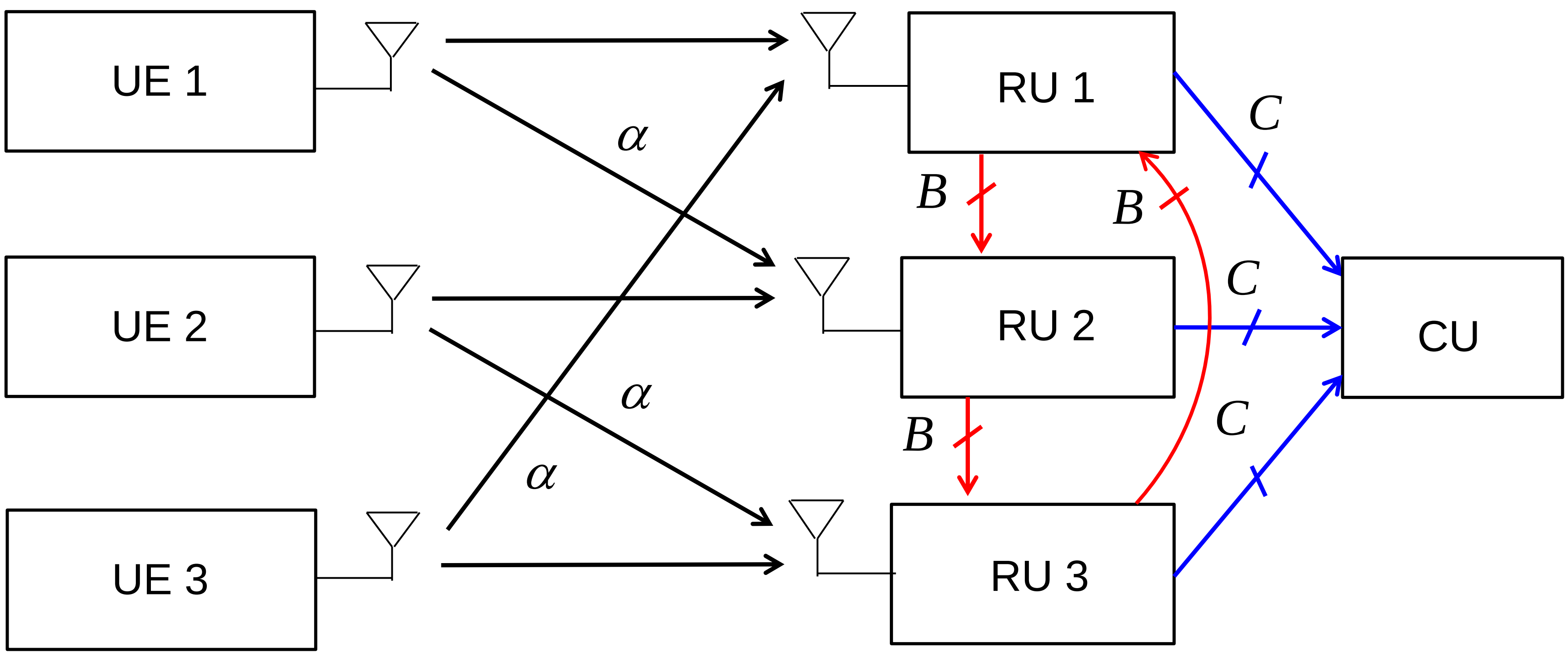
- Inter-RU cooperation for non-cooperative cellular systems:
  - Analysis for Wyner, Circular Wyner models [Simeone et al:TIT][Simeone et al:FnT]



  - Other UE and/or Cell-Sites cooperation in Wyner Model [Wigger et al:TIT]

Main Contributions

- Inter-RU cooperation for the uplink of C-RAN:
  - Analysis for circular Wyner model



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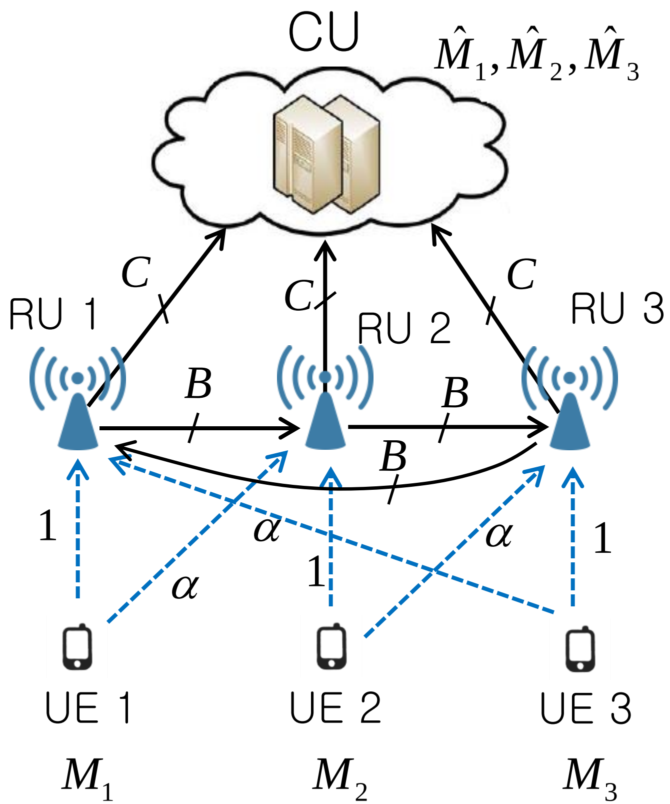
System Model

- Wyner-type C-RAN uplink
  - N pairs of RU-UE ($\mathcal{N} = \{1, 2, \ldots, N\}$)
  - Fronthaul connections
    - C bit/symbol between RU-CU
    - B bit/symbol between RU-RU
  - Uplink channel

$$Y_i = X_i + \alpha X_{[i-1]} + Z_i,$$

where Y_i: Rx signal RU i,
X_i: Tx signal of UE i,
Z_i: Noise at RU i with $Z_i \sim N(0, \sigma^2)$,
α: Inter-cell channel gain with $\alpha \in [0,1]$.



<Example for $N = 3$>

Encoding at UEs

- Encoding at UE i
  - Message $M_i \in \{1, 2, \ldots, 2^{nR_i}\}$

    where R_i is the rate of the message,
    n is the coding block length (assumed to be sufficiently large).

  - Encoded signal X_i
    - Message M_i is encoded to obtain an encoded signal

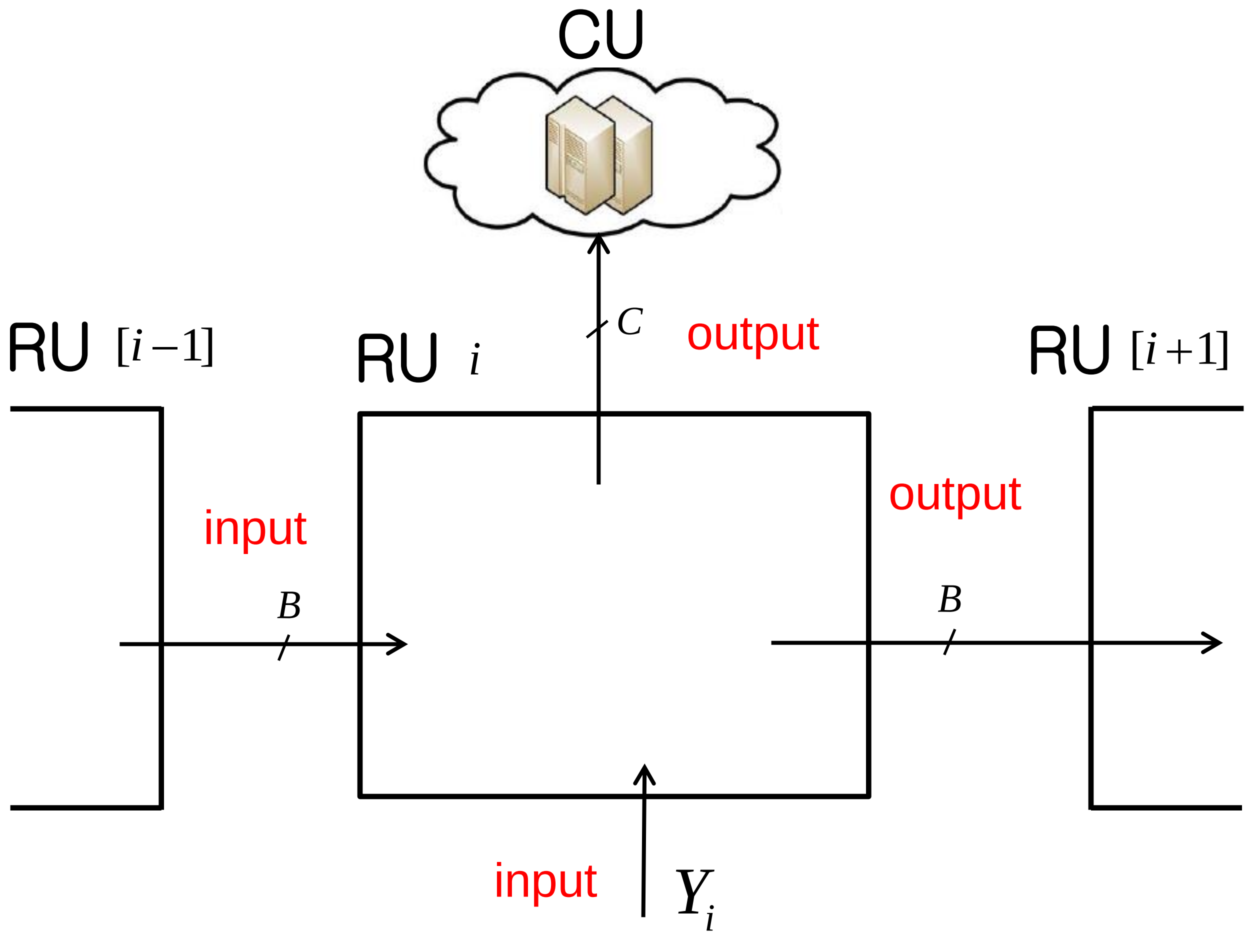
$$X_i \sim N(0, P).$$

    - Signal-to-noise ratio (SNR) of the uplink channel

$$\mathrm{SNR} = \frac{P}{\sigma^2}.$$

Oblivious Processing at RUs

- In-network processing (INP) at RU i



- Oblivious/Nomadic: no structure information (code-books) of UE's is available at the RUs

Oblivious Processing at RUs

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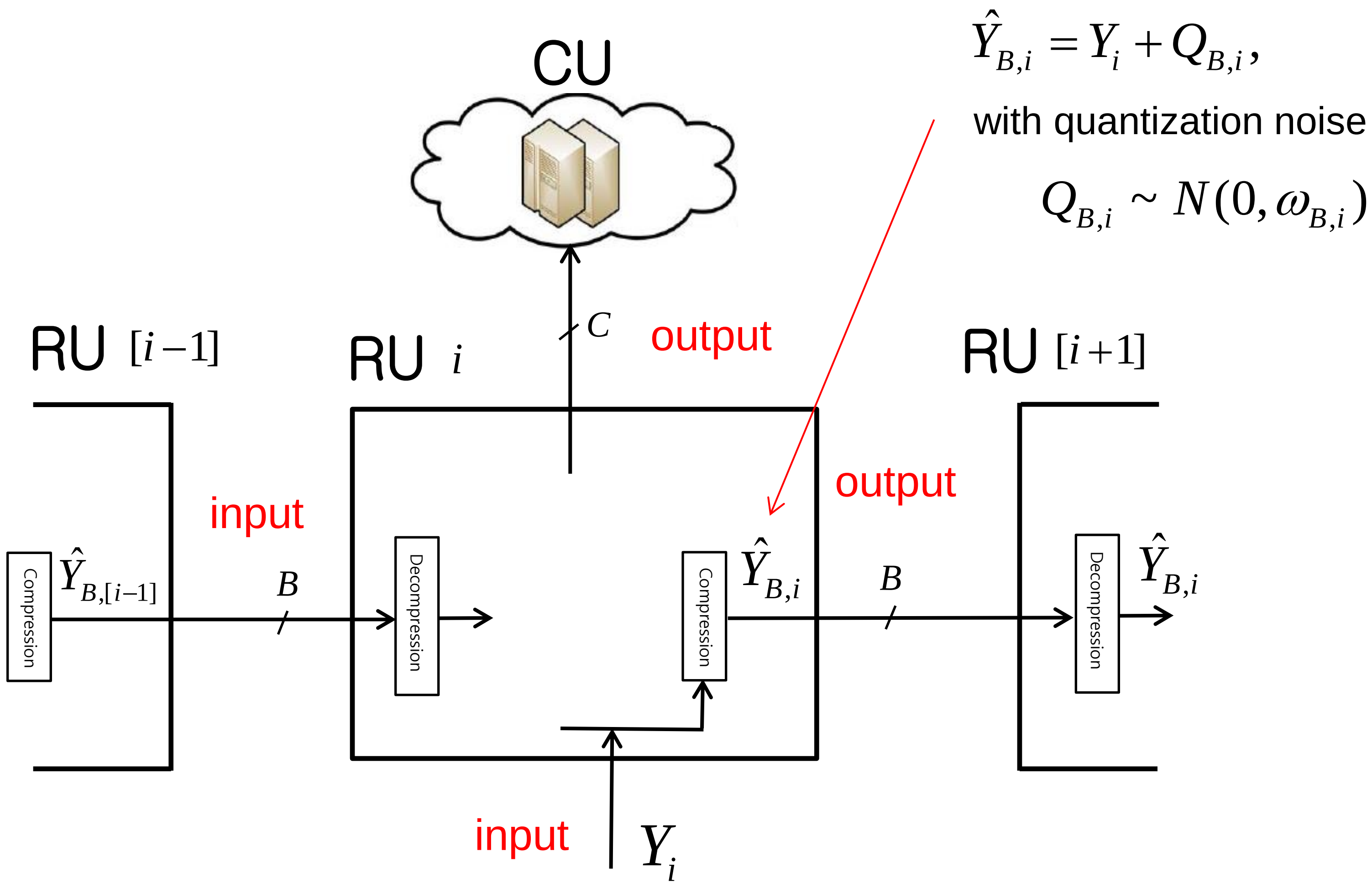


  - Oblivious/Nomadic: no structure information (code-books) of UE's is available at the RUs

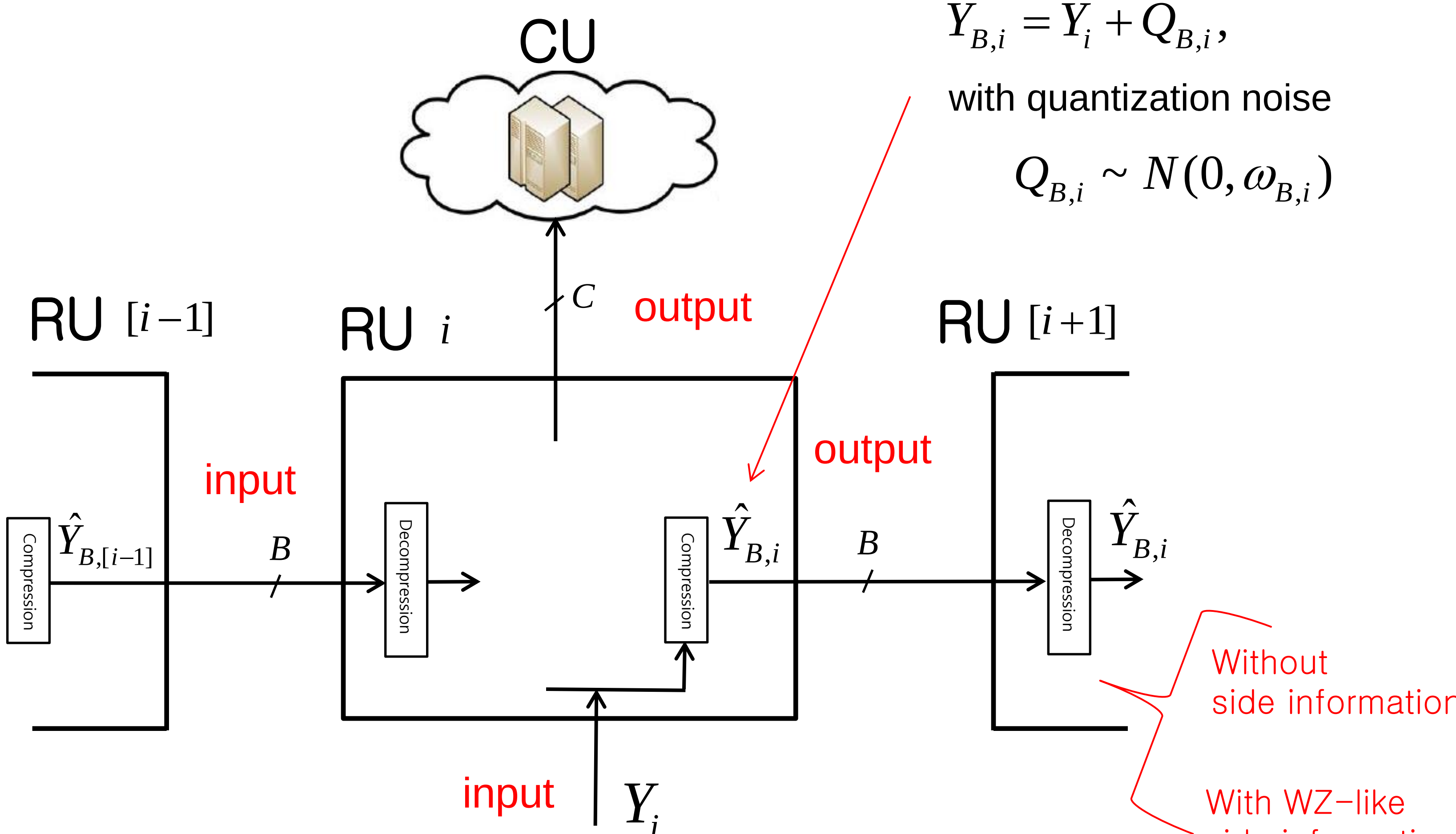
Oblivious Processing at RUs

- In-network processing (INP) at RU i

$$\hat{Y}_{B,i} = Y_i + Q_{B,i},$$

with quantization noise

$$Q_{B,i} \sim N(0, \omega_{B,i})$$



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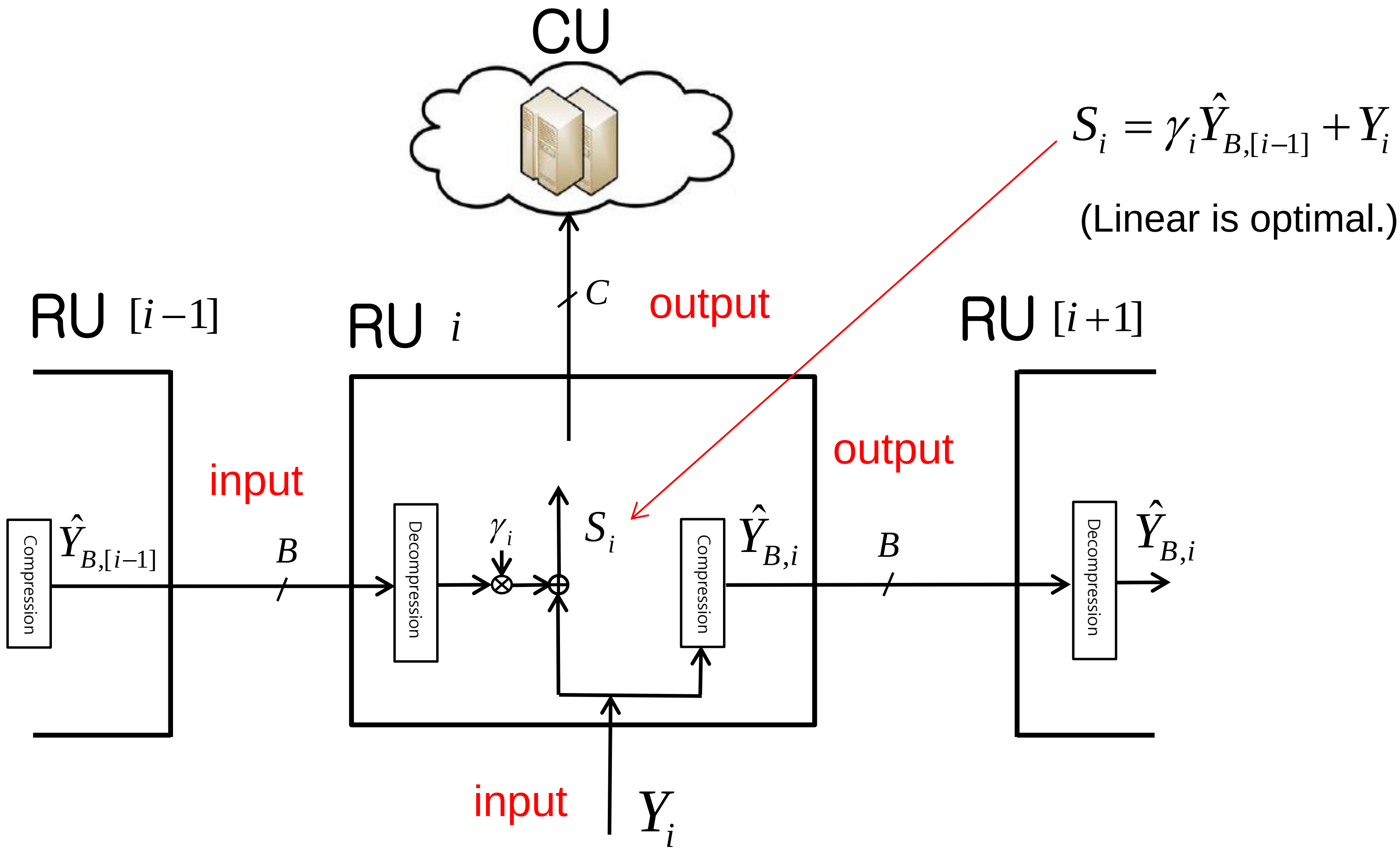


  - Oblivious/Nomadic: no structure information (code-books) of UE's is available at the RUs

Oblivious Processing at RUs

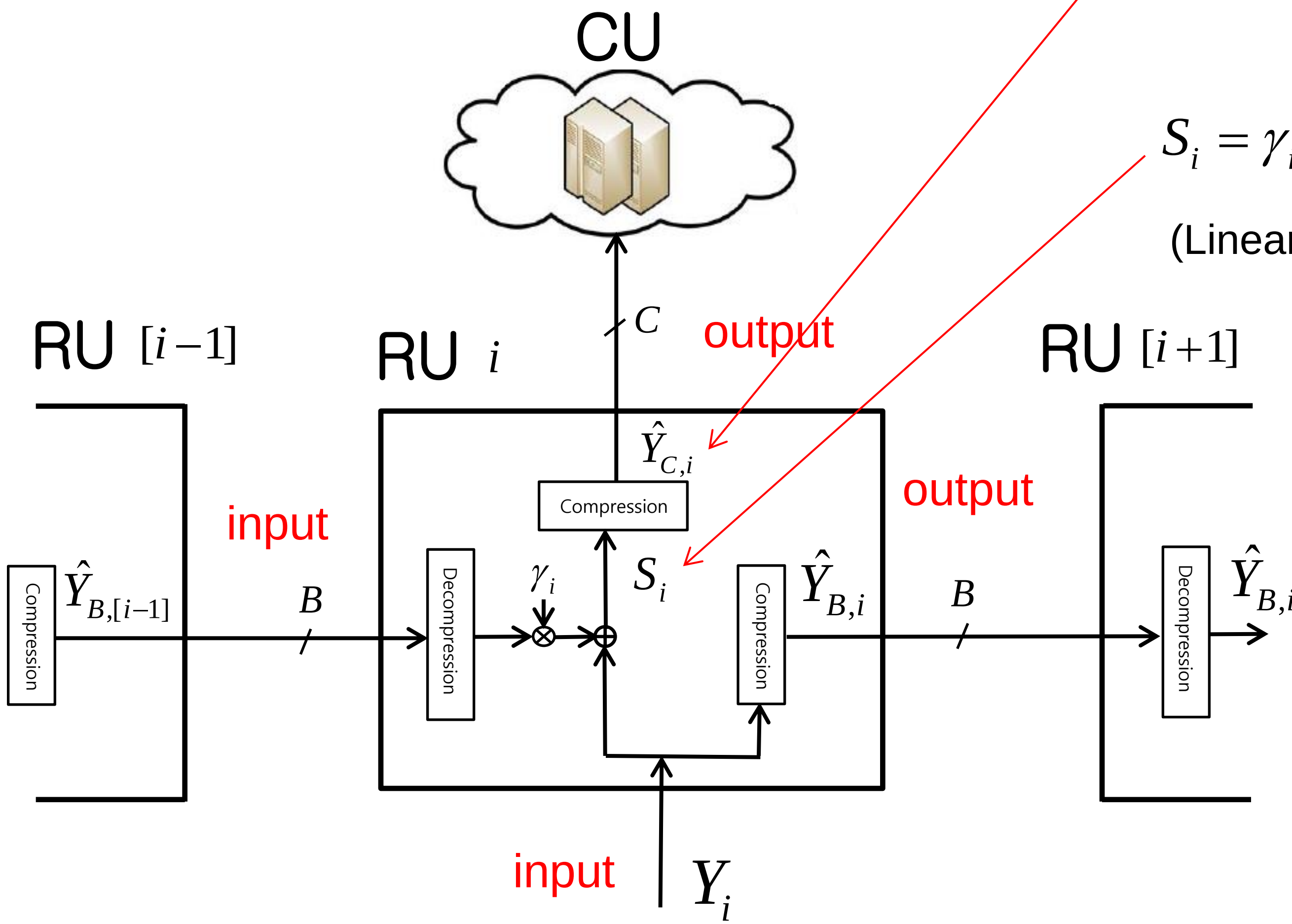
- In-network processing (INP) at RU i

$$\hat{Y}_{C,i} = S_i + Q_{C,i}$$

with $Q_{C,i} \sim N(0, \omega_{C,i})$

$$S_i = \gamma_i \hat{Y}_{B,[i-1]} + Y_i$$

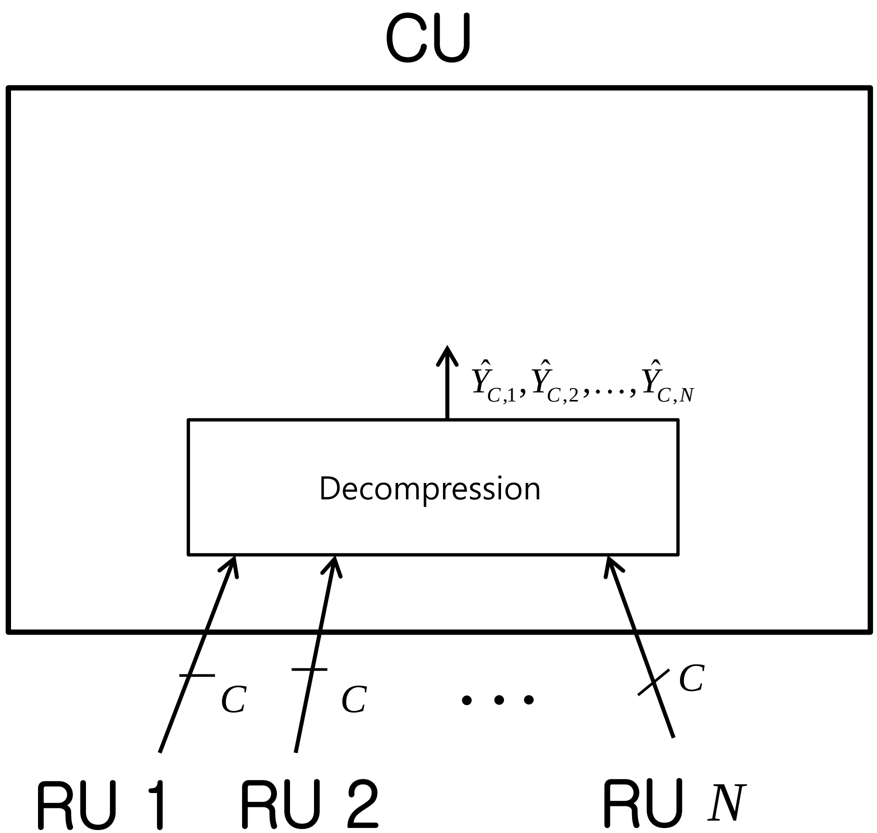
(Linear is optimal.)



- Oblivious/Nomadic: no structure information (code-books) of UE's is available at the RUs

Decoding at CU

- Decompression and decoding at CU
  - CU recovers the quantized INP output signals $\hat{Y}_{C,1}, \hat{Y}_{C,2}, \ldots, \hat{Y}_{C,N}$.



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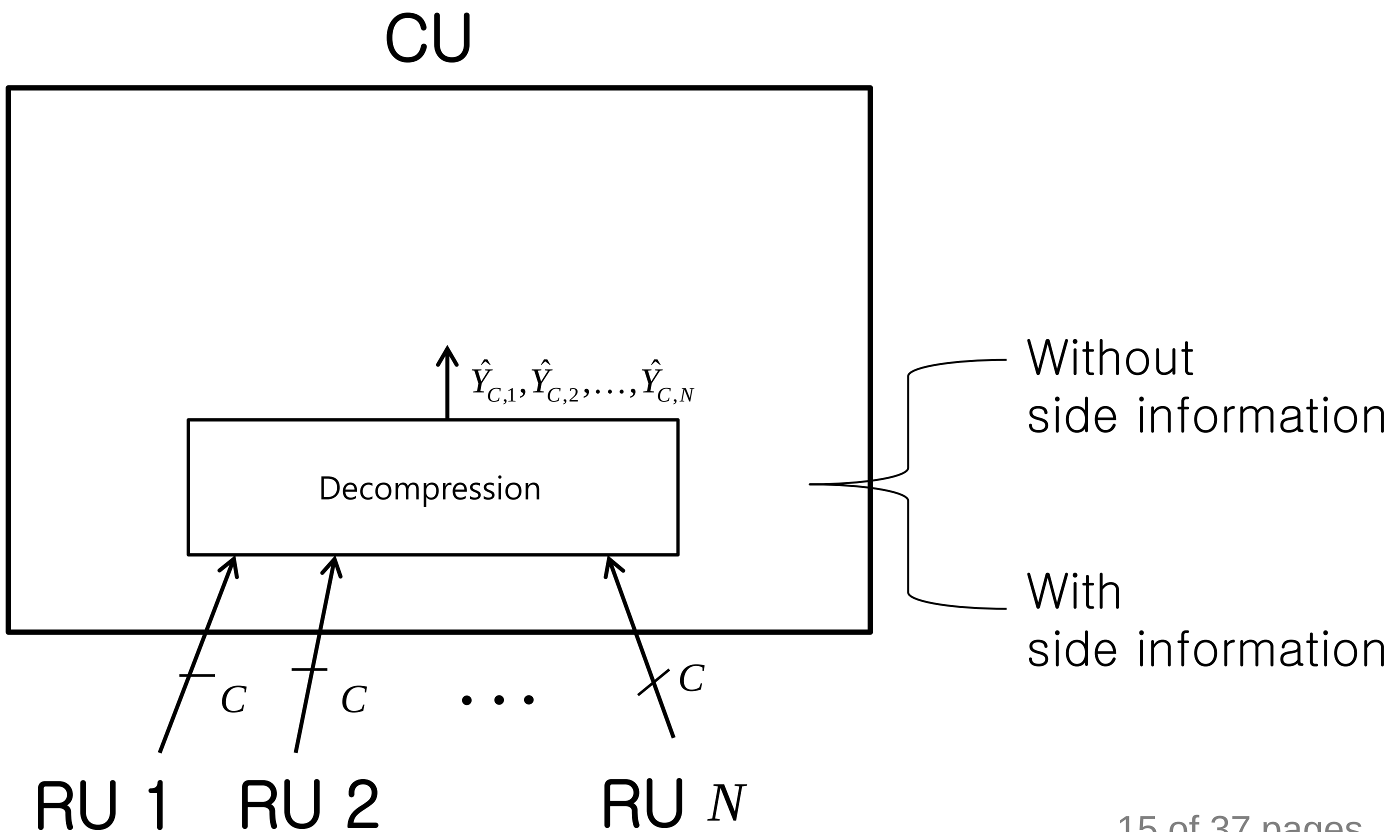
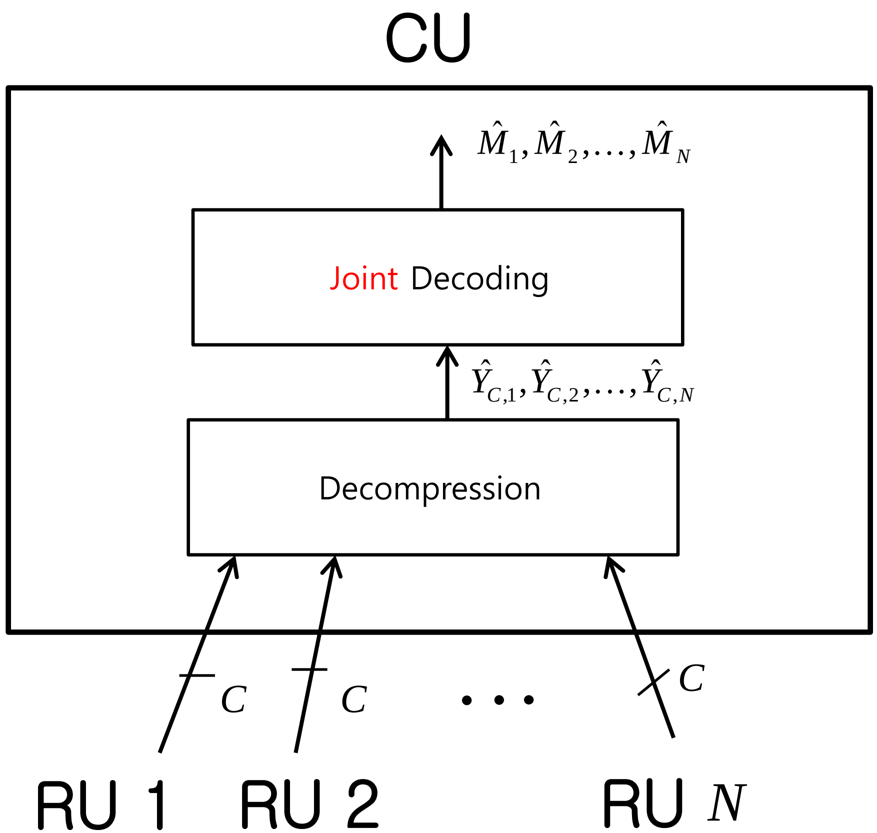


Decoding at CU

- Decompression and decoding at CU
  - CU recovers the quantized INP output signals $\hat{Y}_{C,1}, \hat{Y}_{C,2}, \ldots, \hat{Y}_{C,N}$.
  - Then, it jointly decodes the messages $\hat{M}_1, \hat{M}_2, \ldots, \hat{M}_N$.



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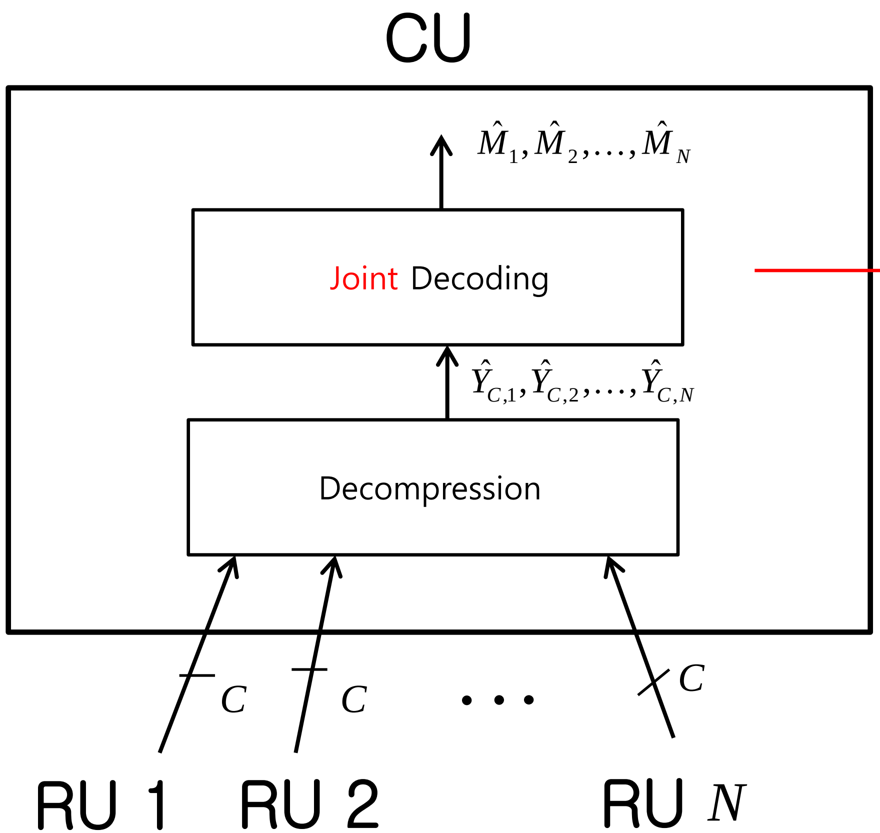

$$R_{\text{sum}} = \sum_{i \in \mathcal{N}} R_i$$
$$= I\left(\{X_i\}_{i\in\mathcal{N}}; \{\hat{Y}_{C,i}\}_{i\in\mathcal{N}}\right)$$

Decoding at CU

- Vector expression of quantized signals $\{\hat{Y}_{C,i}\}_{i\in\mathcal{N}}$

$$\underbrace{\begin{bmatrix} \hat{Y}_{C,1} \\ \hat{Y}_{C,2} \\ \vdots \\ \hat{Y}_{C,N} \end{bmatrix}}_{\hat{\mathbf{Y}}_C} = \mathbf{H}_X \underbrace{\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{bmatrix}}_{\mathbf{X}} + \mathbf{H}_Z \underbrace{\begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_N \end{bmatrix}}_{\mathbf{Z}} + \mathbf{H}_Q \underbrace{\begin{bmatrix} Q_{B,1} \\ Q_{B,2} \\ \vdots \\ Q_{B,N} \end{bmatrix}}_{\mathbf{Q}_B} + \underbrace{\begin{bmatrix} Q_{C,1} \\ Q_{C,2} \\ \vdots \\ Q_{C,N} \end{bmatrix}}_{\mathbf{Q}_C},$$

where $\mathbf{H}_X = \mathbf{I} + (\gamma+\alpha)\mathbf{E}_1 + \gamma\alpha\mathbf{E}_2,$ with $\mathbf{E}_1 = \text{circulant matrix with first row } [0 \cdots 0\ 0\ 1],$

$\mathbf{H}_Z = \mathbf{I} + \gamma\mathbf{E}_1,$ $\mathbf{E}_2 = \text{circulant matrix with first row } [0 \cdots 0\ 1\ 0].$

$\mathbf{H}_Q = \gamma\mathbf{E}_1,$ (We have $\mathbf{E}_1\mathbf{E}_1^T = \mathbf{E}_2\mathbf{E}_2^T = \mathbf{I},\ \mathbf{E}_1\mathbf{E}_2^T = \mathbf{E}_1^T,\ \mathbf{E}_2\mathbf{E}_1^T = \mathbf{E}_1$)

Decoding at CU

- Sum-rate R_{sum} can be written as

$$R_{\text{sum}} = I\left(\{X_i\}_{i\in\mathcal{N}}; \{\hat{Y}_{C,i}\}_{i\in\mathcal{N}}\right)$$
$$= \frac{1}{2}\log_2 \det\left(\mathbf{I} + P\left(\sigma^2 \mathbf{H}_Z \mathbf{H}_Z^T + \omega_B \mathbf{H}_Q \mathbf{H}_Q^T + \omega_C \mathbf{I}\right)^{-1} \mathbf{H}_X \mathbf{H}_X^T\right)$$
$$= \frac{1}{2}\sum_{i\in\mathcal{N}} \log_2\left(1 + P\frac{1+(\gamma+\alpha)^2+\gamma^2\alpha^2+(\gamma+\alpha)(1+\gamma\alpha)\lambda_{1,i}+\gamma\alpha\lambda_{2,i}}{\sigma^2\gamma\lambda_{1,i}+\sigma^2(\gamma^2+1)+\omega_B\gamma^2+\omega_C}\right),$$

where $\lambda_{k,l}$: lth largest eigenvalue of $\mathbf{E}_k + \mathbf{E}_k^T$ given as

$$\lambda_{k,l} = 2\cos\left(2k\pi\frac{l-1}{N}\right).$$

Design Space

- Optimization variables
  - ω_B : quantization noise power for RU-RU links
  - ω_C : quantization noise power for RU-CU links
  - γ : combining coefficient for in-network processing
- Objective function
  - Sum-rate R_{sum}
- Constraints
  - Capacity B of RU-RU links
  - Capacity C of RU-CU links

Design Space

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- Optimization variables
  - ω_B : quantization noise power for RU-RU links
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  - γ : combining coefficient for in-network processing

- Objective function
  - Sum-rate R_{sum}

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  - Capacity B of RU-RU links
  - Capacity C of RU-CU links

Modeled differently depending on decompression strategy

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Point-to-Point Compression

- In this strategy, the quantized signals $\hat{Y}_{B,i}$ and $\hat{Y}_{C,i}$ are decompressed without leveraging side information.

- Constraints on ω_B for RU-RU links [ElGamal-Kim, Ch. 3]

$$I(Y_i;\hat{Y}_{B,i}) = \frac{1}{2}\log_2\left(1+\frac{P(1+\alpha^2)+\sigma^2}{\omega_B}\right) \le B.$$

- Constraints on ω_C for RU-CU links [ElGamal-Kim, Ch. 3]

$$I(\underbrace{\gamma\hat{Y}_{B,[i-1]}+Y_i}_{S_i};\hat{Y}_{C,i}) = \frac{1}{2}\log_2\left(1+\frac{\left(\gamma^2\alpha^2+(\gamma+\alpha)^2+1\right)P+\gamma^2\omega_B+(1+\gamma^2)\sigma^2}{\omega_C}\right) \le C.$$

Problem Description

- Sum-rate maximization problem (P1)

$$
\begin{aligned}
\underset{\omega_B,\,\omega_C,\,\gamma}{\text{maximize}} \quad & \frac{1}{2}\sum\nolimits_{i\in\mathcal{N}} \log_2\left(1+P\frac{1+(\gamma+\alpha)^2+\gamma^2\alpha^2+(\gamma+\alpha)(1+\gamma\alpha)\lambda_{1,i}+\gamma\alpha\lambda_{2,i}}{\sigma^2\gamma\lambda_{1,i}+\sigma^2(\gamma^2+1)+\omega_B\gamma^2+\omega_C}\right) \\
\text{s.t.} \quad & \frac{1}{2}\log_2\left(1+\frac{P(1+\alpha^2)+\sigma^2}{\omega_B}\right)\le B, \\
& \frac{1}{2}\log_2\left(1+\frac{\left(\gamma^2\alpha^2+(\gamma+\alpha)^2+1\right)P+\gamma^2\omega_B+(1+\gamma^2)\sigma^2}{\omega_C}\right)\le C.
\end{aligned}
$$

  - The problem is non-convex.

Optimization

- At optimal point, the capacity constraints should be tight.
  - Without loss of optimality, we can set

$$\omega_B = \beta_B \left(P(1+\alpha^2) + \sigma^2 \right),$$
$$\omega_C = \beta_C \left(\left(\gamma^2\alpha^2 + (\gamma+\alpha)^2 + 1 \right) P + \gamma^2\omega_B + (1+\gamma^2)\sigma^2 \right),$$

with $\beta_B = 1/(2^{2B}-1)$ and $\beta_C = 1/(2^{2C}-1)$.

- Therefore, the optimal value for (P1) can be found via one-dimensional search over the coefficient γ.

Upper Bound

- For reference, we consider the Cut-Set upper bound on R_{sum} as

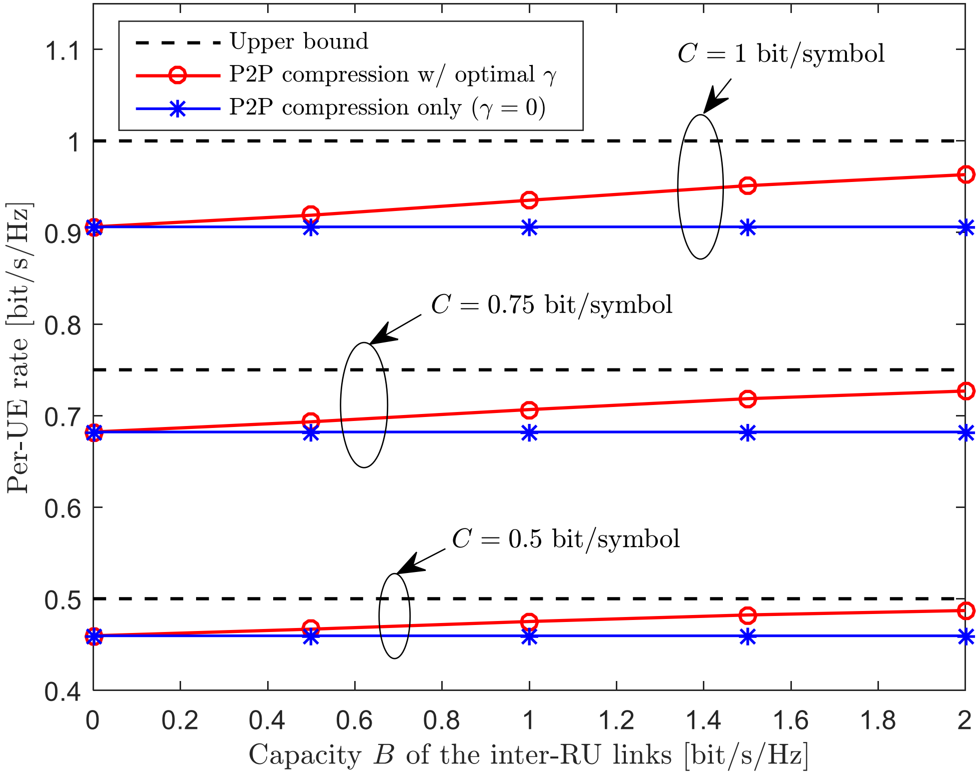
$$R_{\text{sum}} \le \min\left\{NC,\ R_{\text{full}}\right\},$$

where R_{full} is the sum-rate achievable when full cooperation among RUs is possible, i.e.,

$$\begin{aligned} R_{\text{full}} &= I\left(\{X_i\}_{i\in\mathcal{N}};\{Y_i\}_{i\in\mathcal{N}}\right) \\ &= \frac{1}{2}\log_2\det\left(\mathbf{I} + P\left(\sigma^2\mathbf{H}_Z\mathbf{H}_Z^T\right)^{-1}\mathbf{H}_X\mathbf{H}_X^T\right). \end{aligned}$$

Numerical Example

- Per-UE rate versus RU-RU capacity B
  - $N = 3$, $\mathrm{SNR} = 20$ dB, $\alpha = 0.7$



- With INP, the performance approaches upper bound as B increases.

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Leveraging Side Information

- In this strategy, the quantized signals $\hat{Y}_{B,i}$ and $\hat{Y}_{C,i}$ are decompressed while leveraging (WZ-style) side information.

- Decompression for RU-RU links
  - Uplink received signal can be leveraged as side information.
    - As long as inter-cell channel gain $\alpha > 0$

- Decompression for RU-CU links
  - Suppose successive decompression of $\hat{Y}_{C,1}, \hat{Y}_{C,2}, \ldots, \hat{Y}_{C,N}$.
  - Then, previously decompressed signals can be leveraged as side information.

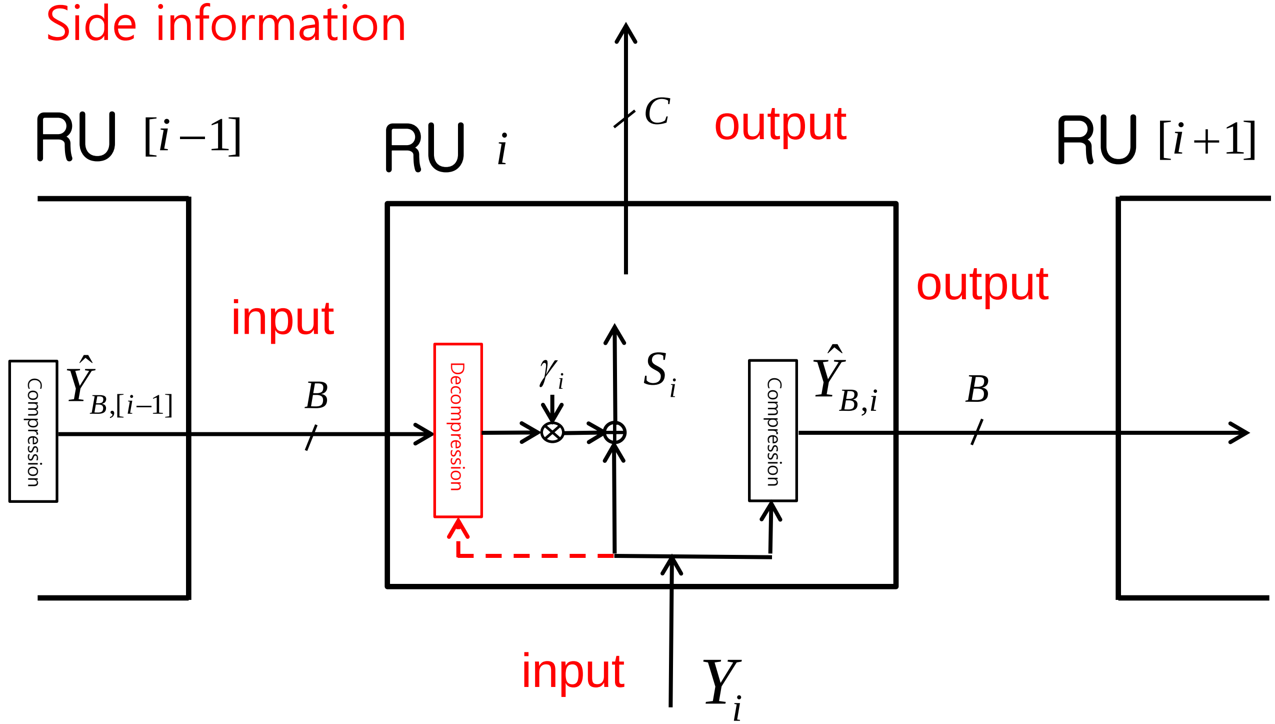
Side Information for RU-RU Links

- Decompression of $\hat{Y}_{B,i}$ at RU $[i+1]$
  - Leveraging side information $Y_{[i+1]}$
  - Constraint on $\omega_{B,i}$ [ElGamal-Kim, Ch. 10]

$$I(Y_i;\hat{Y}_{B,i}\,|\,Y_{[i+1]}) = \frac{1}{2}\log_2\left(1+\frac{E[Y_i^2\,|\,Y_{[i+1]}]}{\omega_{B,i}}\right) \le B,$$

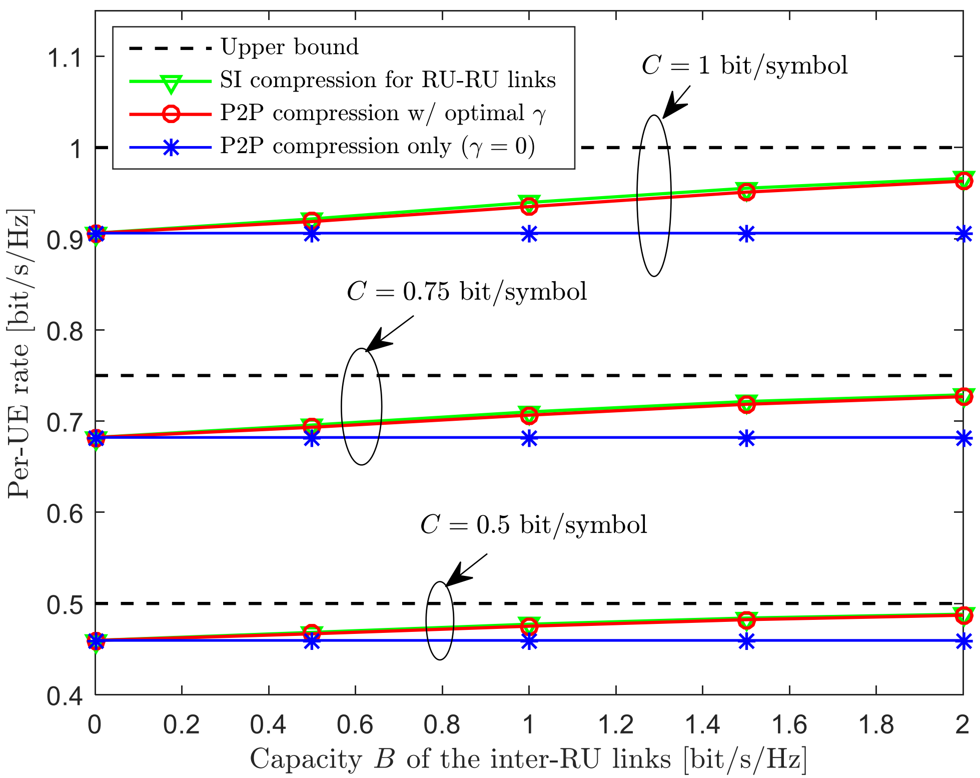
with $E[Y_i^2\,|\,Y_{[i+1]}] = (1+\alpha^2)P+\sigma^2 - \frac{\alpha^2P^2}{(1+\alpha^2)P+\sigma^2}.$

Side information



Numerical Example

- Per-UE rate versus RU-RU capacity B
  - $N = 3$, $\text{SNR} = 20$ dB, $\alpha = 0.7$



– With INP, the performance approaches upper bound as B increases.

- Leveraging SI for RU-RU link provides a slight sum-rate gain.

Side Information for RU-CU Links

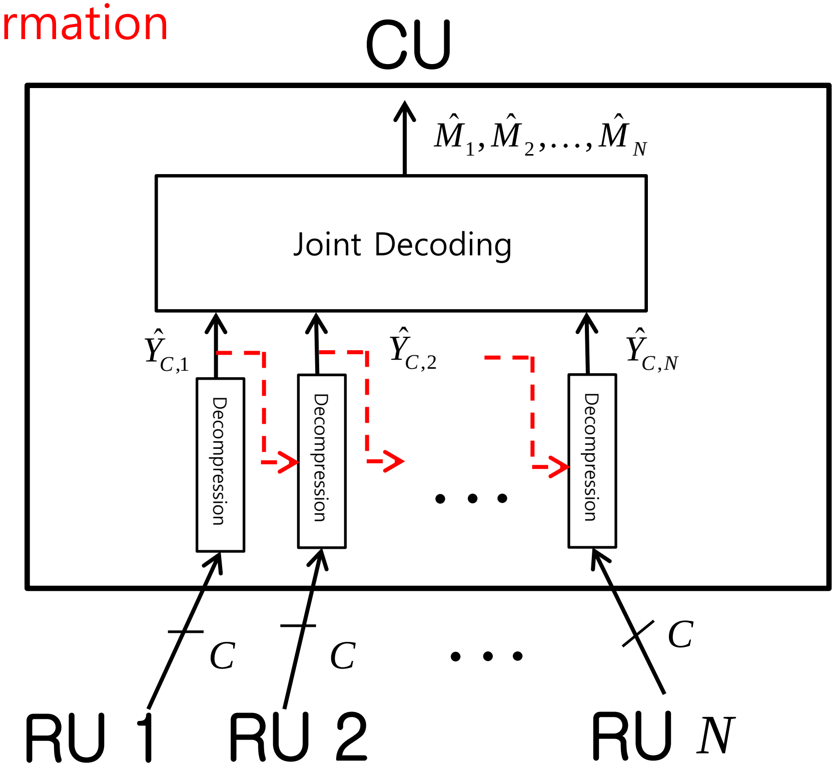
- Decompression of $\hat{Y}_{C,1}, \hat{Y}_{C,2}, \ldots, \hat{Y}_{C,N}$ at CU
  - Consider a successive decompression with order $\hat{Y}_{C,1} \rightarrow \hat{Y}_{C,2} \rightarrow \ldots \rightarrow \hat{Y}_{C,N}$
  - Condition on $\omega_{B,i}$

$$I(S_i; \hat{Y}_{C,i} \mid \hat{Y}_{C,i-1}) = \frac{1}{2}\log_2\left(1 + \frac{E\left[S_i^2 \mid \hat{Y}_{C,i-1}\right]}{\omega_C}\right) \le C,$$

with $E\left[S_i^2 \mid \hat{Y}_{C,i-1}\right]$

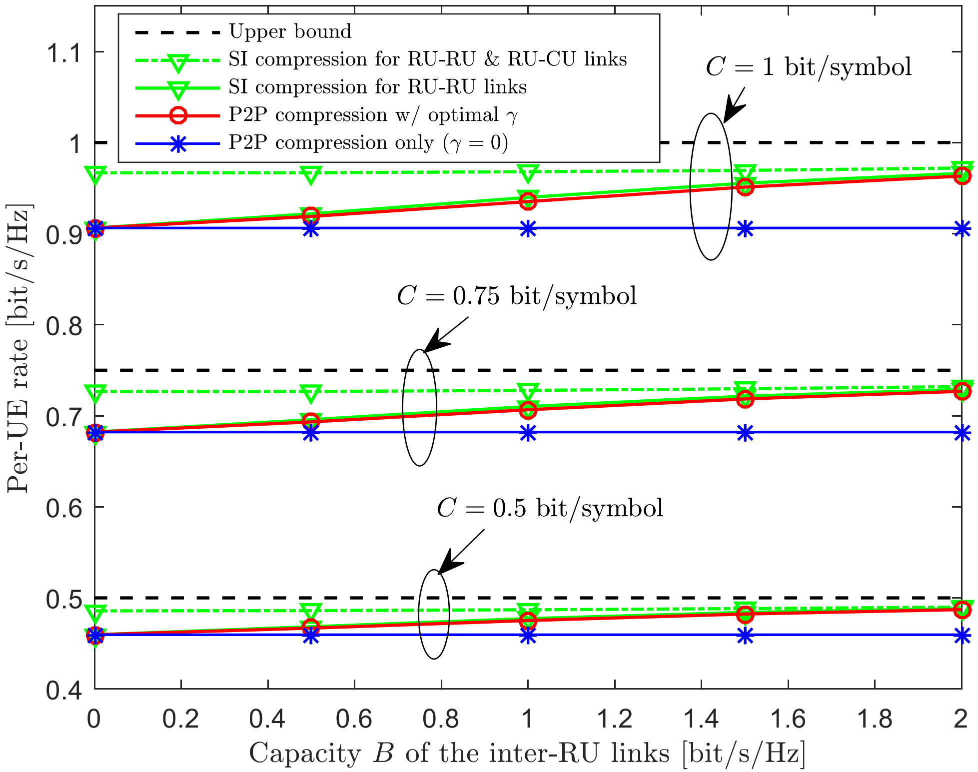
$$= \left(\gamma_i^2\alpha^2 + (\gamma_i + \alpha)^2 + 1\right)P + \gamma_i^2\omega_B + (1+\gamma_i^2)\sigma^2 - \frac{\left[(\gamma_i + \alpha)P + \gamma_i\alpha(\gamma_{[i-1]} + \alpha)P + \gamma_i\sigma^2\right]^2}{\left(\gamma_i^2\alpha^2 + (\gamma_i + \alpha)^2 + 1\right)P + \gamma_i^2\omega_B + (1+\gamma_i^2)\sigma^2}.$$

Side information



Numerical Example

- Per-UE rate versus RU-RU capacity B
  - $N = 3,\ \text{SNR} = 20\ \text{dB},\ \alpha = 0.7$



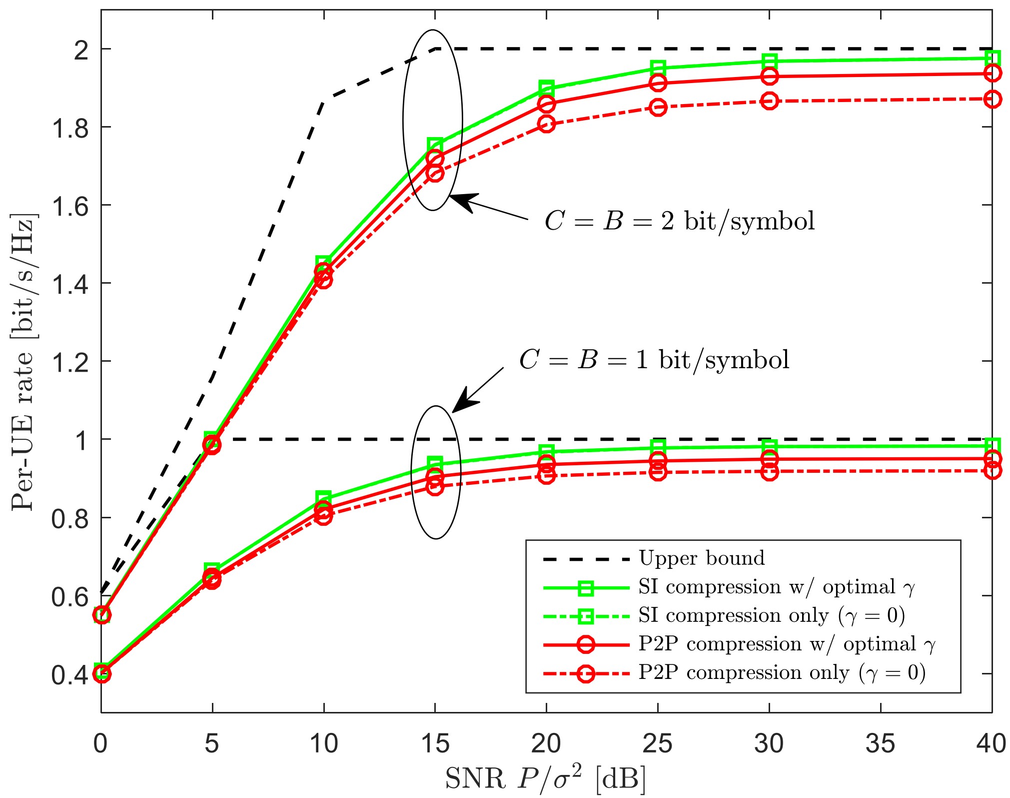
– With INP, the performance approaches upper bound as B increases.

– Leveraging SI for RU–RU link provides a slight sum–rate gain.

- Leveraging SI for RU-CU link leads to a significant sum-rate gain especially for small B.

Numerical Example

- Per-UE rate versus SNR P/σ^2
  - $N=3,\ \alpha=0.7,\ C=B\in\{1,2\}$



- When side information is leveraged, the impact of INP is not so significant.

- There is still a large gap between the upper bound and the sum-rate performance.
  - Can the gap be reduced by joint decompression and decoding at CU (Noisy network coding)? [Sanderovich et al:TIT][Lim et al:TIT][Park et al:SPL]

  This is the optimal oblivious processing [Aguerri et al:arXiv].

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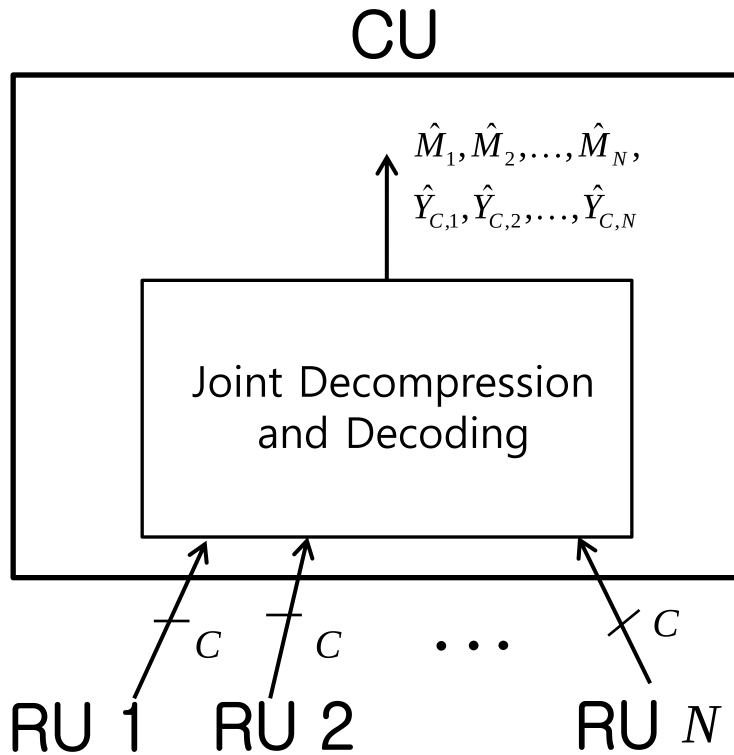
Joint Decompression and Decoding

- Joint decompression and decoding (JDD)
  - Potentially larger rates can be achieved with JDD at CU [Sanderovich et al:TIT][Lim et al:TIT][Park et al:SPL].
    - Now often seen as an instance of noisy network coding [Lim et al:TIT].
    - Optimal oblivious processing [Aguerri et al:arXiv]



Joint Decompression and Decoding

- Joint decompression and decoding (JDD)
  - Achievable sum-rate under JDD for given $\omega_B,\ \omega_C,\ \gamma$ [Lim et al:TIT]

$$R_{\text{sum}} = \min_{\mathcal{S}\subseteq\mathcal{N}} \left\{|\mathcal{S}|C - \sum_{i\in\mathcal{S}} I\left(S_i;\hat{Y}_{C,i}\right) + I\left(\mathbf{X};\ \{\hat{Y}_{C,i}\}_{\mathcal{N}\setminus\mathcal{S}}\right)\right\}$$
$$= \min_{\mathcal{S}\subseteq\mathcal{N}} \left\{|\mathcal{S}|\left(C - \tilde{g}_C(\omega_B,\omega_C,\gamma)\right) + f_{C,\mathcal{S}}(\omega_B,\omega_C,\gamma)\right\},$$

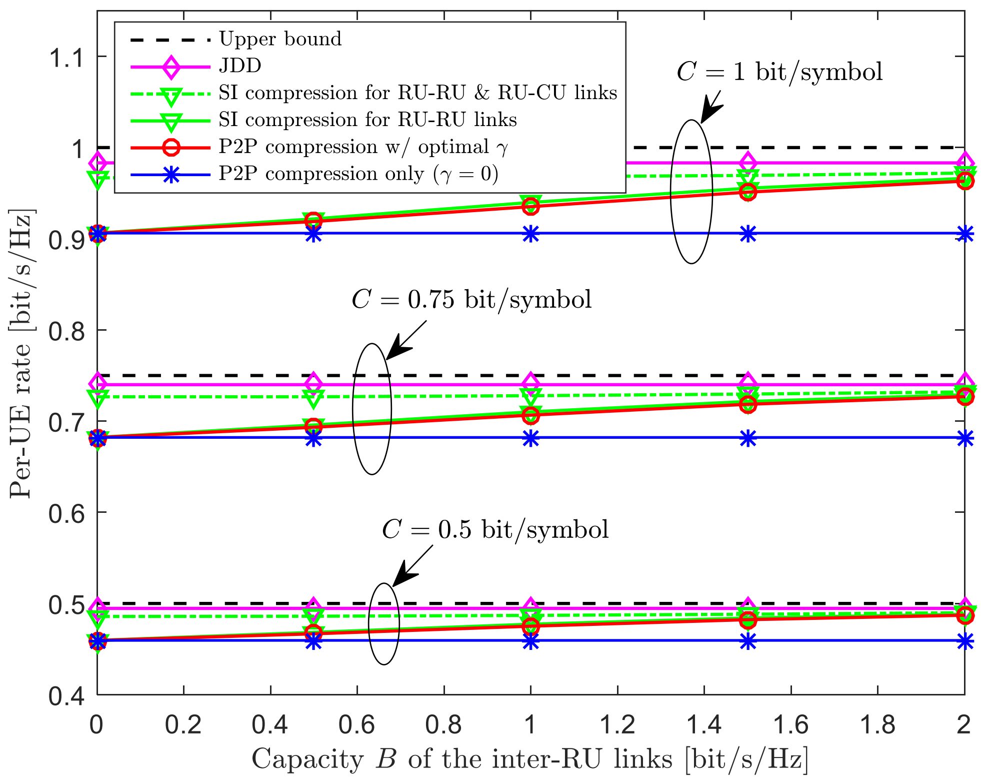
where $\tilde{g}_C(\omega_B,\omega_C,\gamma) = \frac{1}{2}\log_2\left(1+\frac{\gamma^2\omega_B+(1+\gamma^2)\sigma^2}{\omega_C}\right),$

$$f_{C,\mathcal{S}}(\omega_B,\omega_C,\gamma) = \frac{1}{2}\log_2\det\left(\mathbf{I}+P\left(\sigma^2\mathbf{H}_{Z,\mathcal{S}}\mathbf{H}_{Z,\mathcal{S}}^T+\omega_B\mathbf{H}_{Q,\mathcal{S}}\mathbf{H}_{Q,\mathcal{S}}^T+\omega_C\mathbf{I}\right)^{-1}\mathbf{H}_{X,\mathcal{S}}\mathbf{H}_{X,\mathcal{S}}^T\right),$$

$\mathbf{H}_{X,\mathcal{S}},\ \mathbf{H}_{Z,\mathcal{S}},\ \mathbf{H}_{Q,\mathcal{S}}$: Submatrices of $\mathbf{H}_X,\ \mathbf{H}_Z,\ \mathbf{H}_Q$ with rows in $\mathcal{S}$ removed.

Numerical Example

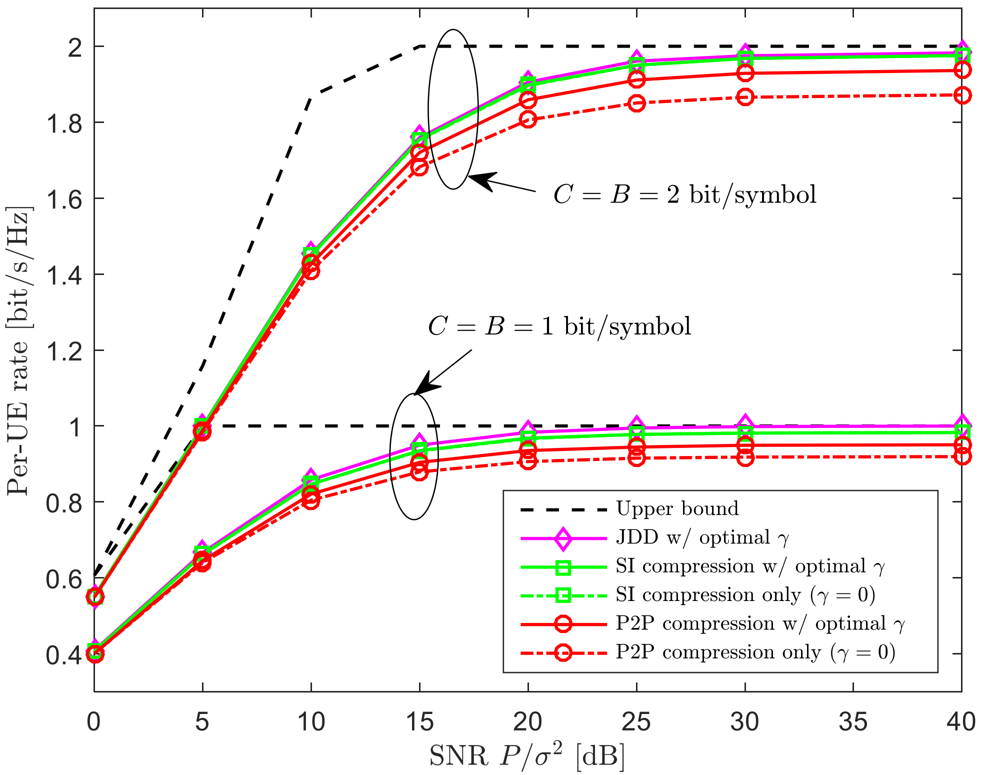
- Per-UE rate versus RU-RU capacity B
  - $N = 3$, SNR $= 20$ dB, $\alpha = 0.7$



- With INP, the performance approaches upper bound as B increases.
- Leveraging SI for RU−RU link provides a slight sum−rate gain.
- Leveraging SI for RU-CU link leads to a significant sum-rate gain especially for small B.
- JDD further improves the sum-rate performance.

Numerical Example

- Per-UE rate versus SNR P/σ^2
  - $N=3,\ \alpha=0.7,\ C=B\in\{1,2\}$



- JDD shows slightly improved performance, but the gap to upper bound is still large.

- This calls for the development of
  - Improved scheme based on
    - Non-oblivious RU processing
  - Improved upper bound
    - Extending the idea as [Wu et al:arXiv]

Outline

- Introduction
- System Model
- Point-to-Point Compression
- Leveraging Side Information
- Joint Decompression and Decoding
- **Concluding Remarks**

Concluding Remarks

- We have studied the role of inter-RU links for improving the sum-rate of C-RAN uplink.
  - Under the assumptions of
    - Oblivious processing at RUs
    - Wyner-type Gaussian channel

- Future work
  - Non-oblivious processing at RUs
    - Compute-and-Forward based techniques [Aguerri-Zaidi][Hong-Caire]
    - Edge processing
  - Improved outer bounds over the cut-set bound, extending ideas as: [Wu et al:arXiv]
  - General uplink C-RAN networks
  - Downlink of C-RAN (Oblivious and Non-oblivious schemes)
    - Possibly with edge processing or edge caching

Thank you!

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Abstract

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Sum-Rates for Wyner-type C-RAN Uplink with Inter-Connected Oblivious Radio Units

This study addresses the achievable sum-rate for the uplink of a cloud radio access network (C-RAN) operating in a linear Wyner-type topology. In the system, a set of radio units (RUs) is connected to a control unit (CU) by means of digital finite-capacity fronthaul links, and the messages sent by the users equipment (UEs) served by the RUs are jointly decoded at the CU based on the compressed baseband signals received on the fronthaul links. The potential advantages of utilizing the inter-RU links to improve the sum-rate performance is examined. In the considered strategy, each RU performs in-network processing of the uplink received signal and of the compressed baseband signal received from the adjacent RU, with the CU performing channel decoding incorporating the in-network processing output signals. A closed-form expression of the achievable sum-rate is derived assuming point-to-point compression, and analytic expressions for other advanced options are also provided in the presence of compression schemes leveraging side information. Numerical examples provide insights into the advantages of inter-RU communications and into the performance gap to sum-rate upper bounds.

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