On Uplink Cloud Radio Access Networks With Interconnected Radio Units

Shlomo Shamai (Shitz)

The Andrew and Erna Viterbi Faculty of Electrical Engineering
Technion - Israel Institute of Technology

Joint work with Seok-Hwan Park and Osvaldo Simeone

Northeastern University: August 8, 2018

Supported by the European Union's Horizon 2020 Research And Innovation Programme, grant agreement no. 694630.

Outline

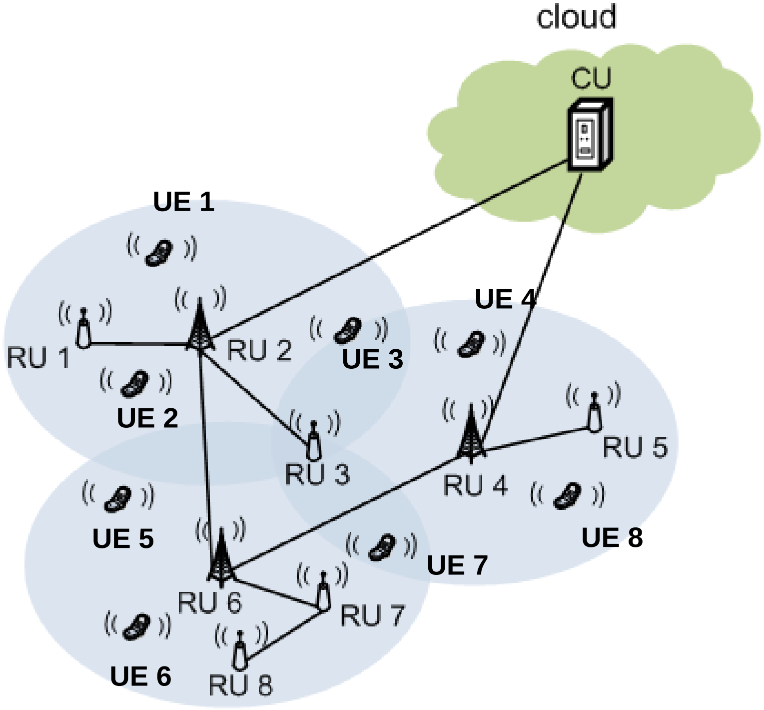
- Introduction
- System Model
- Point-to-Point Compression
- Leveraging Side Information
- Joint Decompression and Decoding
- Numerical Examples
- Concluding Remarks

Outline

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

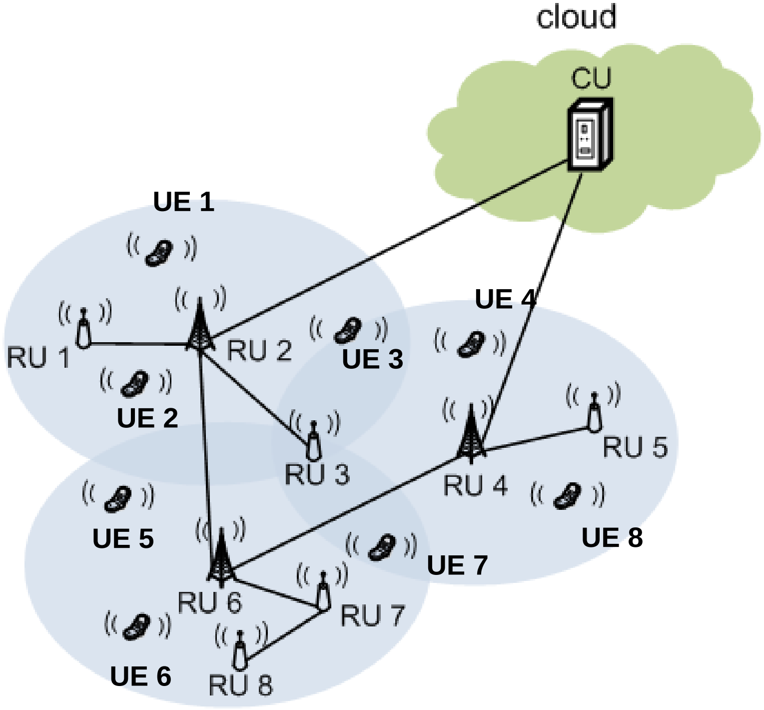
Cloud Radio Access Network (C-RAN)

- Base Stations (BSs) operate as radio units (RUs) [China][Simeone et al:JCN].



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".

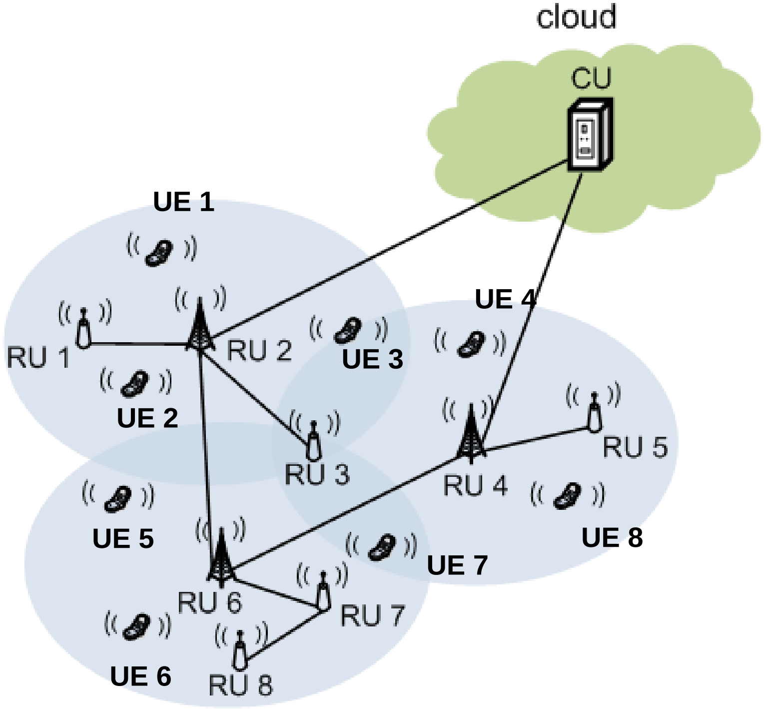


Cloud Radio Access Network (C-RAN)

- Base Stations (BSs) operate as radio units (RUs) [China][Simeone et al:JCN].

- Baseband processing takes place in the “cloud”.

- Advantages
  - Low-cost deployment of BSs [China][Segel-Weldon]

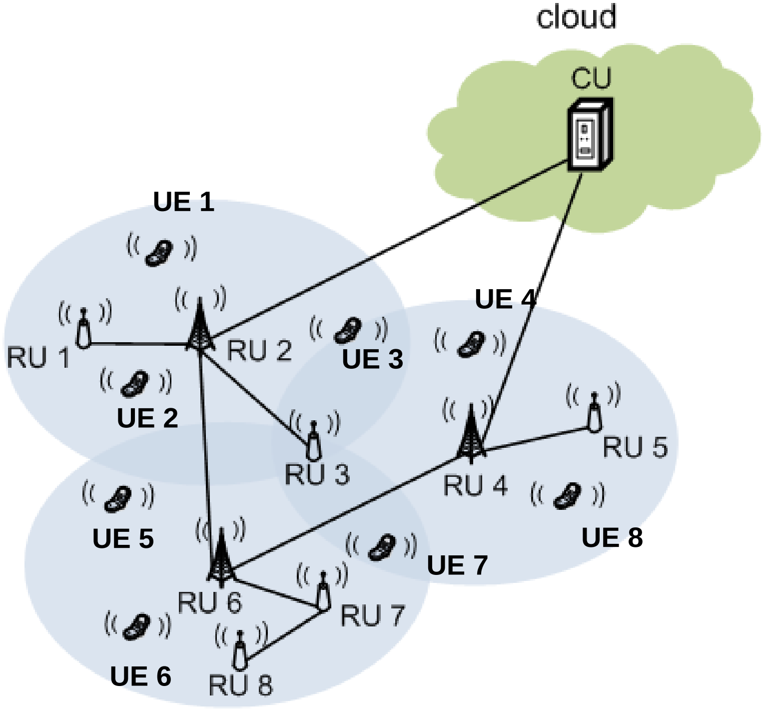


Cloud Radio Access Network (C-RAN)

- Base Stations (BSs) operate as radio units (RUs) [China][Simeone et al:JCN].

- Baseband processing takes place in the "cloud".

- Advantages
  - Low-cost deployment of BSs [China][Segel-Weldon]
  - Effective interference mitigation via joint baseband processing [Shamai et al:JWCC][Somekh et al:TIT]

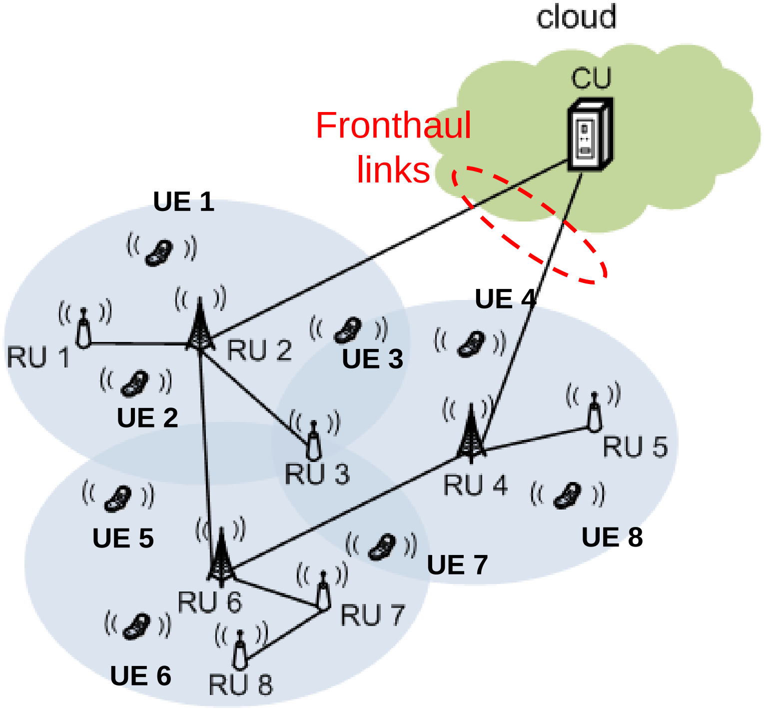


Cloud Radio Access Network (C-RAN)

- Base Stations (BSs) operate as radio units (RUs) [China][Simeone et al:JCN].

- Baseband processing takes place in the “cloud”.

- Advantages
  - Low-cost deployment of BSs [China][Segel-Weldon]
  - Effective interference mitigation via joint baseband processing [Shamai et al:JWCC][Somekh et al:TIT]



Cloud Radio Access Network (C-RAN)

- Made possible by fronthaul links that
  - Carry complex (IQ) baseband samples [CPRI][Andrews et al:JSAC]

Cloud Radio Access Network (C-RAN)

- Made possible by fronthaul links that
  - Carry complex (IQ) baseband samples [CPRI][Andrews et al:JSAC]
  - Have finite capacity [CPRI][China][IDC]

Cloud Radio Access Network (C-RAN)

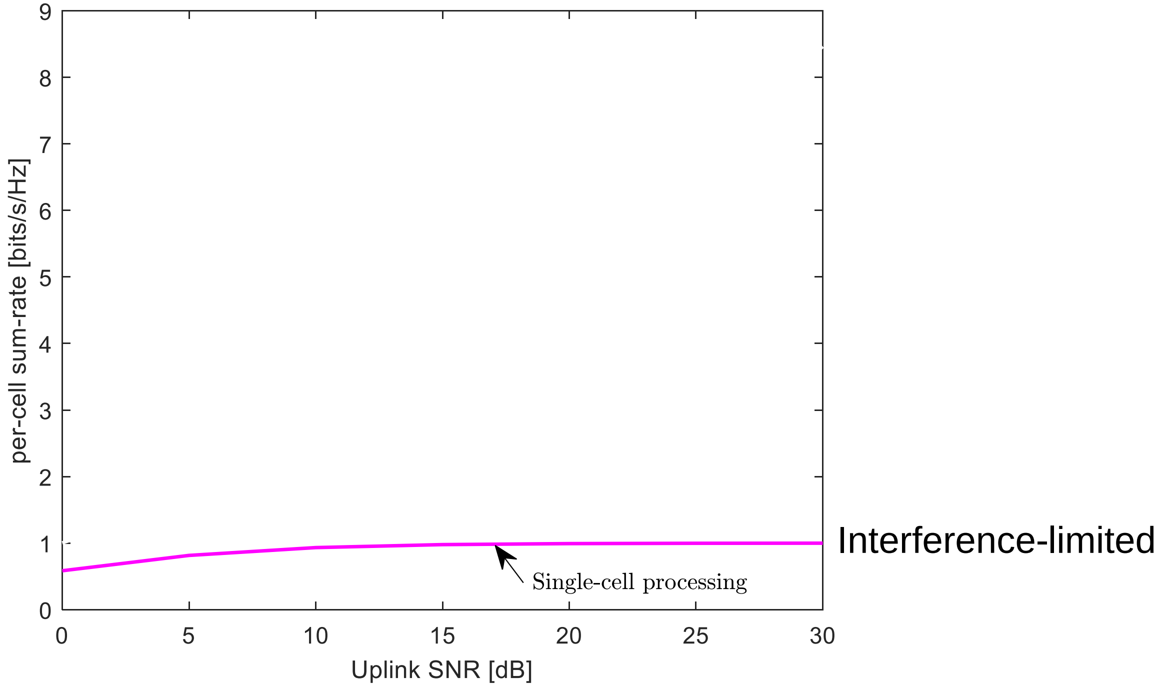
- Made possible by fronthaul links that
  - Carry complex (IQ) baseband samples [CPRI][Andrews et al:JSAC]
  - Have finite capacity [CPRI][China][IDC]
  - Transfer quantized IQ baseband samples

Cloud Radio Access Network (C-RAN)

- Made possible by fronthaul links that
  - Carry complex (IQ) baseband samples [CPRI][Andrews et al:JSAC]
  - Have finite capacity [CPRI][China][IDC]
  - Transfer quantized IQ baseband samples
- Key challenges: Effective transfer of quantized IQ samples
  - Standard technique: CPRI [CPRI]

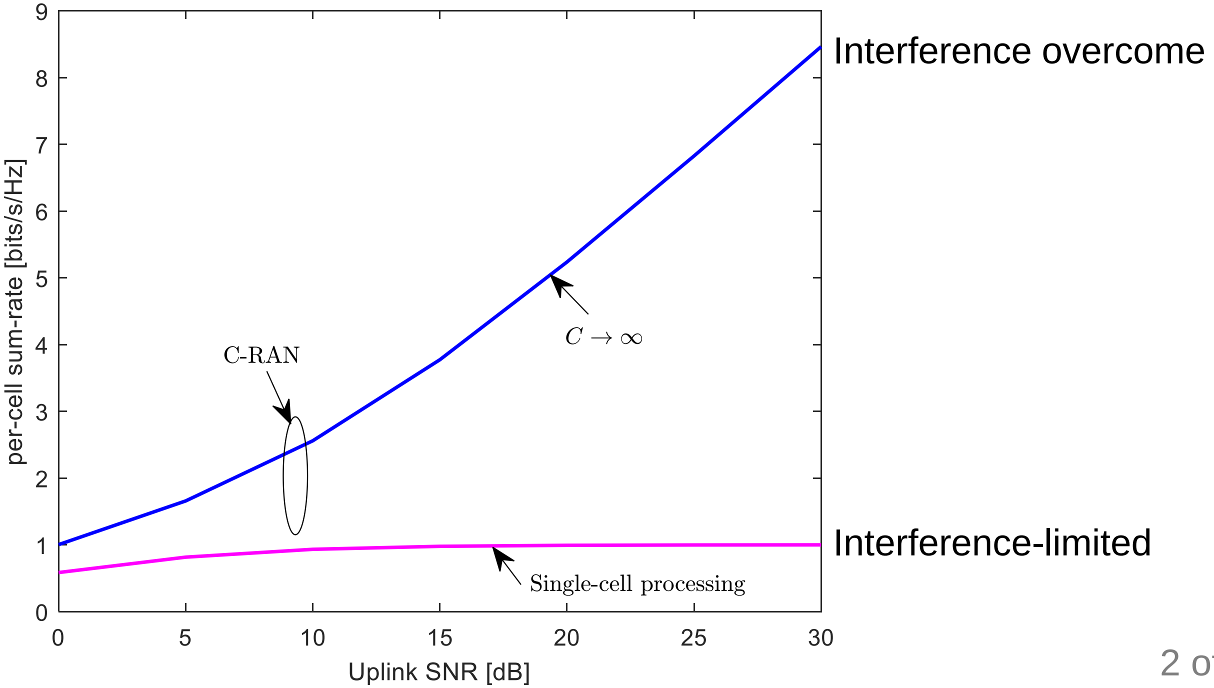
Cloud Radio Access Network (C-RAN)

- Made possible by fronthaul links that
  - Carry complex (IQ) baseband samples [CPRI][Andrews et al:JSAC]
  - Have finite capacity [CPRI][China][IDC]
  - Transfer quantized IQ baseband samples
- Key challenges: Effective transfer of quantized IQ samples
  - Standard technique: CPRI [CPRI]



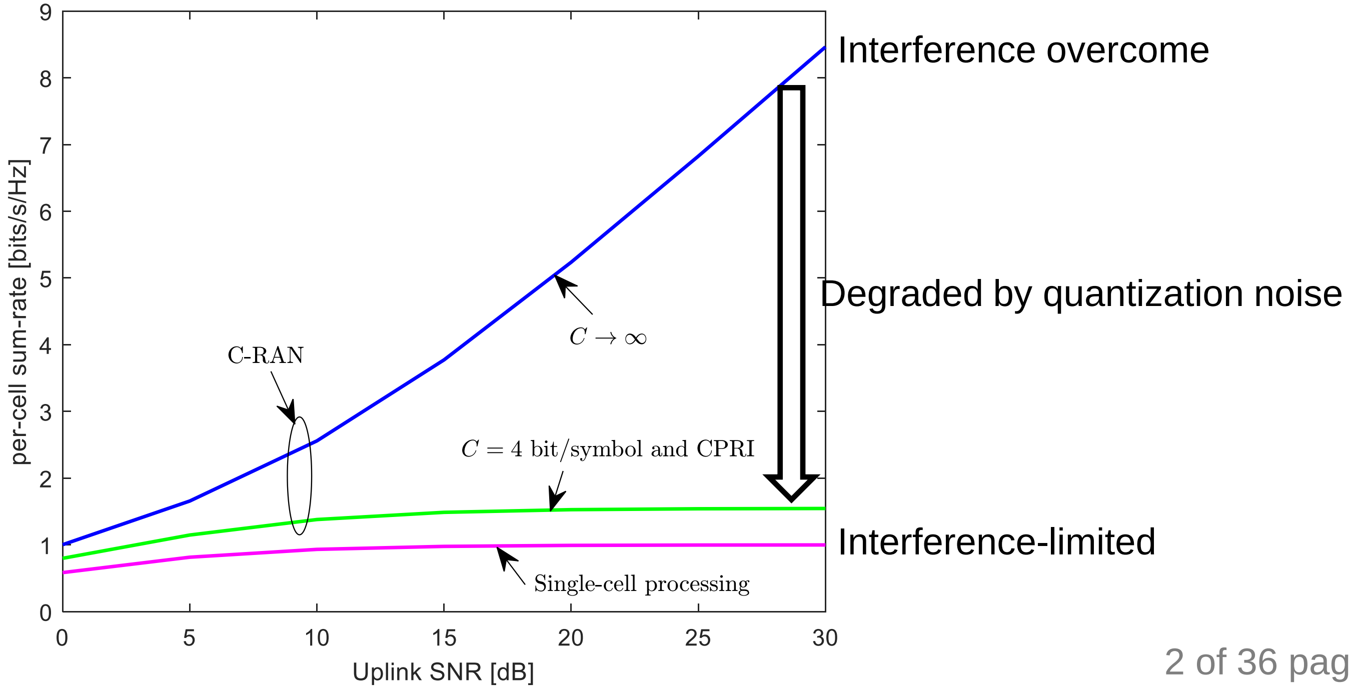
Cloud Radio Access Network (C-RAN)

- Made possible by fronthaul links that
  - Carry complex (IQ) baseband samples [CPRI][Andrews et al:JSAC]
  - Have finite capacity [CPRI][China][IDC]
  - Transfer quantized IQ baseband samples
- Key challenges: Effective transfer of quantized IQ samples
  - Standard technique: CPRI [CPRI]



Cloud Radio Access Network (C-RAN)

- Made possible by fronthaul links that
  - Carry complex (IQ) baseband samples [CPRI][Andrews et al:JSAC]
  - Have finite capacity [CPRI][China][IDC]
  - Transfer quantized IQ baseband samples
- Key challenges: Effective transfer of quantized IQ samples
  - Standard technique: CPRI [CPRI]

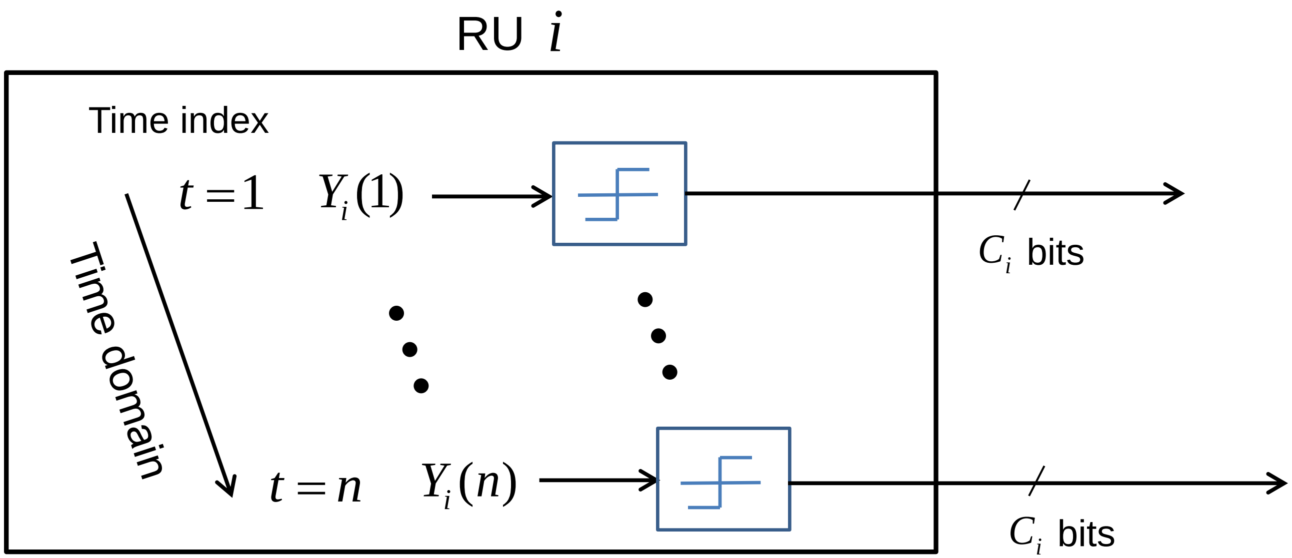


State-of-the-Art: C-RAN

- Common public radio interface (CPRI) [CPRI]
  - Issued by a consortium of radio equipment manufacturers
  - With the aim of standardizing the communication interface between BBU and RRHs
  - Prescribes the use of
    - Sampling
    - Scalar quantization for the digitization of the baseband IQ samples
      - 8~20 bits per I/Q sample (typically around 15)
  - Supports 3GPP GSM/EDGE, 3GPP UTRA and LTE
  - Allows for star, chain, tree, ring and multi-hop fronthaul topologies
  - Different bit rates up to 9.8 Gbps
  - Error probability (10^{-12}), timing accuracy (0.002 ppm), delay ($5\mu s$)

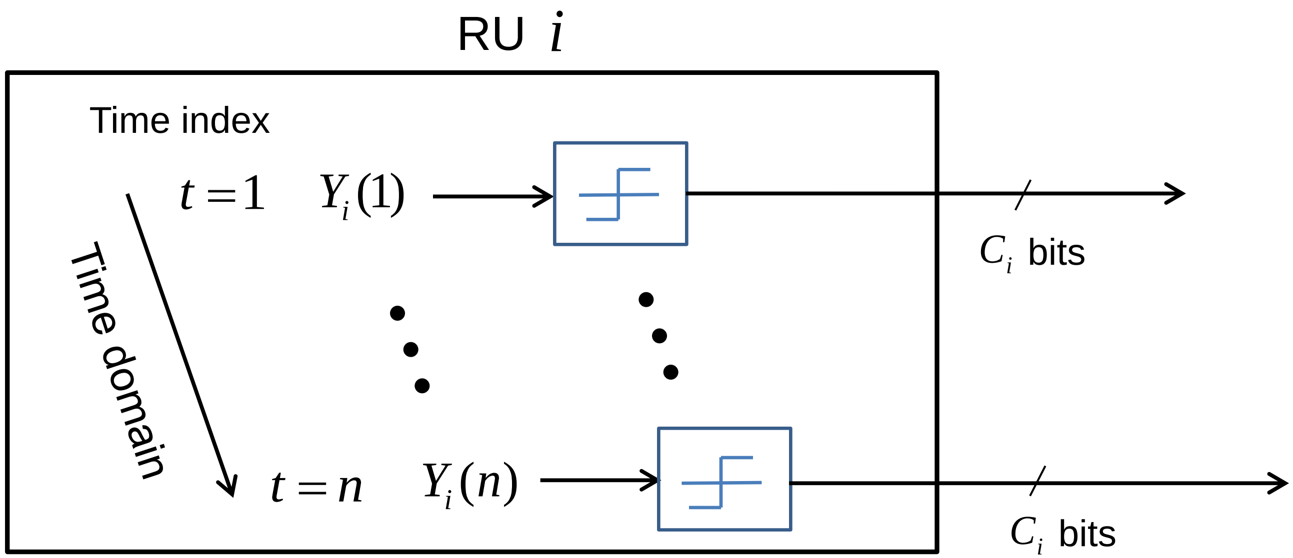
State-of-the-Art: C-RAN

Sample-wise quantization (CPRI)

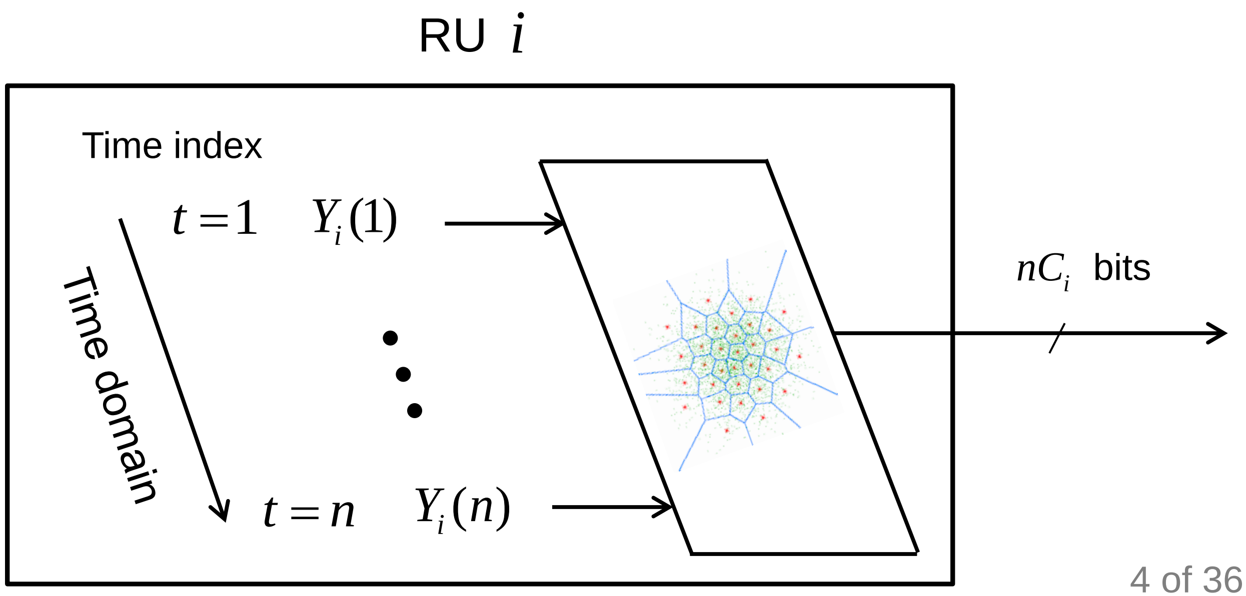


State-of-the-Art: C-RAN

Sample-wise quantization (CPRI)

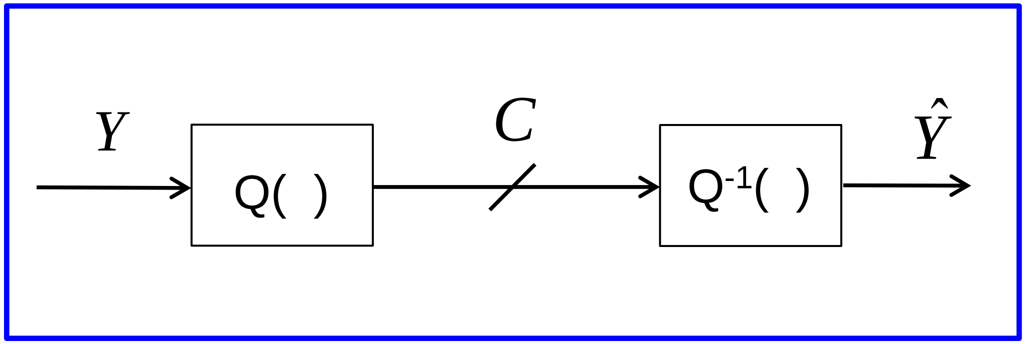


Vector quantization



Source Coding Results

- Conventional source coding
  [ElGamal-Kim, Ch. 3]

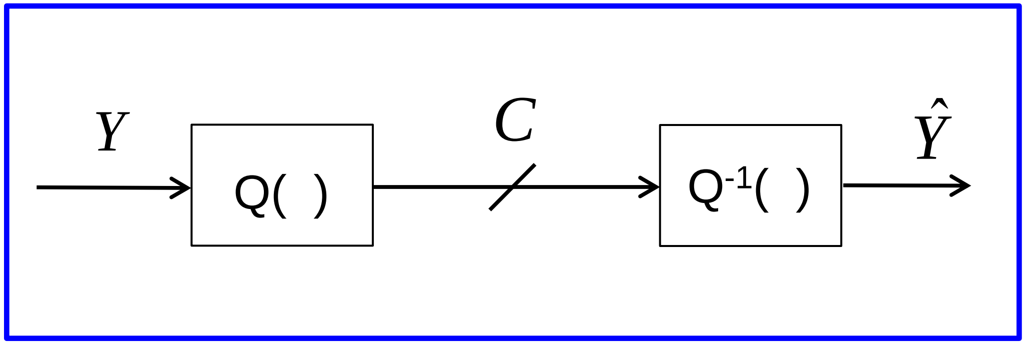


Q( ):   Compression encoder;
Q^{-1}( ): Compression decoder.

Source Coding Results

- Conventional source coding
  [ElGamal-Kim, Ch. 3]

test channel: $p(\hat{Y} \mid Y)$



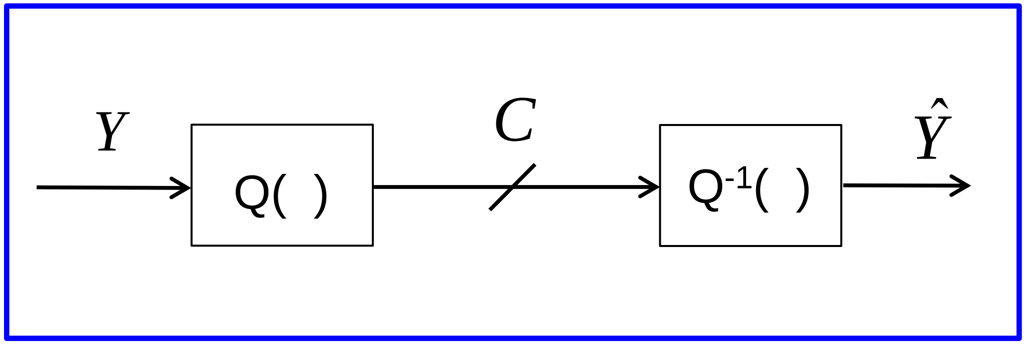
Q( ): Compression encoder;
Q^{-1}( ): Compression decoder.

Source Coding Results

- Conventional source coding
  [ElGamal-Kim, Ch. 3]

test channel: $p(\hat{Y} \mid Y)$

An equivalent Gaussian test channel



$$\hat{Y} = Y + Q,$$
$$\text{with } Q \sim \mathcal{CN}(0, \omega).$$

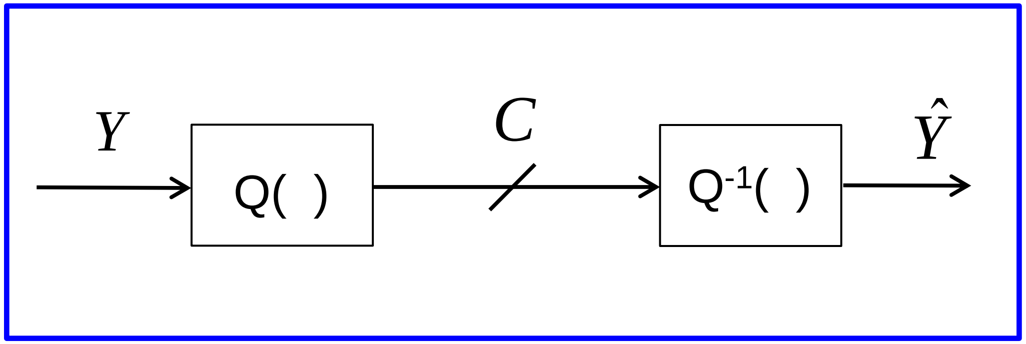
Q( ): Compression encoder;
Q^{-1}( ): Compression decoder.

($\omega = E\left[|Q|^2\right]$: Quantization noise power)

Source Coding Results

- Conventional source coding
  [ElGamal-Kim, Ch. 3]

test channel: $p(\hat{Y} \mid Y)$



An equivalent Gaussian test channel

$$\hat{Y} = Y + Q,$$
$$\text{with } \; Q \sim \mathcal{CN}(0, \omega).$$

$(\omega = E\left[|Q|^2\right]$: Quantization noise power)

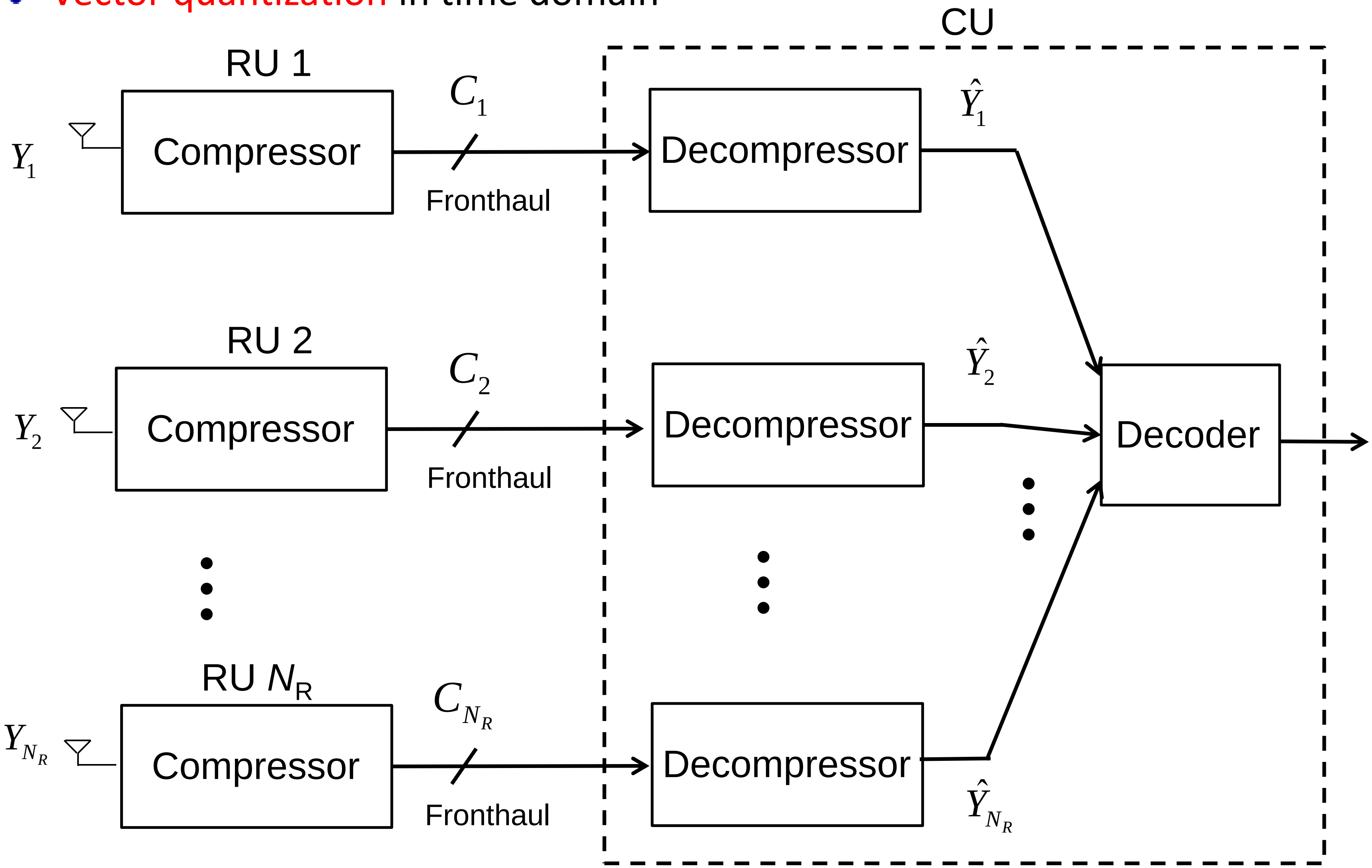
Q( ): Compression encoder;
Q^{-1}( ): Compression decoder.

$$\omega: \; I(Y;\hat{Y}) \leq C$$

($I(Y;\hat{Y})$: Mutual information between Y and $\hat{Y}$)

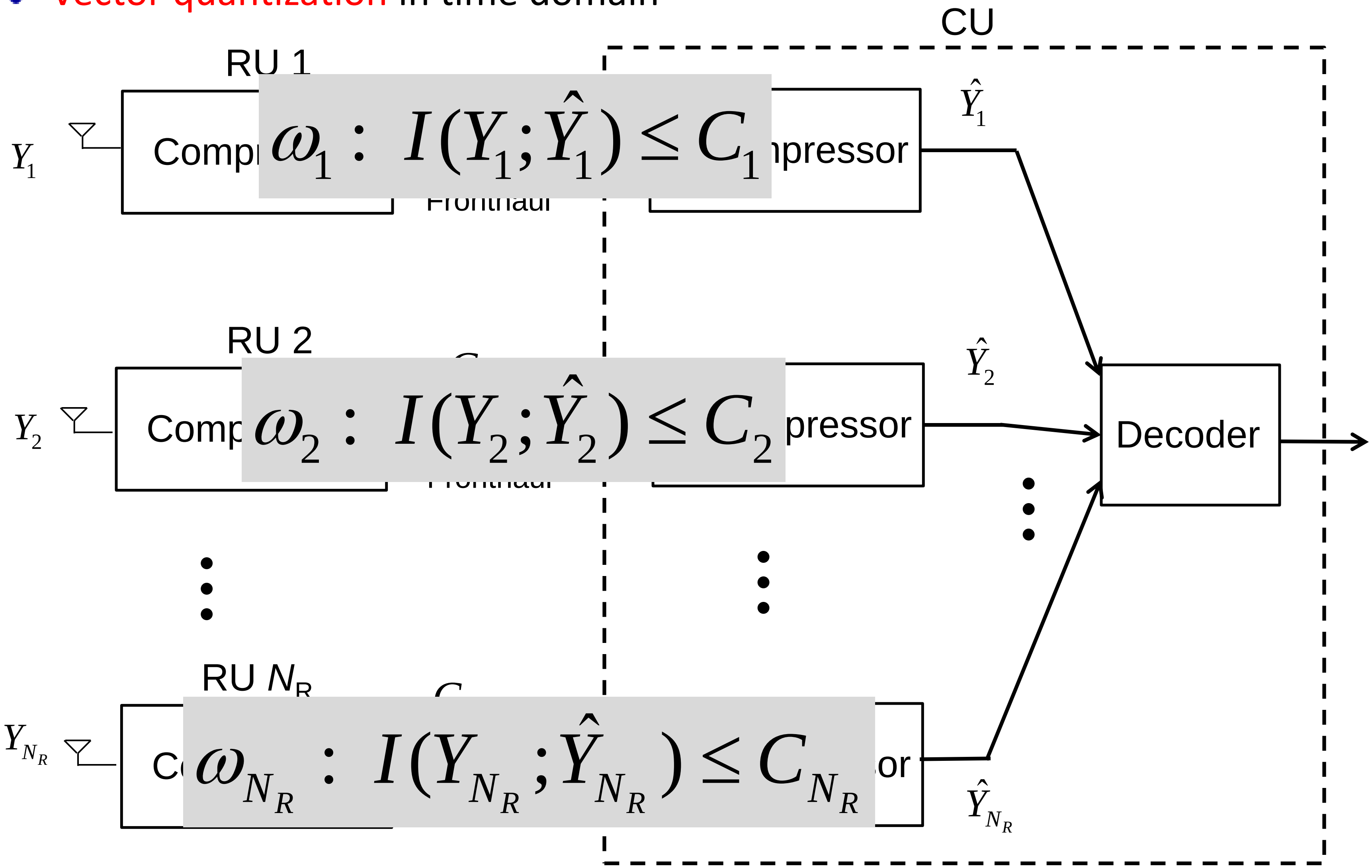
State-of-the-Art: C-RAN

- Point-to-point fronthaul compression [Hoydis et al:TSP][Zhou et al:TIT]
  - Vector quantization in time domain



State-of-the-Art: C-RAN

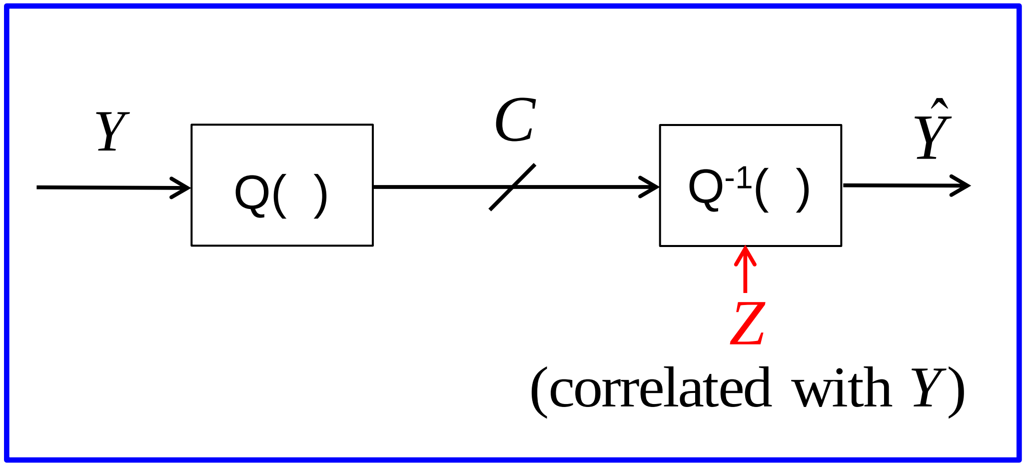
- Point-to-point fronthaul compression [Hoydis et al:TSP][Zhou et al:TIT]
  - Vector quantization in time domain



Distributed Source Coding

- Distributed source coding with side information
  [ElGamal-Kim, Ch. 12]

test channel: $p(\hat{Y} \mid Y)$



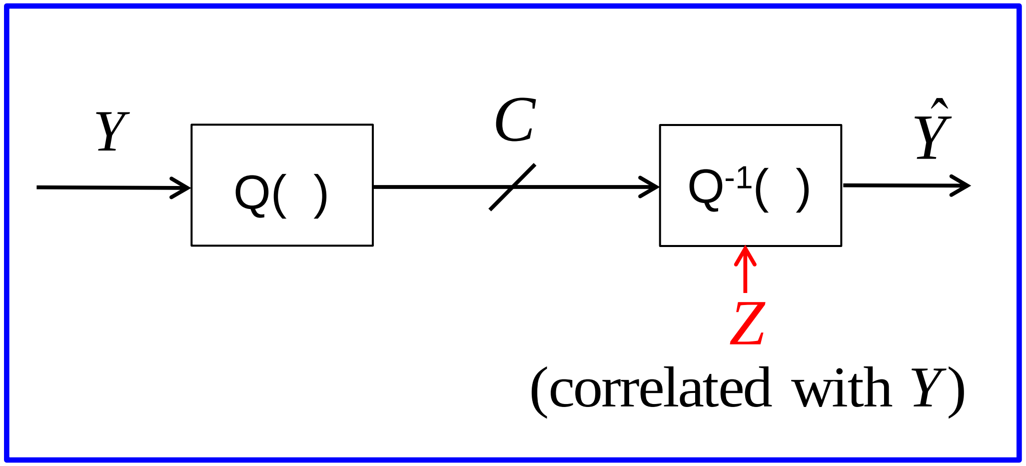
Q( ): Compression encoder;
Q^{-1}( ): Compression decoder.

Distributed Source Coding

- Distributed source coding with side information
  [ElGamal-Kim, Ch. 12]

test channel: $p(\hat{Y} \mid Y)$

An equivalent Gaussian test channel



$$\hat{Y} = Y + Q,$$
$$\text{with } Q \sim \mathcal{CN}(0, \omega).$$

$$\omega: \; I(Y; \hat{Y} \mid Z) \le C$$

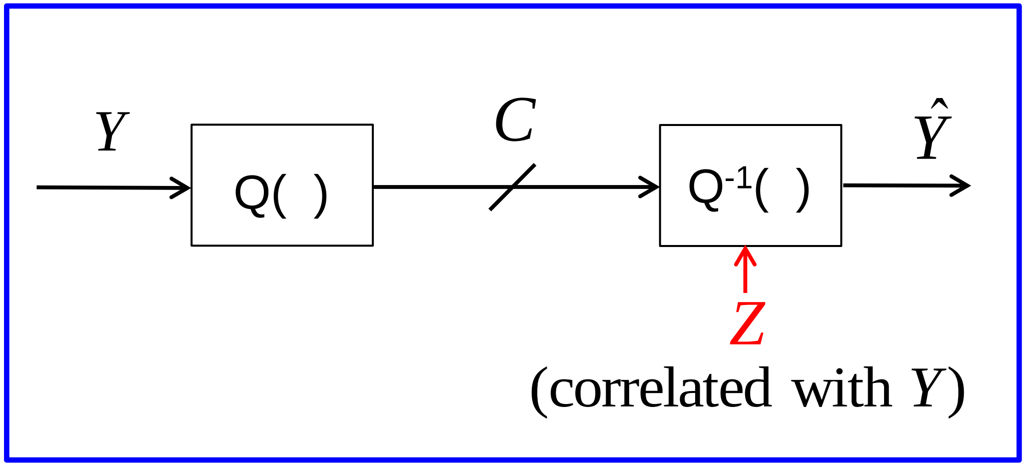
Q( ): Compression encoder;
Q^{-1}( ): Compression decoder.

Distributed Source Coding

- Distributed source coding with side information

  [ElGamal-Kim, Ch. 12]

test channel: $p(\hat{Y} \mid Y)$



Q( ): Compression encoder;

Q^{-1}( ): Compression decoder.

An equivalent Gaussian test channel

$$\hat{Y} = Y + Q,$$

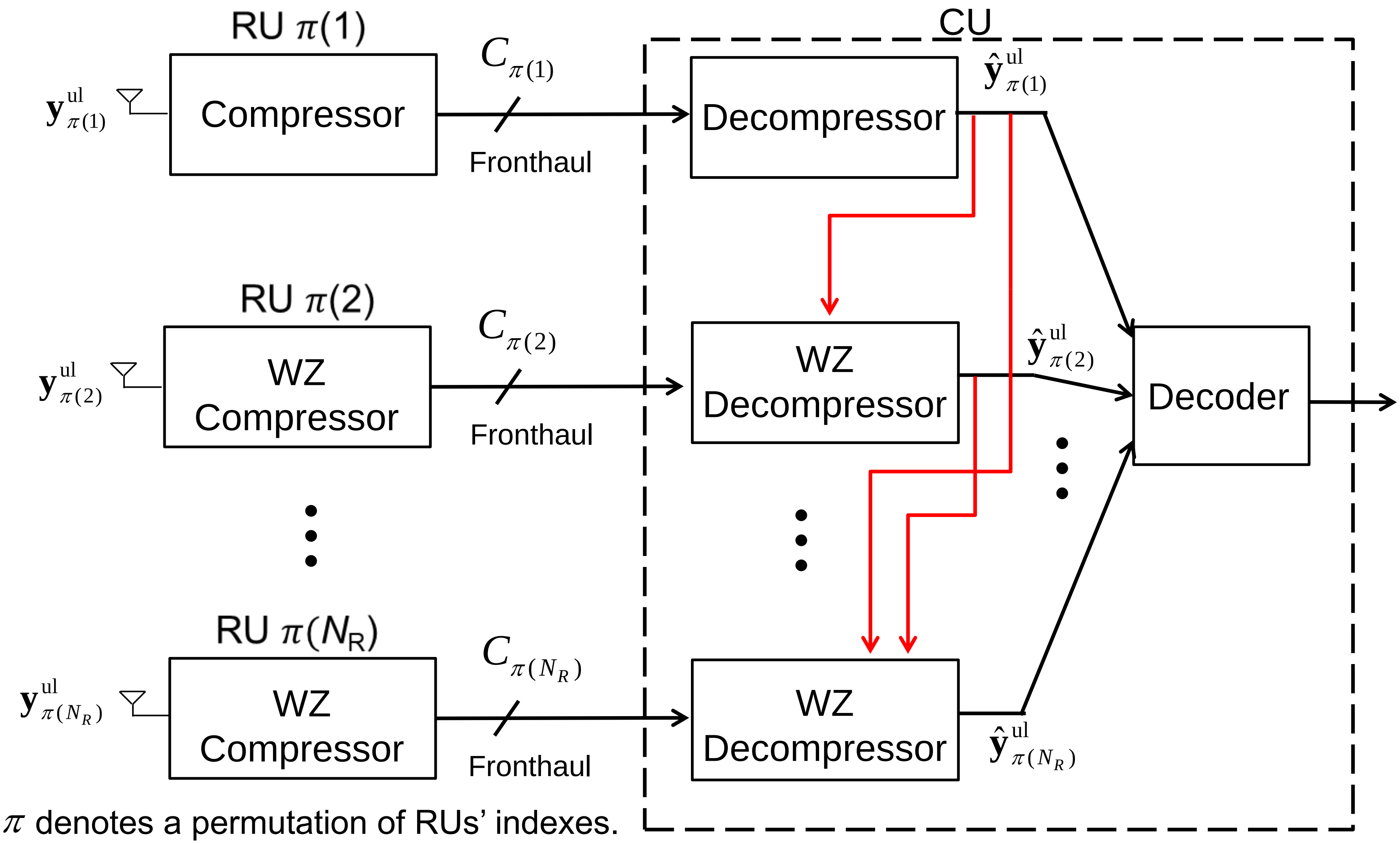
$$\text{with } Q \sim \mathcal{CN}(0, \omega).$$

$$\omega: \; I(Y; \hat{Y} \mid Z) \le C$$

(Relaxed constraint than $I(Y;\hat{Y}) \le C$)

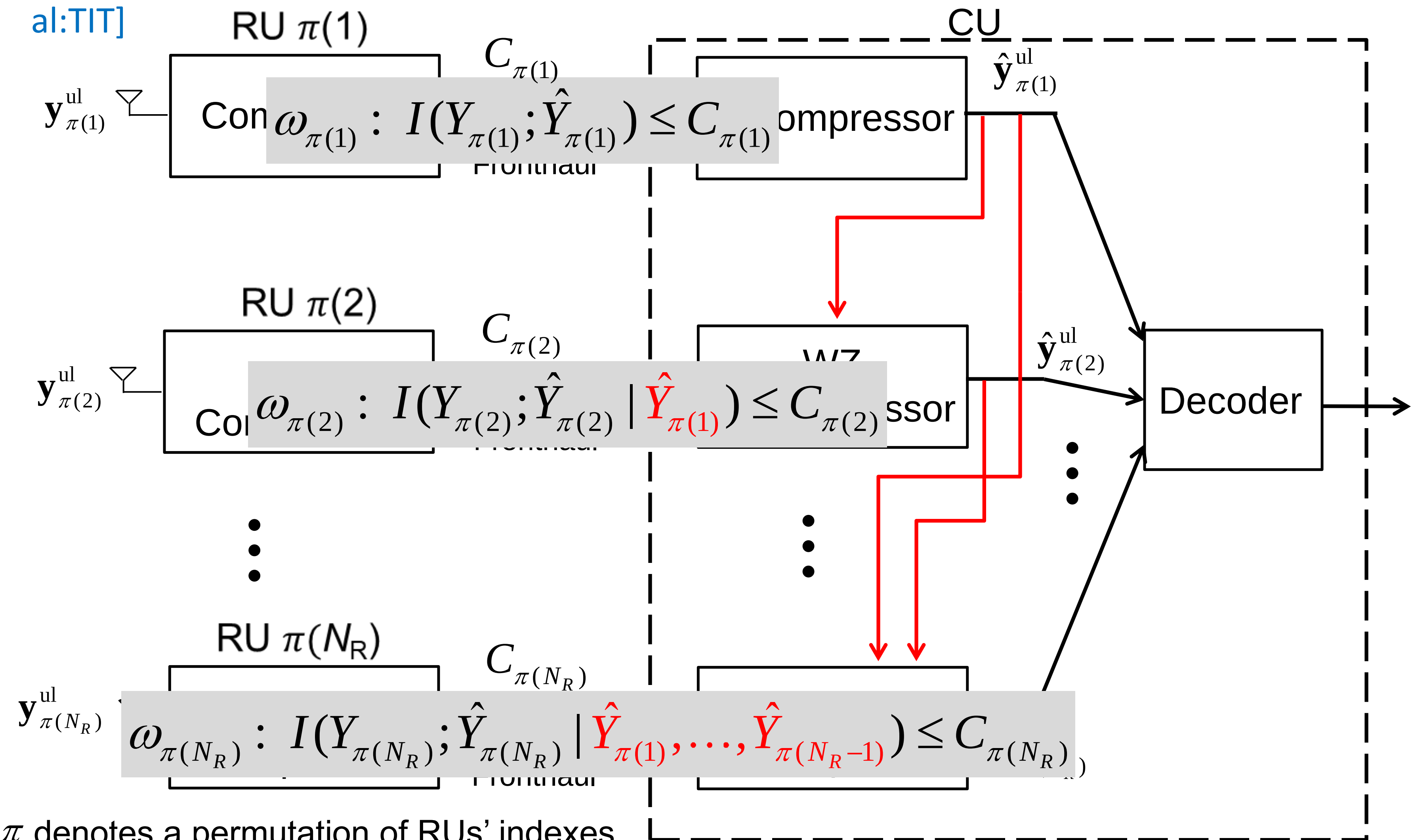
State-of-the-Art: C-RAN

- 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.

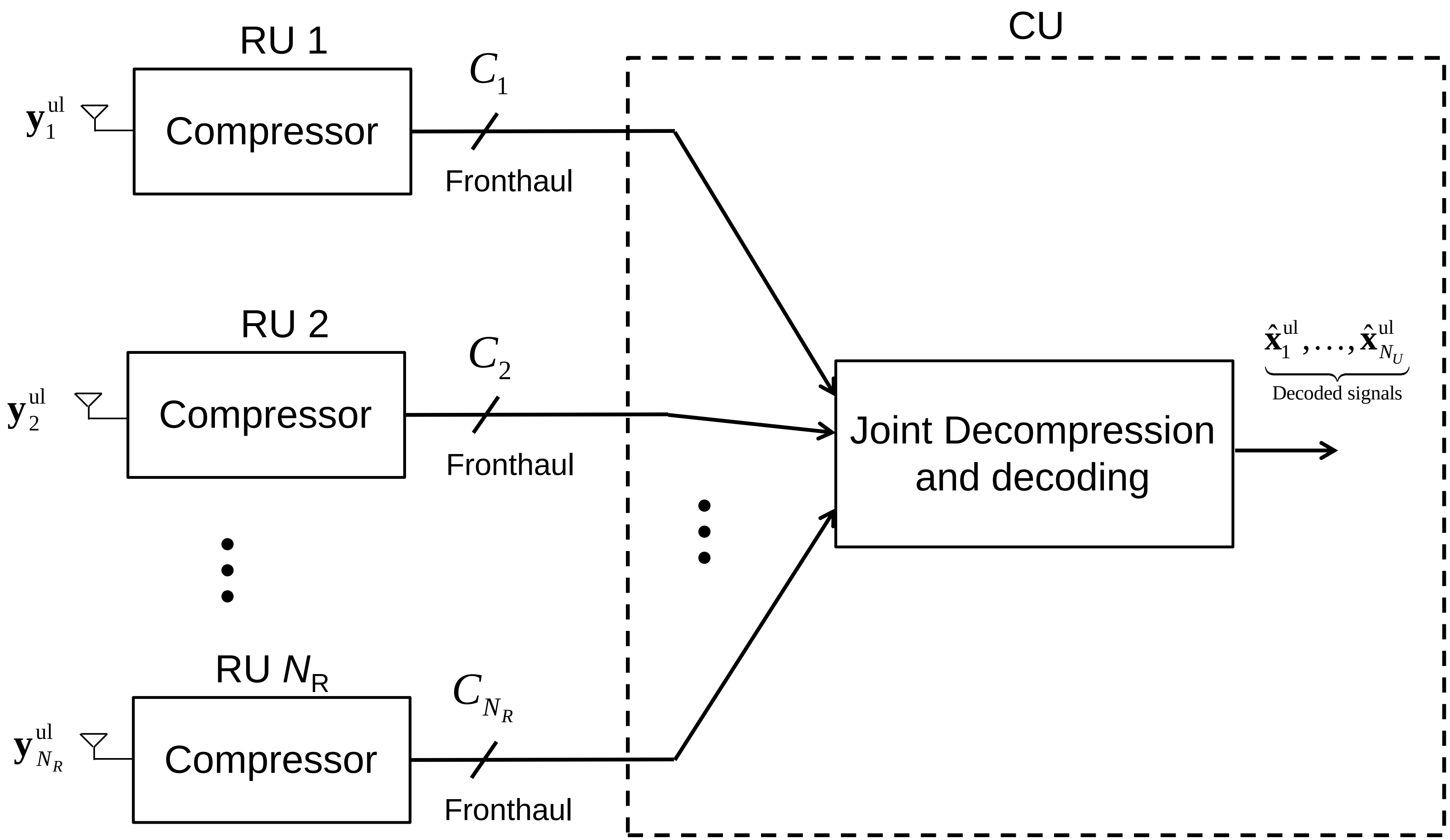
- Distributed fronthaul compression
  [Sanderovich et al:TIT][dCoso-Simosens][Zhou-Yu:JSAC][Park et al:SPM][Zhou et al:TIT]



π denotes a permutation of RUs' indexes.

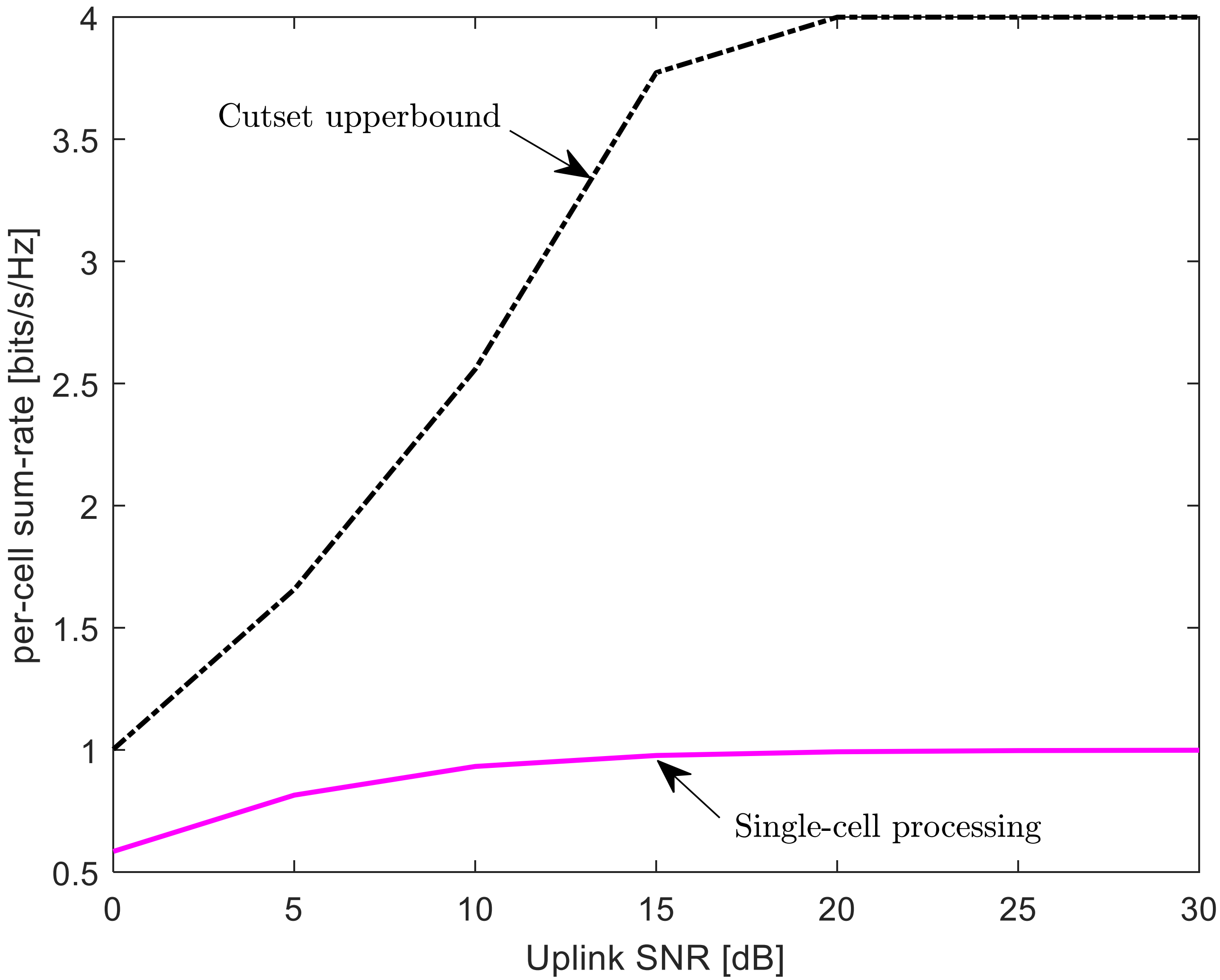
State-of-the-Art: C-RAN

- Joint decompression and decoding (JDD)
  [Sanderovich et al:TIT][Lim et al:TIT][Park et al:SPL][Zhou et al:TIT]
  equivalent to what is latter known as: Noise Network Coding [Lim et al:TIT]



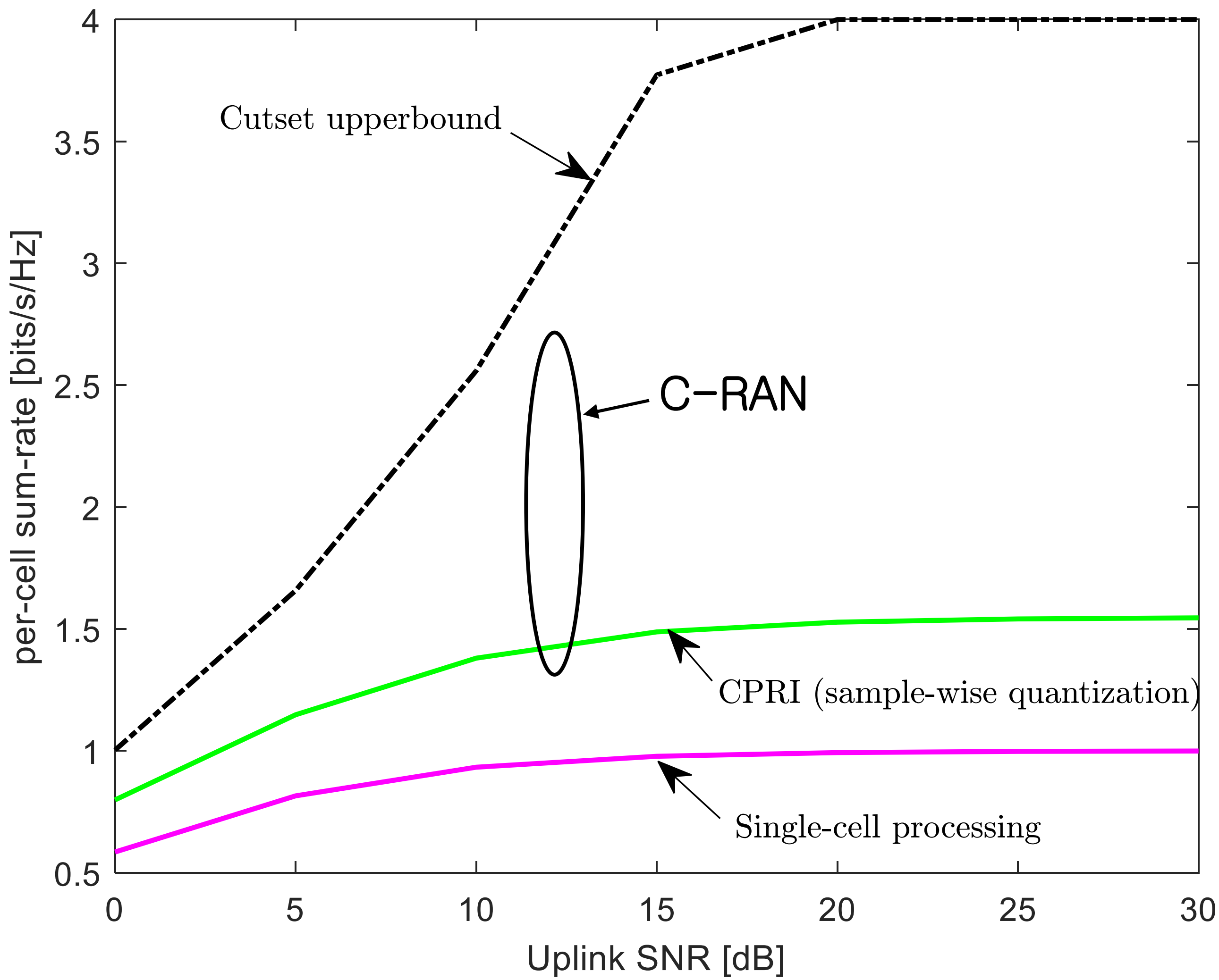
State-of-the-Art: C-RAN

- Numerical example for Wyner uplink model with $C = 4$ bit/symbol



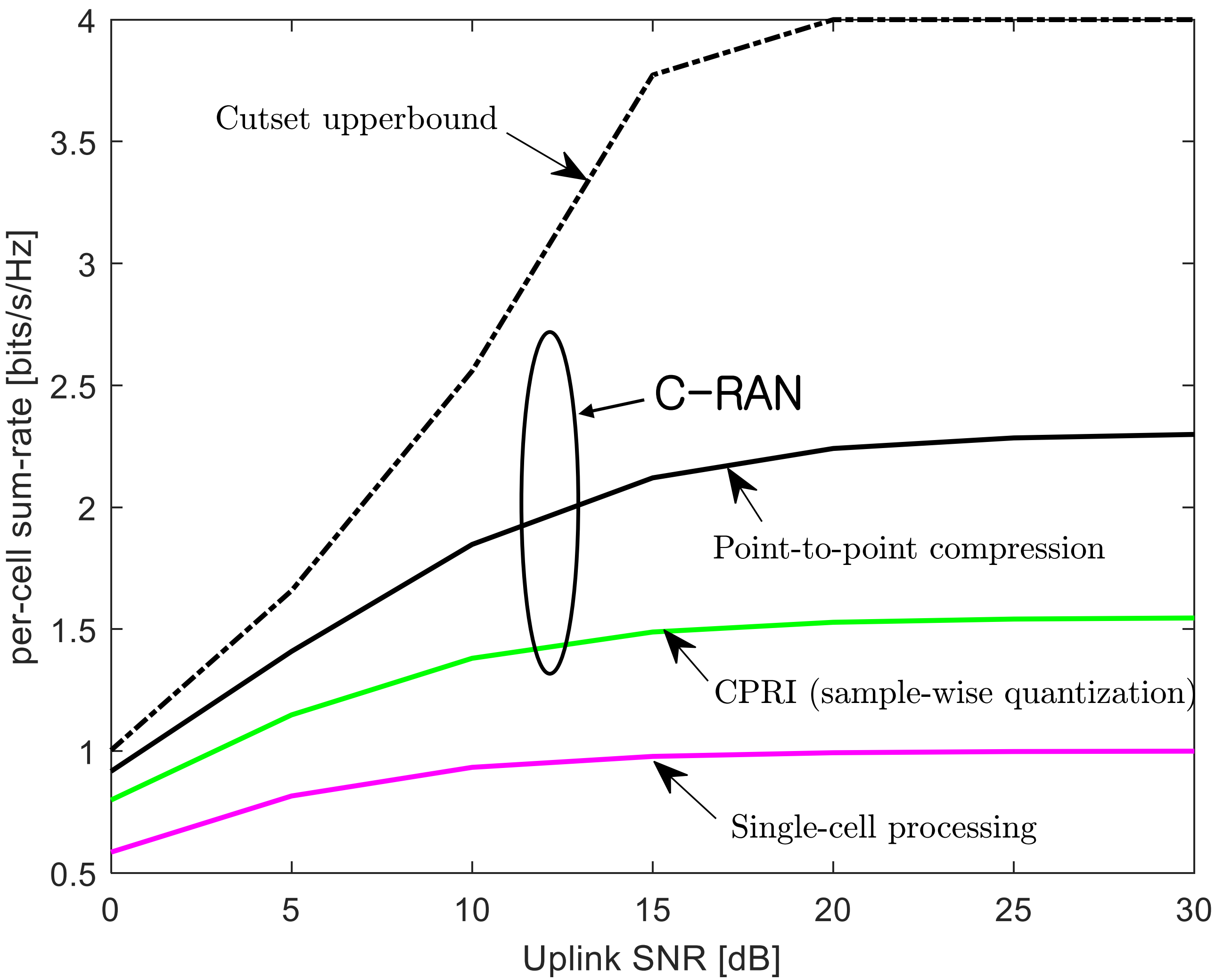
State-of-the-Art: C-RAN

- Numerical example for Wyner uplink model with $C = 4$ bit/symbol



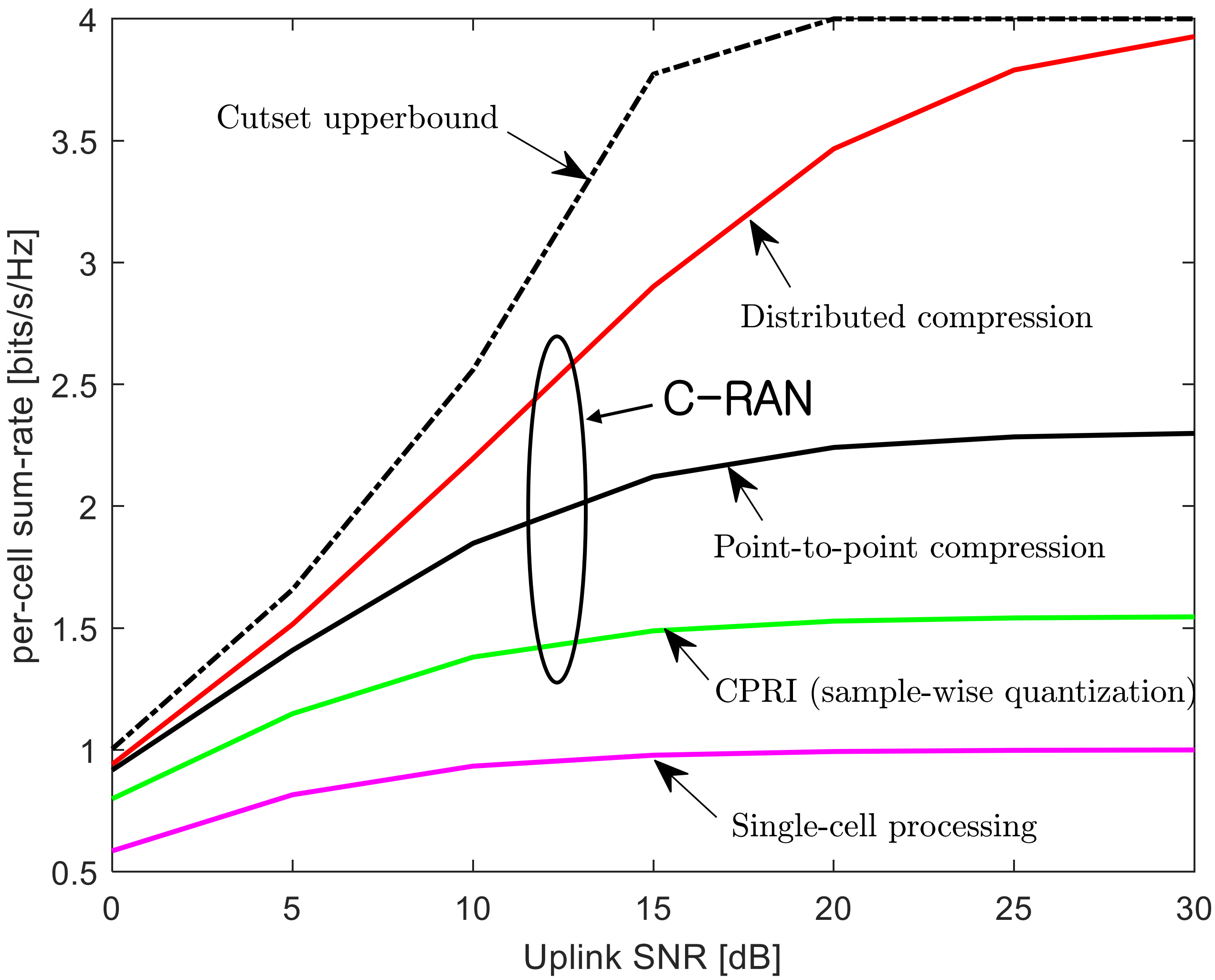
State-of-the-Art: C-RAN

- Numerical example for Wyner uplink model with $C = 4$ bit/symbol



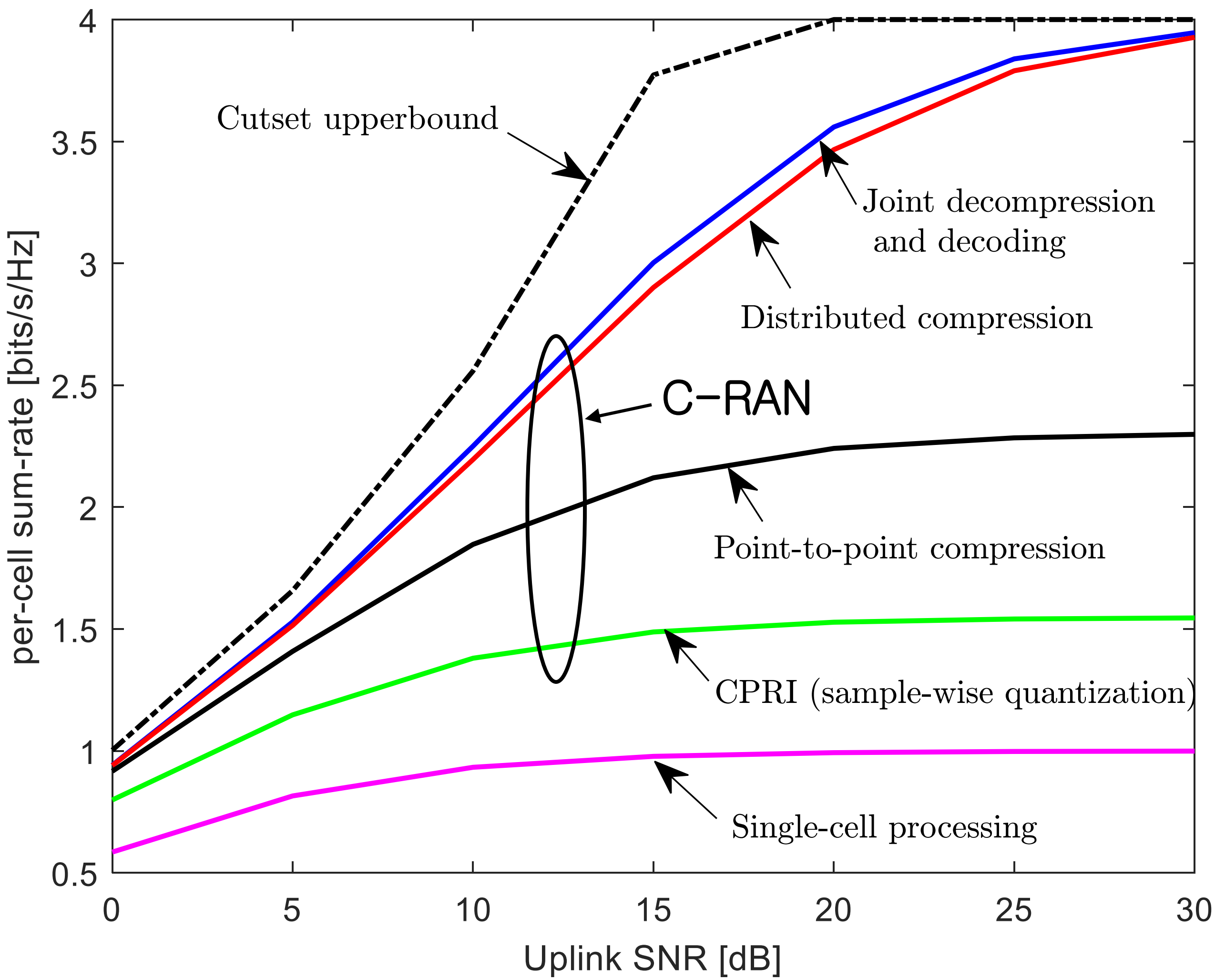
State-of-the-Art: C-RAN

- Numerical example for Wyner uplink model with $C = 4$ bit/symbol



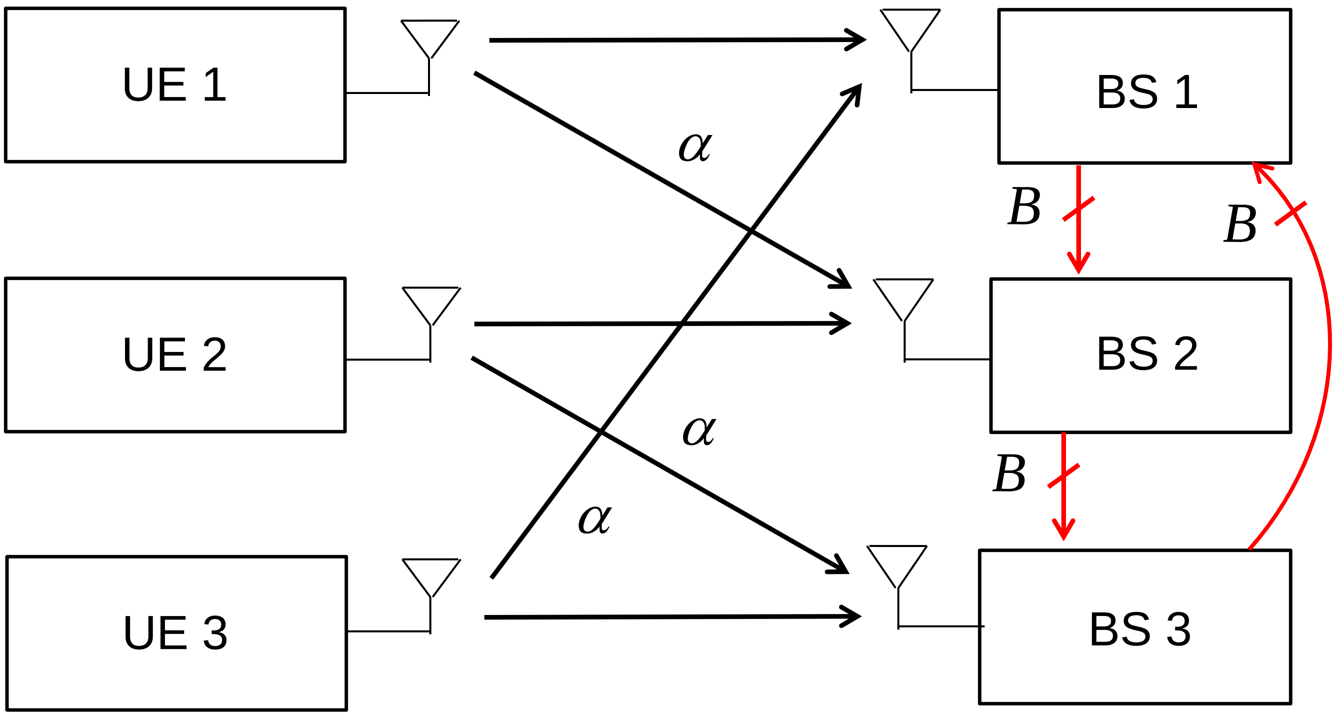
State-of-the-Art: C-RAN

- Numerical example for Wyner uplink model with $C = 4$ bit/symbol



State-of-the-Art: Inter-RU Coop.

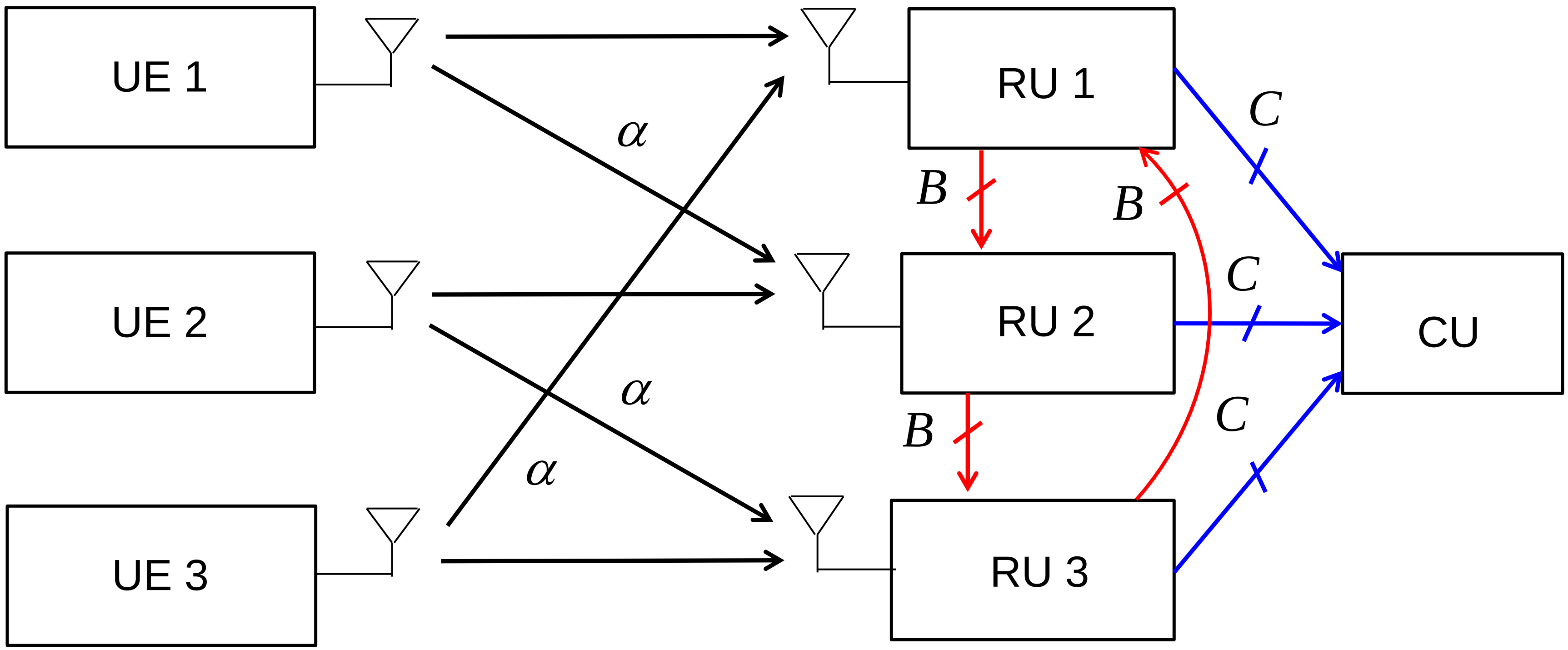
- Inter-RU cooperation for non-cooperative cellular systems:
  - Analysis for Wyner, Circular Wyner models [Simeone et al:TIT][Simeone et al:FnT]



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

This Work

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



Outline

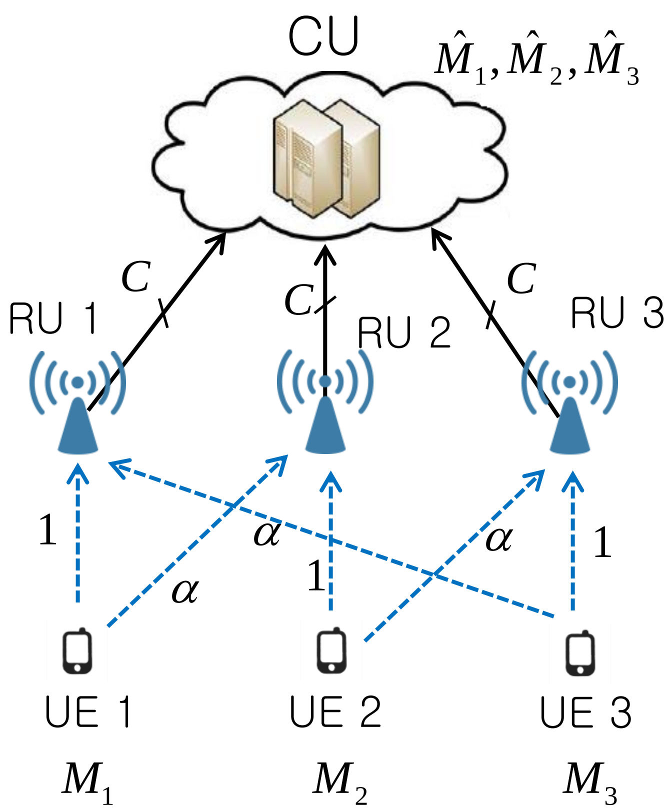
- Introduction
- **System Model**
- Point-to-Point Compression
- Leveraging Side Information
- Joint Decompression and Decoding
- Numerical Examples
- Concluding Remarks

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
  - 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 $\alpha \in [0,1]$.



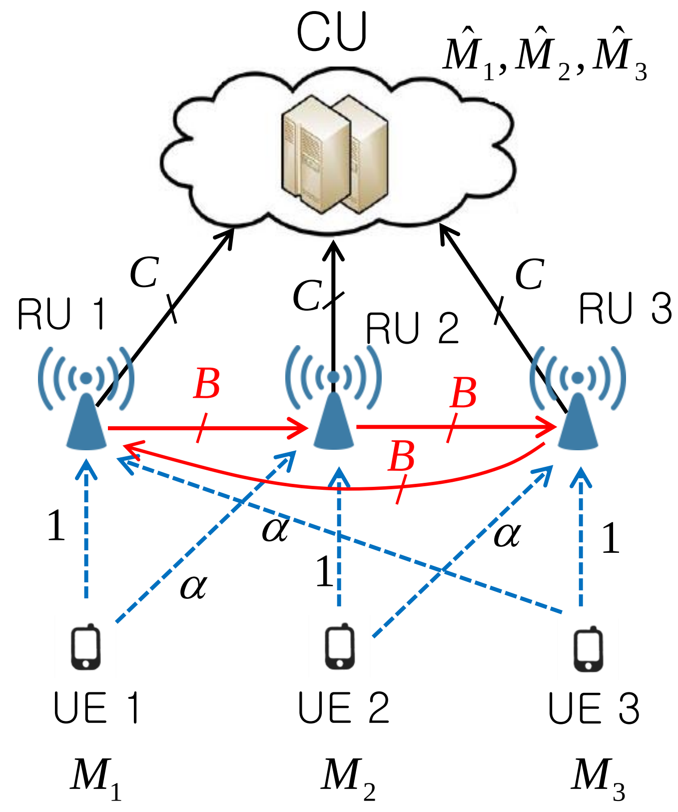
<Example for $N = 3$>

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).

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).

  - Random coding with Gaussian codebook
    - Message M_i is encoded to obtain an encoded signal

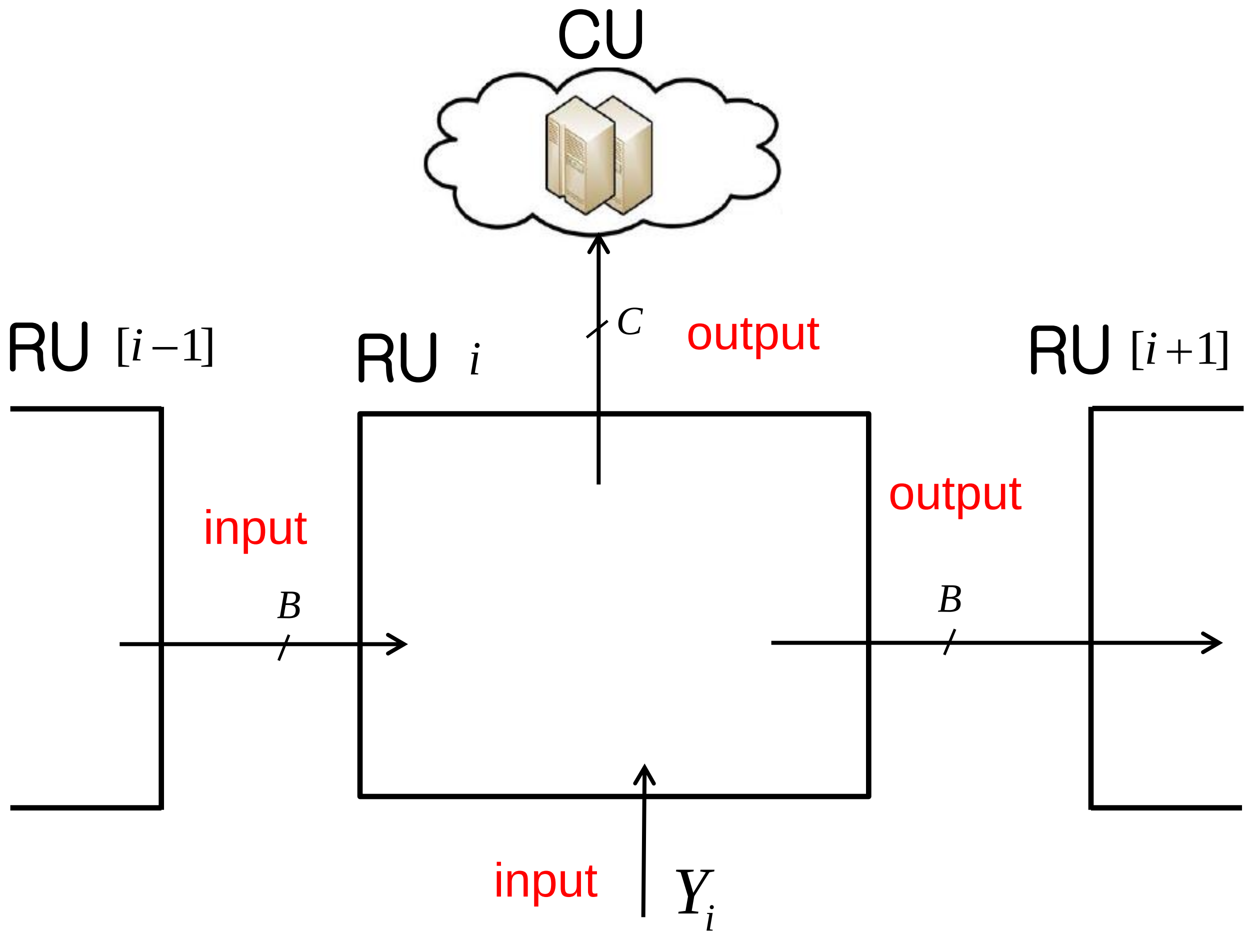
$$X_i \sim N(0, P).$$

    - 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

- In-network processing (INP) at RU i

$$\hat{Y}_{B,[i-1]} = Y_{[i-1]} + Q_{B,[i-1]},$$

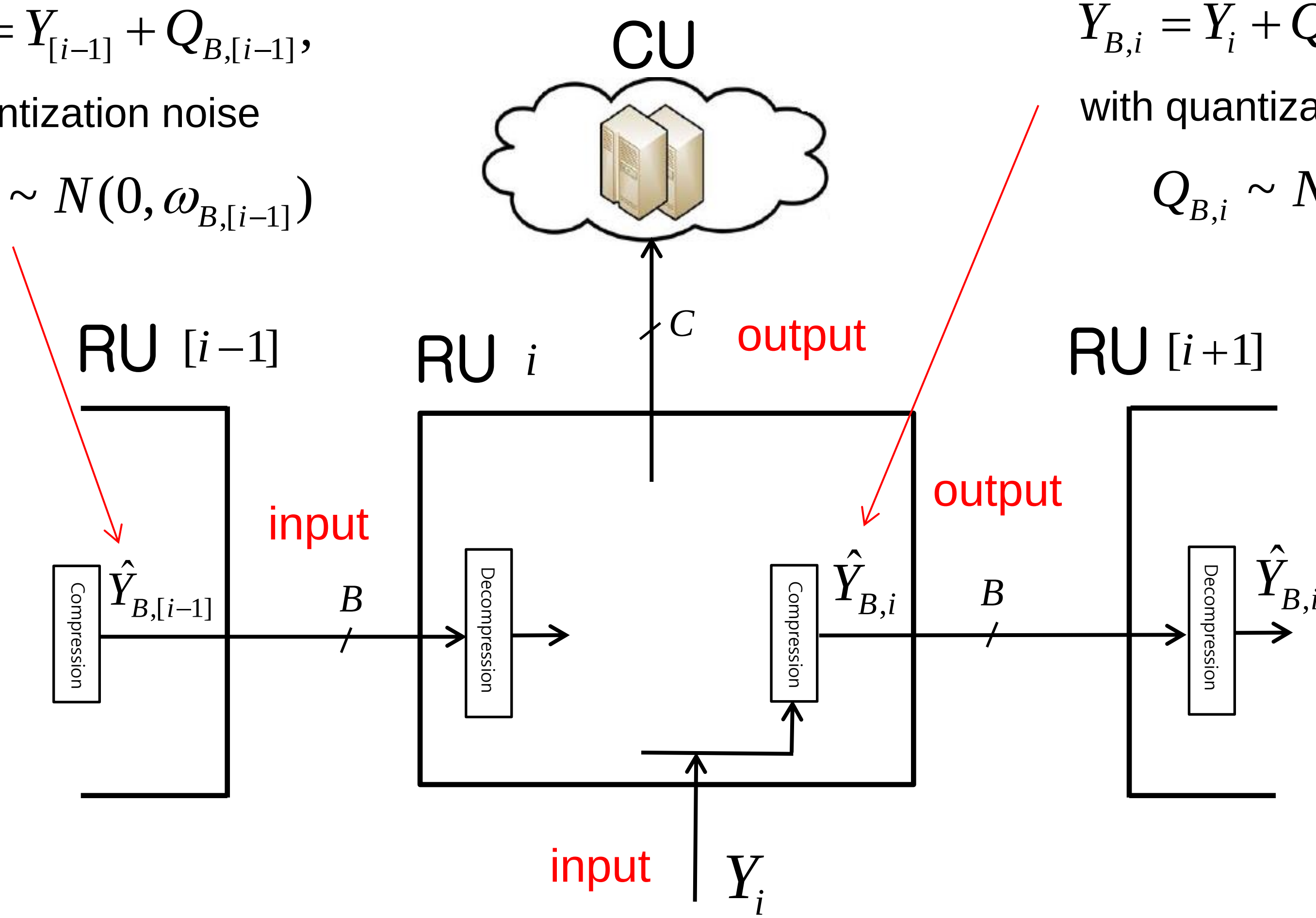
with quantization noise

$$Q_{B,[i-1]} \sim N(0, \omega_{B,[i-1]})$$

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

with quantization noise

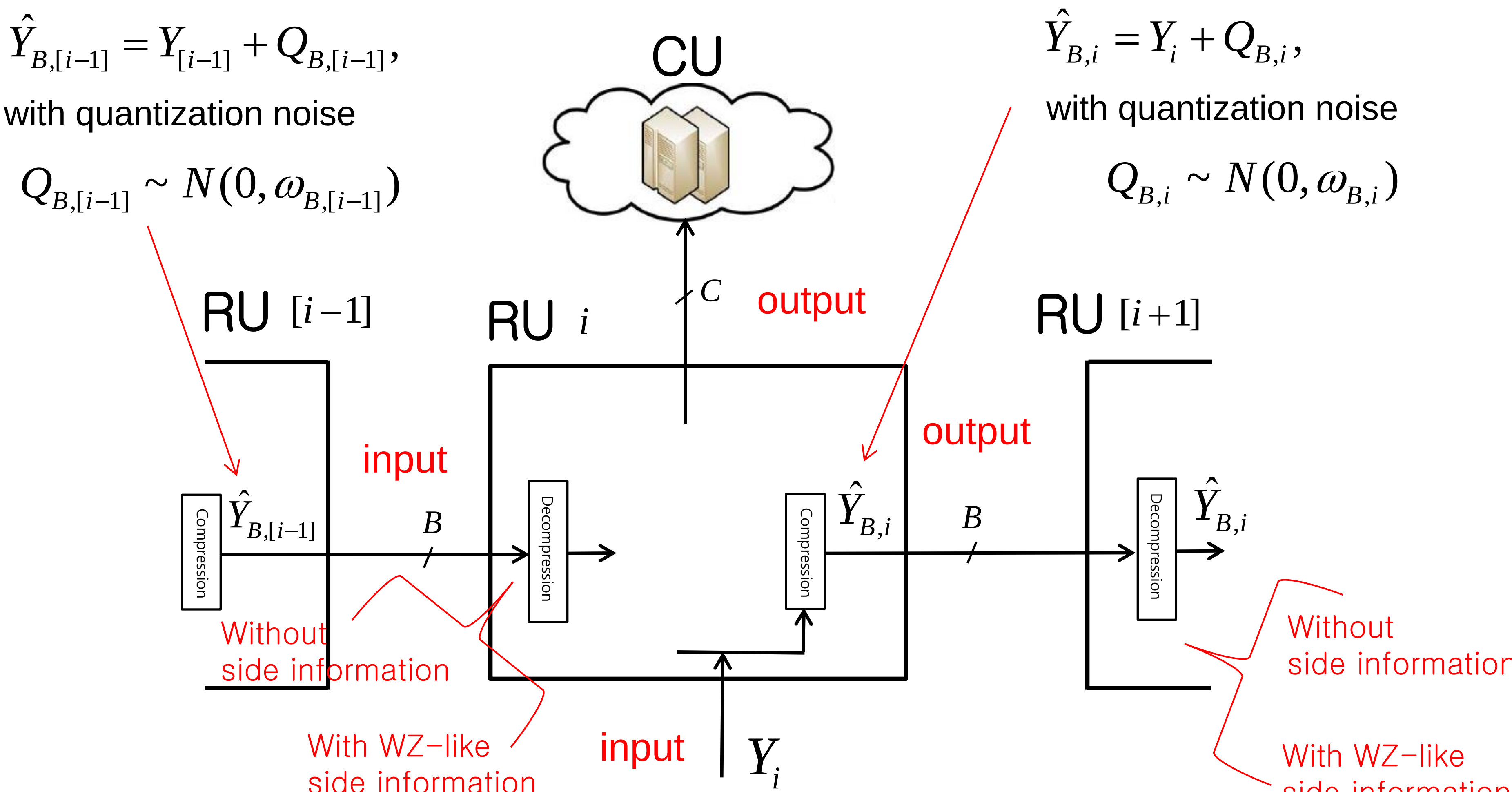
$$Q_{B,i} \sim N(0, \omega_{B,i})$$



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

Oblivious Processing at RUs

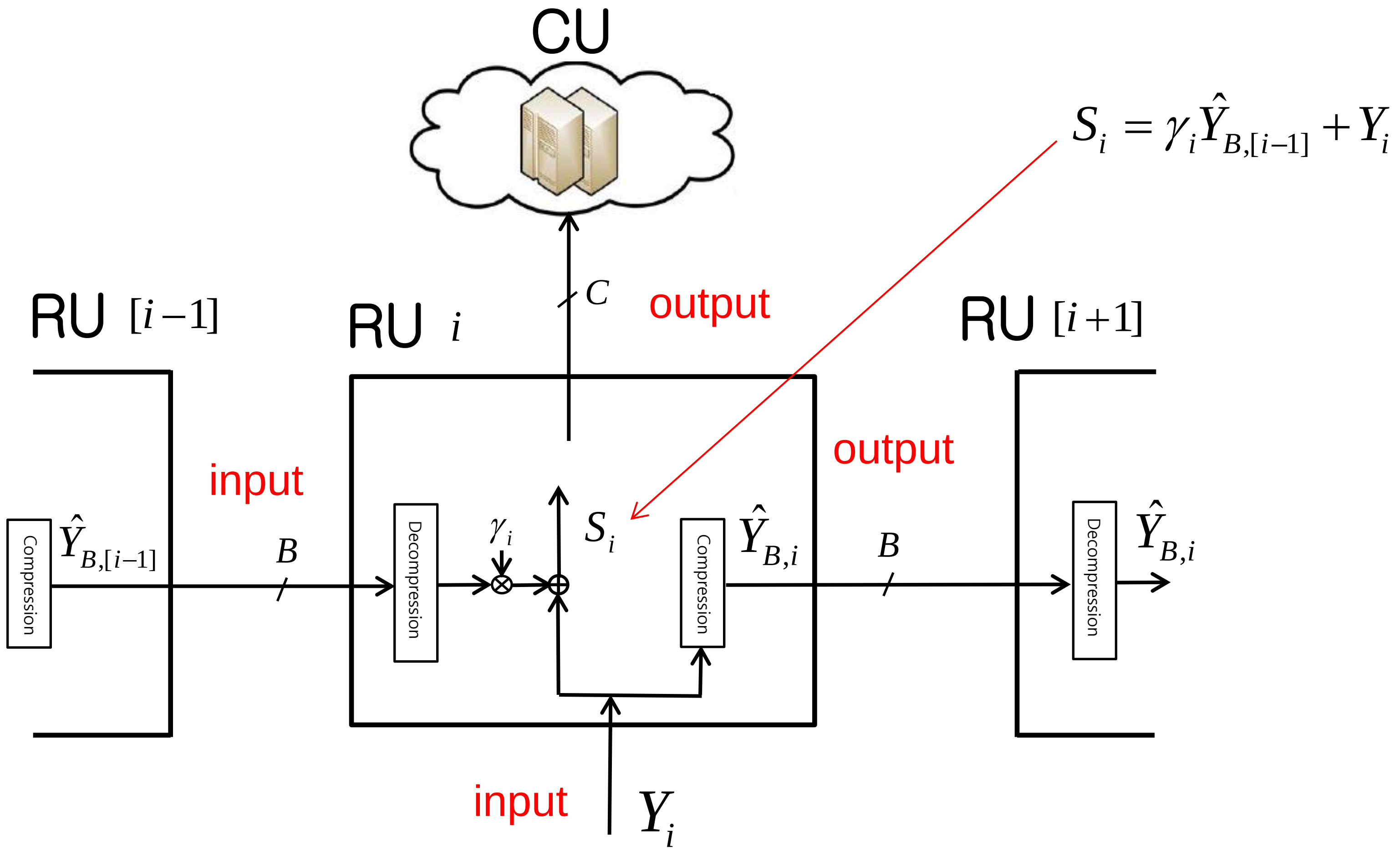
- In-network processing (INP) at RU i



- 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



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

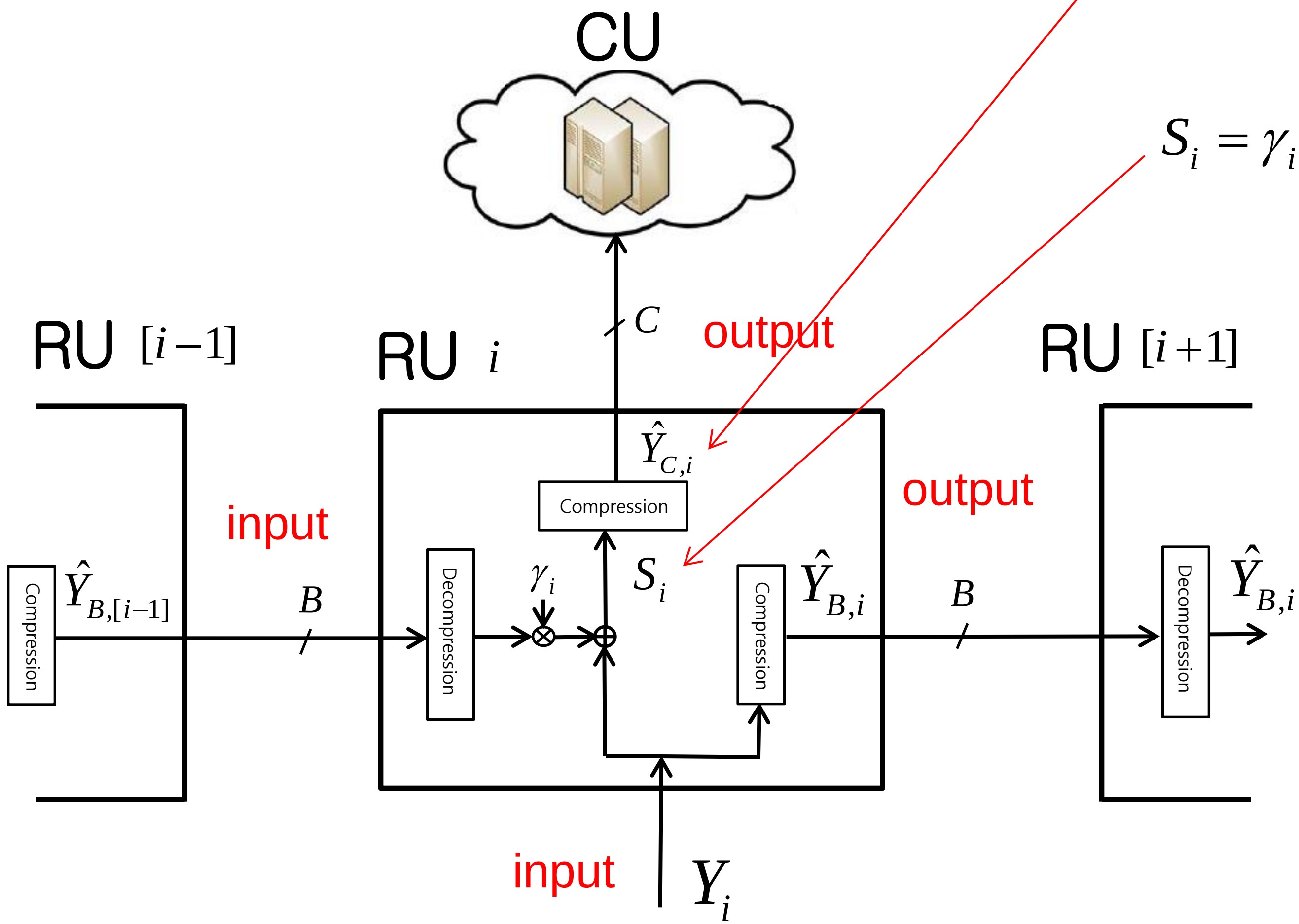
Oblivious Processing at RUs

- In-network processing (INP) at RU i

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

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

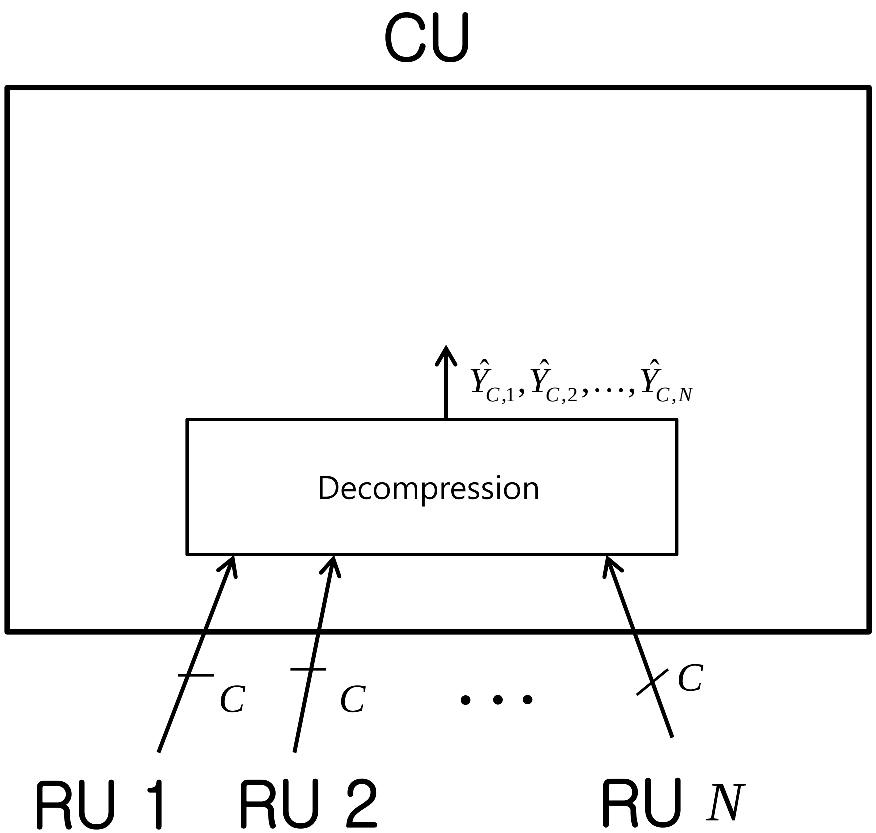
$$S_i = \gamma_i \hat{Y}_{B,[i-1]} + Y_i$$



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

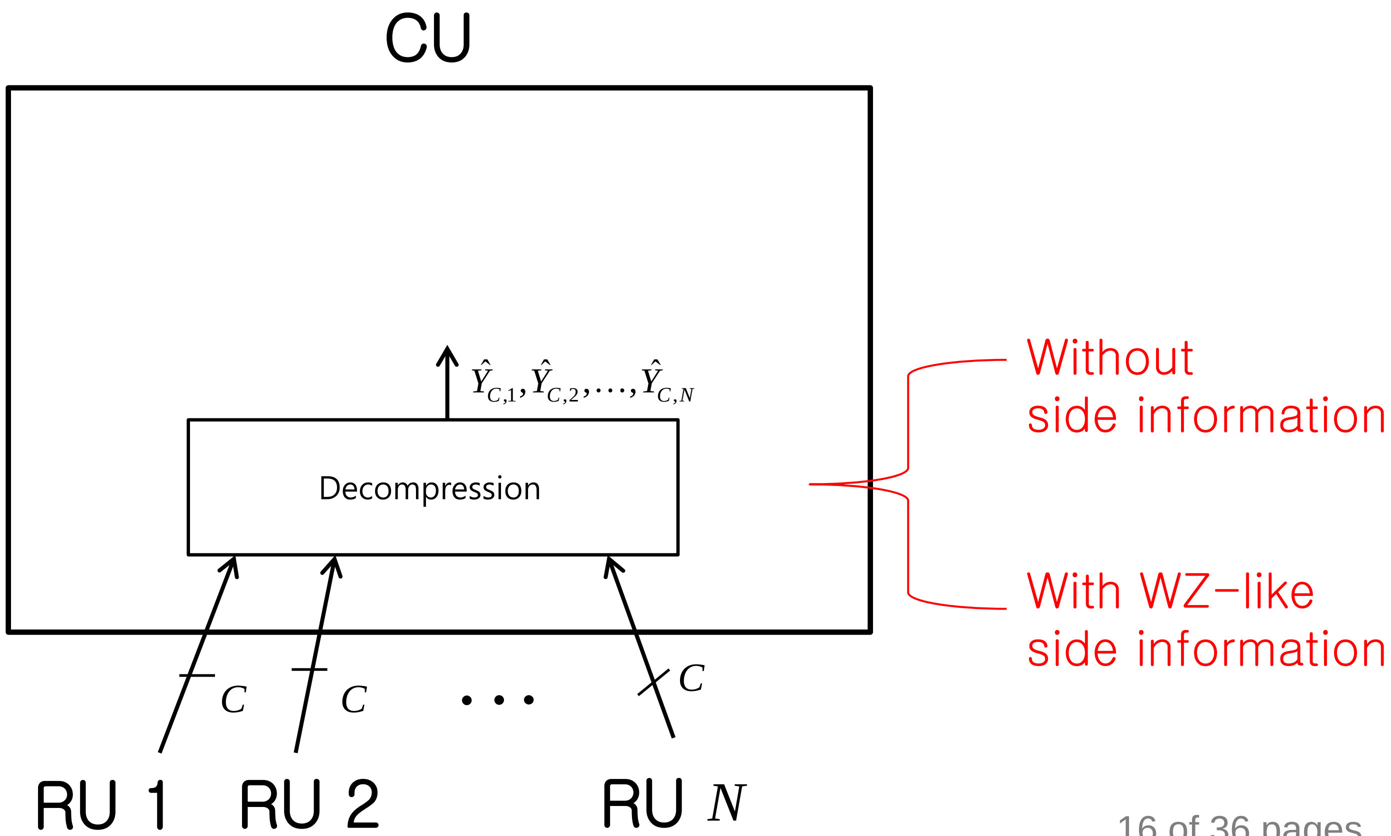
Decoding at CU

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



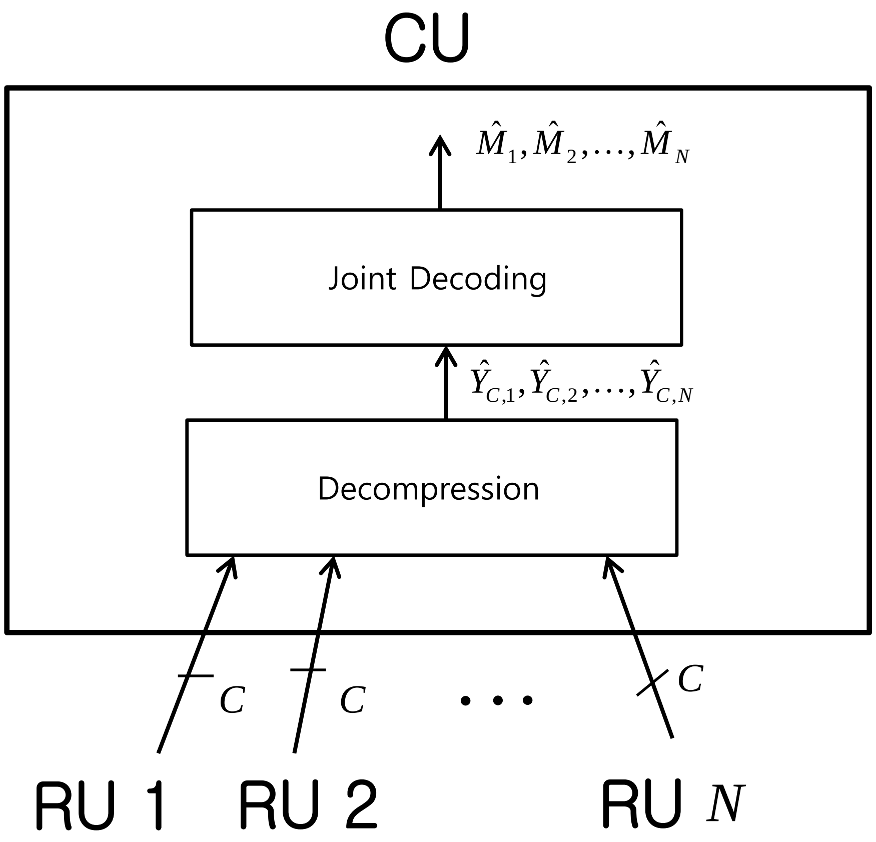
Decoding at CU

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



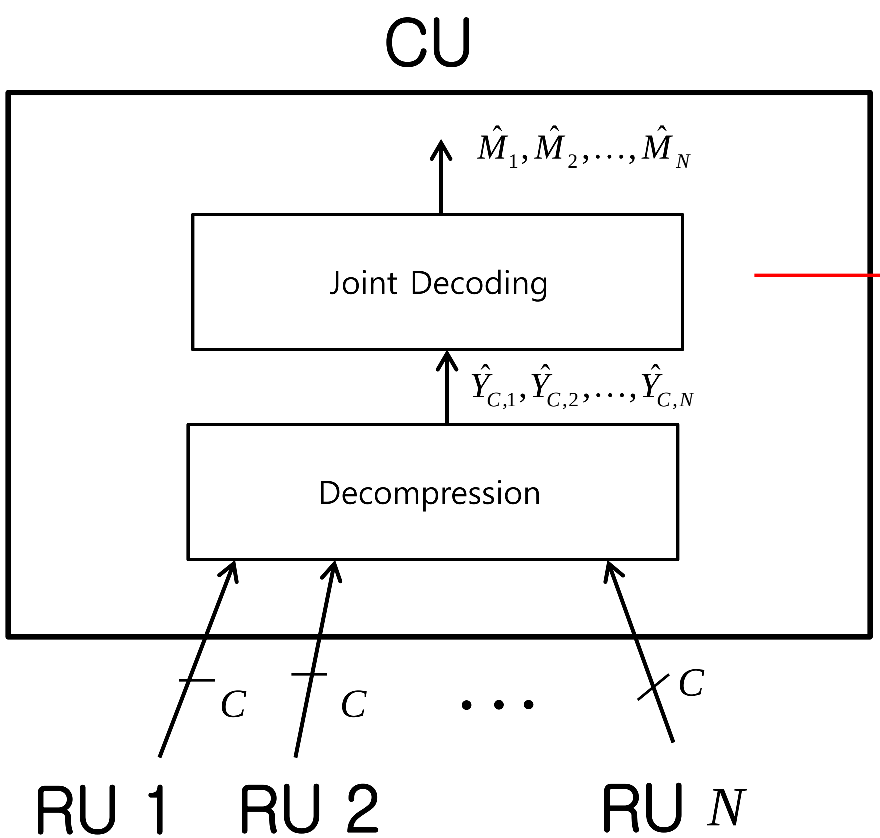
Decoding at CU

- 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 $\hat{M}_1, \hat{M}_2, \ldots, \hat{M}_N$.



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 $\hat{M}_1, \hat{M}_2, \ldots, \hat{M}_N$.



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

Decoding at CU

- Unless stated otherwise, assume that

$$\omega_{B,i} = \omega_B,\ \omega_{C,i} = \omega_C,\ \gamma_i = \gamma,\ i \in \mathcal{N}.$$

- 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

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

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

Technion Israel Institute of Technology

- 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

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}

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

- 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

  } Modeled differently depending on decompression strategy

Outline

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

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]

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

Problem Description

Technion Israel Institute of Technology

- Sum-rate maximization problem (P1)

$$\underset{\omega_B,\,\omega_C,\,\gamma}{\text{maximize}} \quad \frac{1}{2}\sum_{i\in\mathcal{N}}\log_2\left(1+P\frac{1+(\gamma+\alpha)^2+\gamma^2\alpha^2+(\gamma+\alpha)(1+\gamma\alpha)\lambda_{1,i}+\gamma\alpha\lambda_{2,i}}{\sigma^2\gamma\lambda_{1,i}+\sigma^2(\gamma^2+1)+\omega_B\gamma^2+\omega_C}\right)$$

$$\text{s.t.} \quad \frac{1}{2}\log_2\left(1+\frac{P(1+\alpha^2)+\sigma^2}{\omega_B}\right)\le B,$$

$$\frac{1}{2}\log_2\left(1+\frac{\left(\gamma^2\alpha^2+(\gamma+\alpha)^2+1\right)P+\gamma^2\omega_B+(1+\gamma^2)\sigma^2}{\omega_C}\right)\le C.$$

- Not easy to solve the problem due to the non-convexity.

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.

Outline

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

Leveraging Side Information

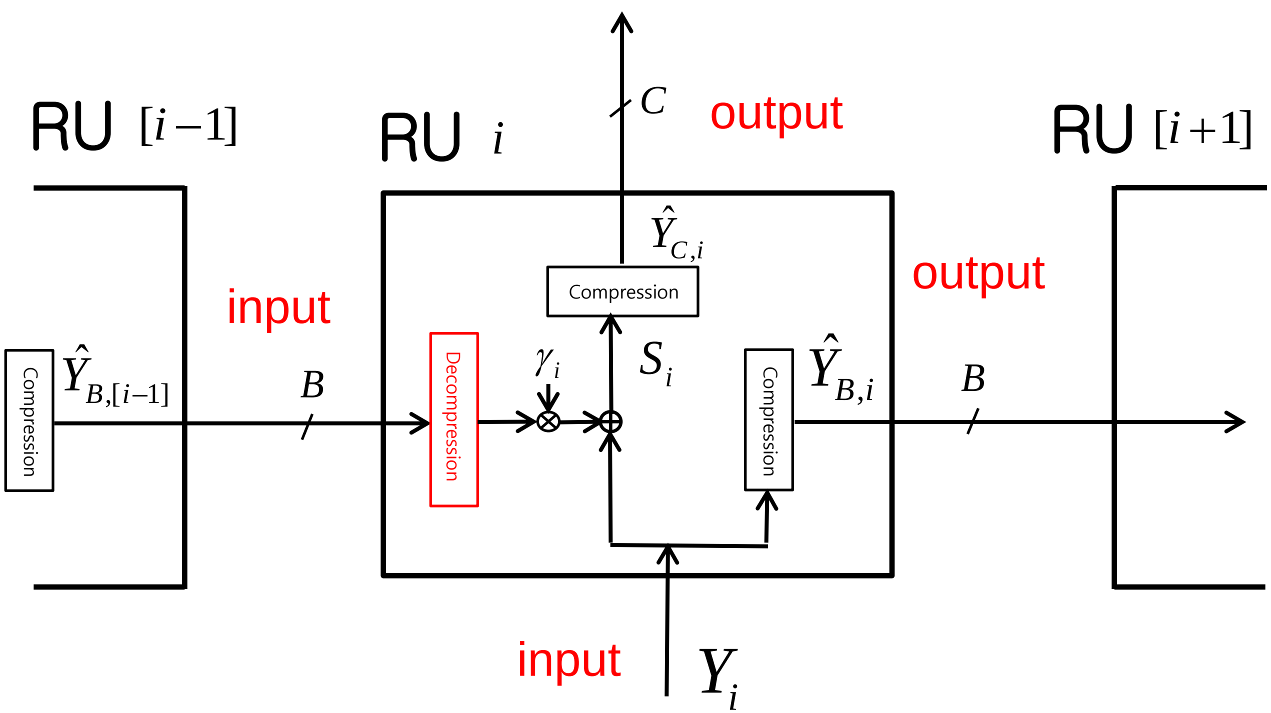
- In this strategy, the quantized signals $\hat{Y}_{B,i}$ and $\hat{Y}_{C,i}$ are decompressed while leveraging (WZ-style) side information.

- 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 $\hat{Y}_{C,1}, \hat{Y}_{C,2}, \ldots, \hat{Y}_{C,N}$.
  - At each step, previously decompressed signals can be leveraged as side information.

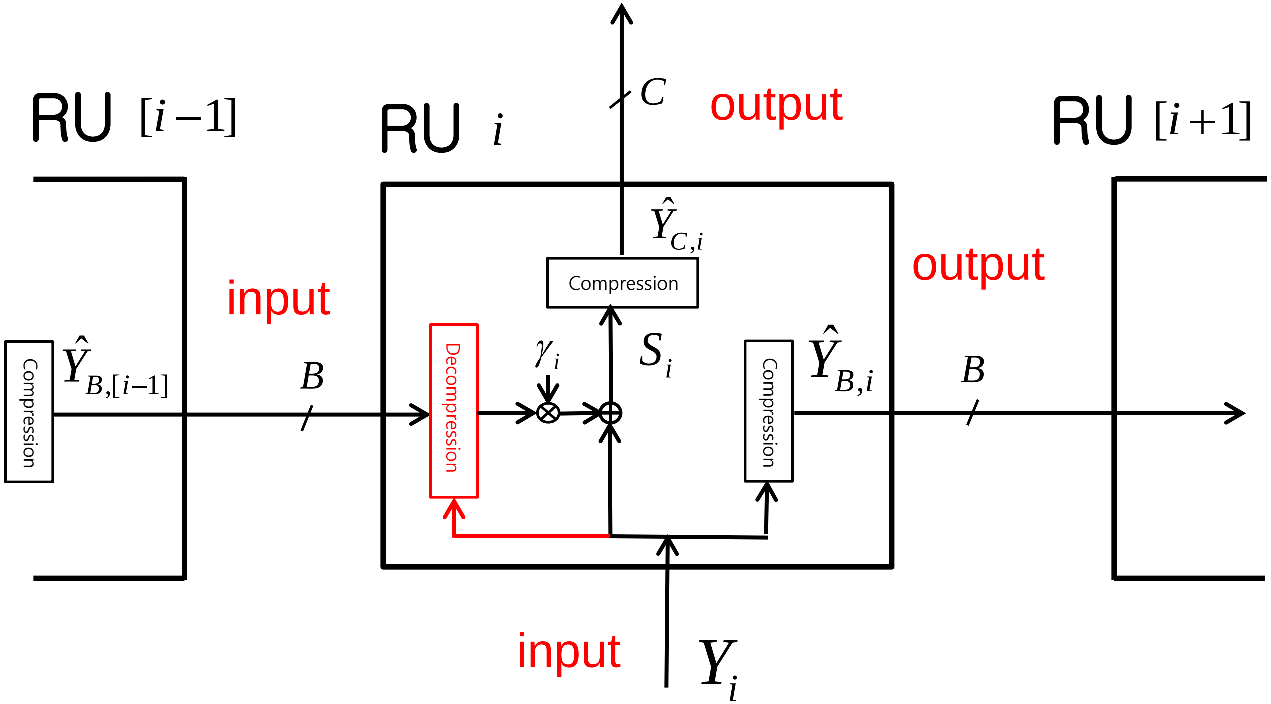
Side Information for RU-RU Links

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



Side Information for RU-RU Links

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



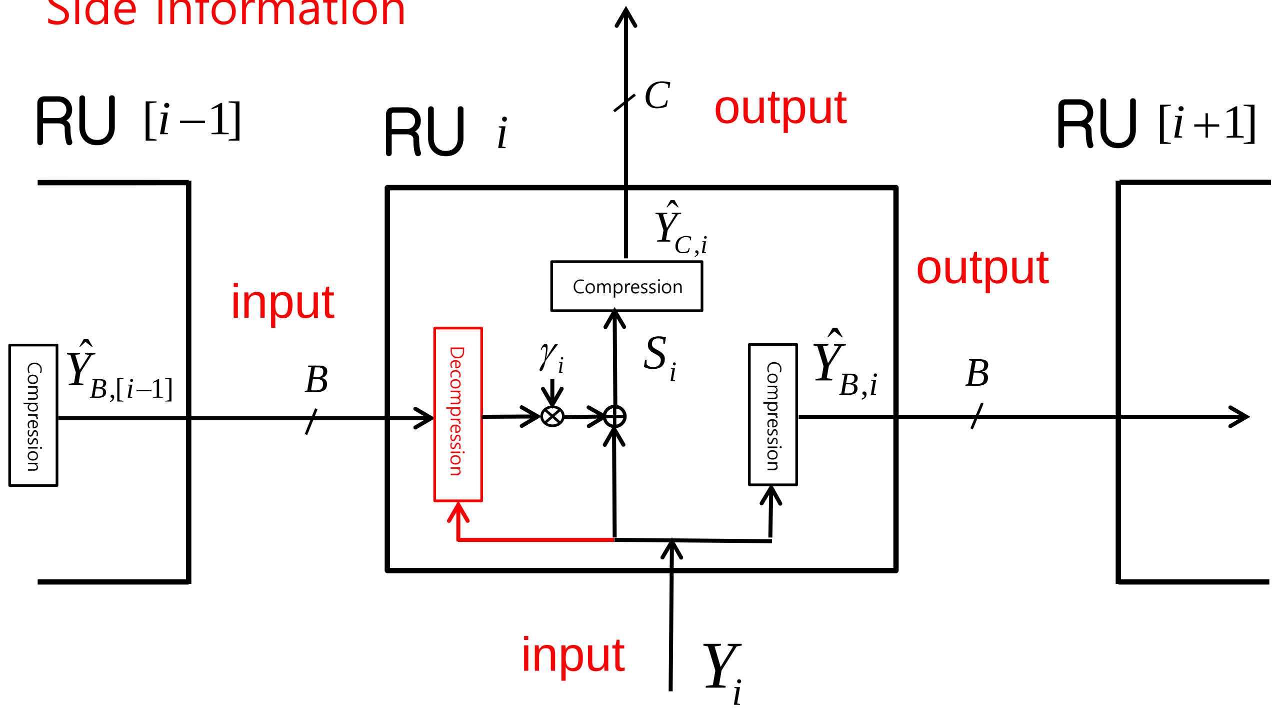
Side Information for RU-RU Links

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

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

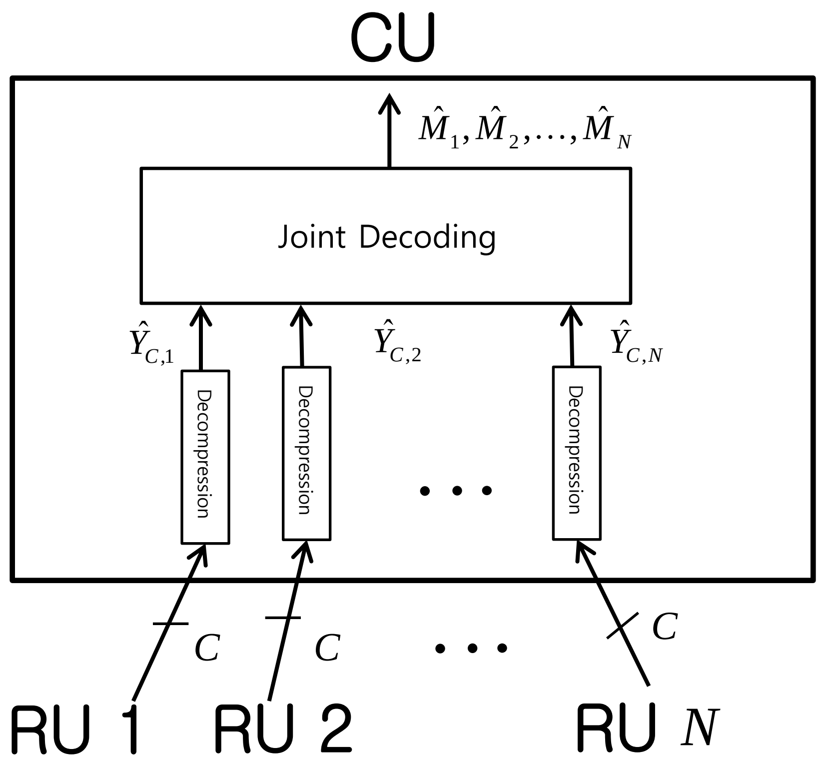
with $E[Y_i^2 \mid Y_{[i+1]}] = (1+\alpha^2)P+\sigma^2 - \frac{\alpha^2 P^2}{(1+\alpha^2)P+\sigma^2}$.

Side information



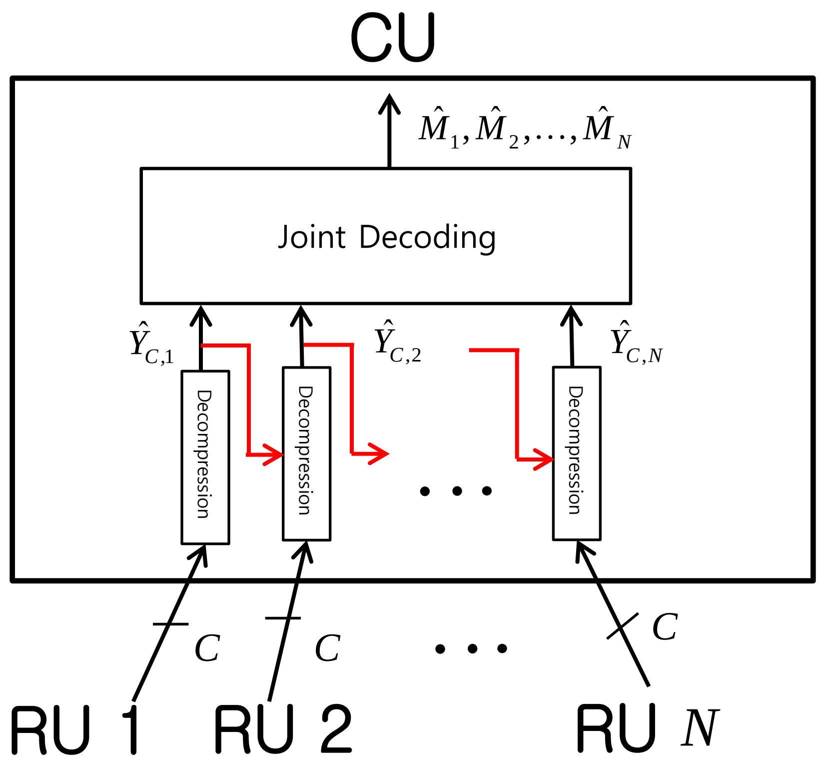
Side Information for RU-CU Links

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



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 $\hat{Y}_{C,1} \rightarrow \hat{Y}_{C,2} \rightarrow \ldots \rightarrow \hat{Y}_{C,N}$



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 $\hat{Y}_{C,1} \rightarrow \hat{Y}_{C,2} \rightarrow \ldots \rightarrow \hat{Y}_{C,N}$
  - Constraint on $\omega_{C,1}$
    - No side information when decompressing $\hat{Y}_{C,1}$

$$I(S_1; \hat{Y}_{C,1}) = \frac{1}{2}\log_2\left(1+\frac{E\left[S_1^2\right]}{\omega_{C,1}}\right) \leq C, \quad \text{with } E\left[S_1^2\right] = \left(\gamma^2\alpha^2 + (\gamma+\alpha)^2 + 1\right)P + \gamma^2\omega_B + (1+\gamma^2)\sigma^2.$$

Side Information for RU-CU Links

- Decompression of $\hat{Y}_{C,1}, \hat{Y}_{C,2}, \dots, \hat{Y}_{C,N}$ at CU
  - Consider a successive decompression with order $\hat{Y}_{C,1} \to \hat{Y}_{C,2} \to \dots \to \hat{Y}_{C,N}$
  - Constraint on $\omega_{C,1}$
    - No side information when decompressing $\hat{Y}_{C,1}$

$$I(S_1; \hat{Y}_{C,1}) = \frac{1}{2}\log_2\left(1 + \frac{E\left[S_1^2\right]}{\omega_{C,1}}\right) \le C, \quad \text{with } E\left[S_1^2\right] = \left(\gamma^2\alpha^2 + (\gamma+\alpha)^2 + 1\right)P + \gamma^2\omega_B + (1+\gamma^2)\sigma^2.$$

  - Constraint on $\omega_{C,i}$ $(i > 1)$
    - $\hat{Y}_{C,i-1}$ is leveraged as side information when decompressing $\hat{Y}_{C,i}$.

$$I(S_i; \hat{Y}_{C,i} \mid \hat{Y}_{C,i-1}) = \frac{1}{2}\log_2\left(1 + \frac{E\left[S_i^2 \mid \hat{Y}_{C,i-1}\right]}{\omega_{C,i}}\right) \le C, \quad \text{with } E\left[S_i^2 \mid \hat{Y}_{C,i-1}\right] = \left(\gamma_i^2\alpha^2 + (\gamma_i+\alpha)^2 + 1\right)P + \gamma_i^2\omega_B + (1+\gamma_i^2)\sigma^2 - \frac{\left[(\gamma+\alpha)P + \gamma\alpha(\gamma+\alpha)P + \gamma\sigma^2\right]^2}{\left(\gamma^2\alpha^2 + (\gamma+\alpha)^2 + 1\right)P + \gamma^2\omega_B + (1+\gamma^2)\sigma^2 + \omega_{C,i-1}}.$$

Side information

Problem Description

- Sum-rate maximization problem (P2)

$$\underset{\omega_B,\,\omega_C,\,\gamma}{\text{maximize}} \quad \frac{1}{2}\sum_{i\in\mathcal{N}}\log_2\left(1+P\frac{1+(\gamma+\alpha)^2+\gamma^2\alpha^2+(\gamma+\alpha)(1+\gamma\alpha)\lambda_{1,i}+\gamma\alpha\lambda_{2,i}}{\sigma^2\gamma\lambda_{1,i}+\sigma^2(\gamma^2+1)+\omega_B\gamma^2+\omega_C}\right)$$

$$\text{s.t.} \quad \frac{1}{2}\log_2\left(1+\frac{E[Y_i^2\,|\,Y_{[i+1]}]}{\omega_B}\right)\le B,\quad i\in\mathcal{N},$$

$$I(S_1;\hat{Y}_{C,1})=\frac{1}{2}\log_2\left(1+\frac{E\left[S_1^2\right]}{\omega_{C,1}}\right)\le C,$$

$$I(S_i;\hat{Y}_{C,i}\,|\,\hat{Y}_{C,i-1})=\frac{1}{2}\log_2\left(1+\frac{E\left[S_i^2\,|\,\hat{Y}_{C,i-1}\right]}{\omega_{C,i}}\right)\le C,\quad i\in\mathcal{N}\setminus\{1\}.$$

- The optimization can be similarly tackled as for (P1).
  - i.e., one-dimensional search with respect to γ.

Optimization

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

$$\omega_B = \beta_B\left((1+\alpha^2)P+\sigma^2-\frac{\alpha^2P^2}{(1+\alpha^2)P+\sigma^2}\right),$$

$$\omega_{C,1} = \beta_C\left(\gamma^2\alpha^2+(\gamma+\alpha)^2+1\right)P+\gamma^2\omega_B+(1+\gamma^2)\sigma^2,$$

$$\omega_{C,i} = \beta_C\begin{pmatrix}\left(\gamma_i^2\alpha^2+(\gamma_i+\alpha)^2+1\right)P+\gamma_i^2\omega_B+(1+\gamma_i^2)\sigma^2 \\ -\dfrac{\left[(\gamma+\alpha)P+\gamma\alpha(\gamma+\alpha)P+\gamma\sigma^2\right]^2}{\left(\gamma^2\alpha^2+(\gamma+\alpha)^2+1\right)P+\gamma^2\omega_B+(1+\gamma^2)\sigma^2+\omega_{C,i-1}}\end{pmatrix},\ i\in\mathcal{N}\setminus\{1\},$$

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

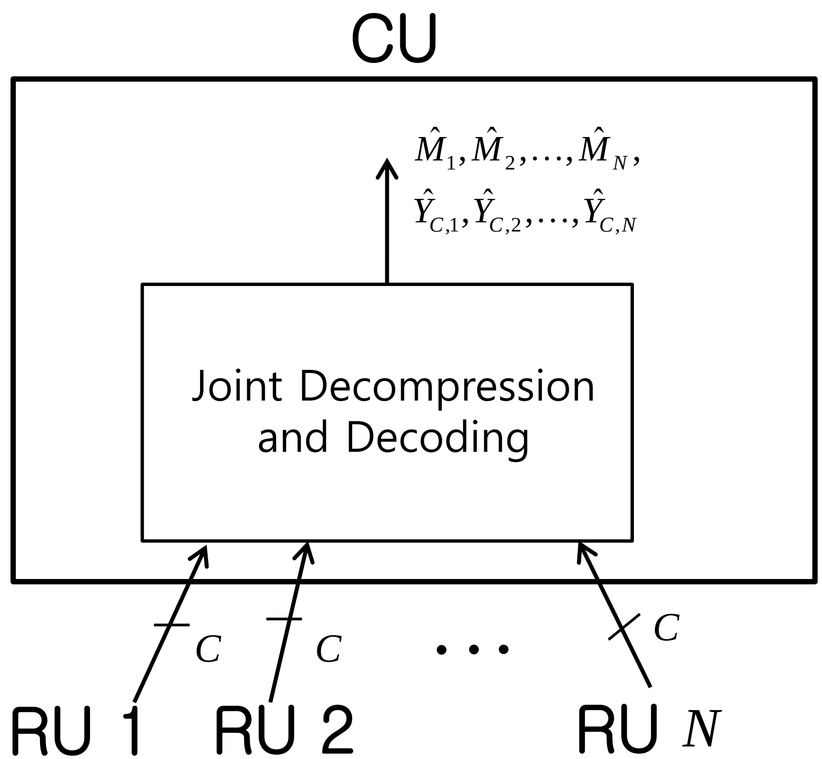
- Therefore, the optimal value for (P2) can be found via one-dimensional search over the coefficient γ.

Outline

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

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 $\omega_B, \omega_C, \gamma$ [Sanderovich et al:TIT] [Lim et al:TIT]

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

$$= \min_{\mathcal{S}\subseteq\mathcal{N}} \left\{ |\mathcal{S}| \left(C - g_C(\omega_B, \omega_C, \gamma)\right) + f_{C,\mathcal{S}}(\omega_B, \omega_C, \gamma) \right\},$$

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

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

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

Problem Description

- Sum-rate maximization problem (P3)

$$\begin{aligned} \underset{\omega_B,\, \omega_C,\, \gamma,\, R_{\text{sum}}}{\text{maximize}} \quad & R_{\text{sum}} \\ \text{s.t.} \quad & R_{\text{sum}} \le |\mathcal{S}|\left(C - \tilde{g}_C(\omega_B, \omega_C, \gamma)\right) + f_{C,\mathcal{S}}(\omega_B, \omega_C, \gamma), \quad \mathcal{S} \subseteq \mathcal{N}, \\ & \frac{1}{2}\log_2\left(1 + \frac{E[Y_i^2 \mid Y_{[i+1]}]}{\omega_B}\right) \le B, \quad i \in \mathcal{N}, \end{aligned}$$

Problem Description

Technion Israel Institute of Technology

- Sum-rate maximization problem (P3)

$$\begin{aligned}
\underset{\omega_B,\, \omega_C,\, \gamma,\, R_{\text{sum}}}{\text{maximize}} \quad & R_{\text{sum}} \\
\text{s.t.} \quad & R_{\text{sum}} \le |\mathcal{S}|\left(C - \tilde{g}_C(\omega_B, \omega_C, \gamma)\right) + f_{C,\mathcal{S}}(\omega_B, \omega_C, \gamma), \quad \mathcal{S} \subseteq \mathcal{N}, \\
& \frac{1}{2}\log_2\left(1 + \frac{E[Y_i^2 \mid Y_{[i+1]}]}{\omega_B}\right) \le B, \quad i \in \mathcal{N},
\end{aligned}$$

  - We propose to perform one-dimensional search w.r.t. γ.
    - For given γ, optimizing ω_B and ω_C is a difference-of-convex (DC) problem.
      - Thus, suboptimal solution of ω_B and ω_C for given γ can be found via concave convex procedure (CCCP) approach.

Outline

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

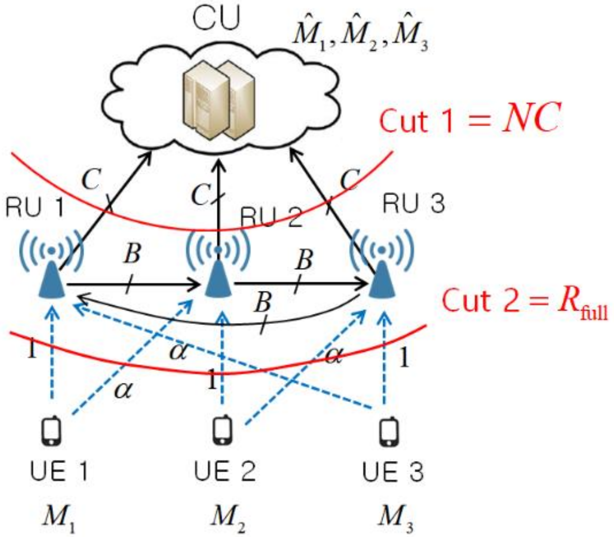
Cut-Set Upper Bound

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

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

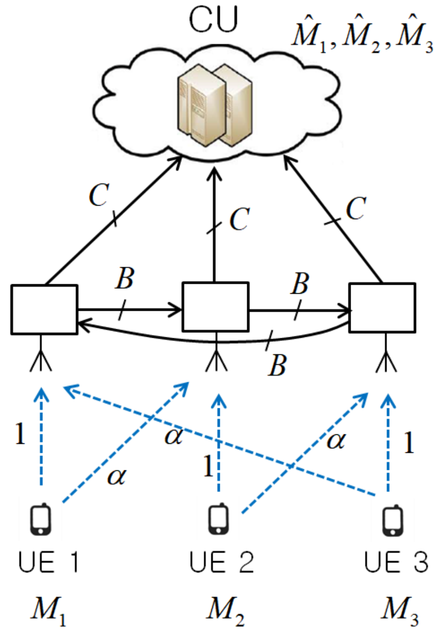
where R_{full} is the sum-rate achievable when full cooperation among RUs is possible, i.e.,

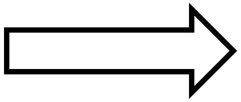
$$\begin{aligned} R_{\mathrm{full}} &= I\left(\{X_i\}_{i\in\mathcal{N}};\{Y_i\}_{i\in\mathcal{N}}\right) \\ &= \frac{1}{2}\log_2 \det\left(\mathbf{I} + P\left(\sigma^2 \mathbf{H}_Z \mathbf{H}_Z^T\right)^{-1} \mathbf{H}_X \mathbf{H}_X^T\right). \end{aligned}$$

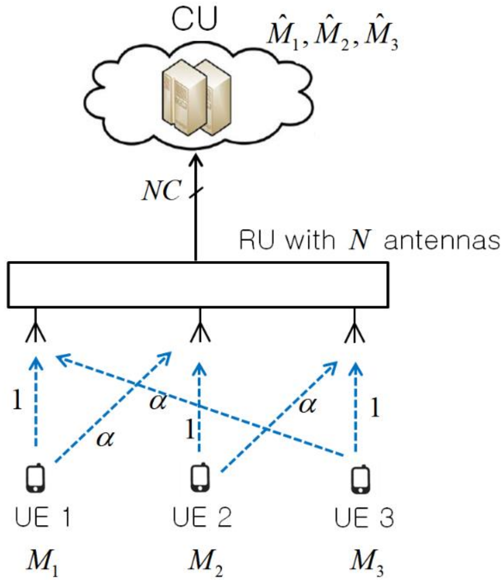


Oblvious Upper Bound

- We also consider an *oblivious upper bound*.
  - Sum-rate that can be achieved when the RUs are co-located and send jointly quantized signals of $\{Y_i\}_{i\in\mathcal{N}}$ to the CU.



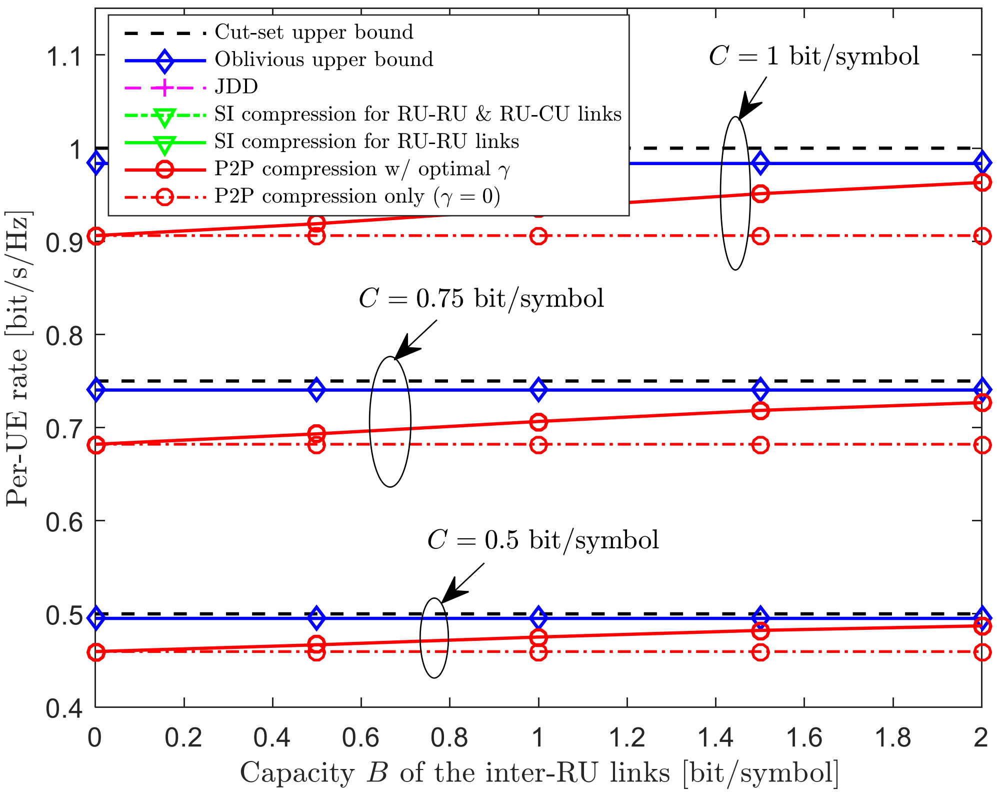




Achievable rate was analyzed in [dCoso-Simoens, Thm. 1].

Numerical Example

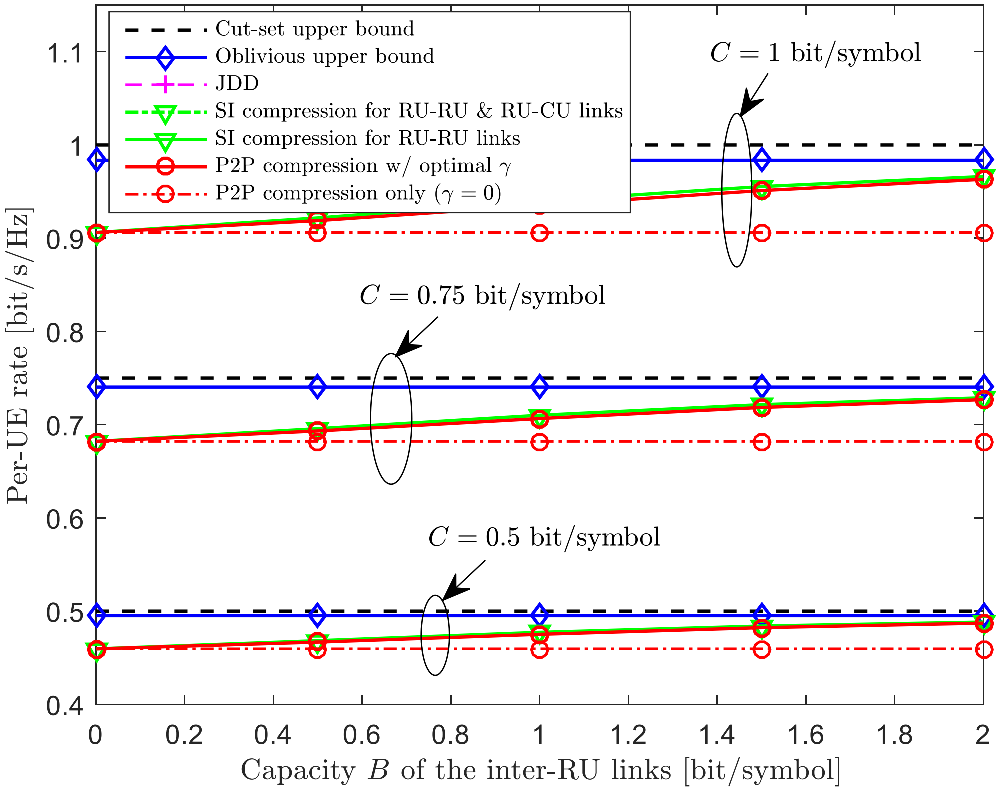
- Per-UE rate versus RU-RU capacity B
  - $N = 3$, SNR $= 20$ dB, $\alpha = 0.7$



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

Numerical Example

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

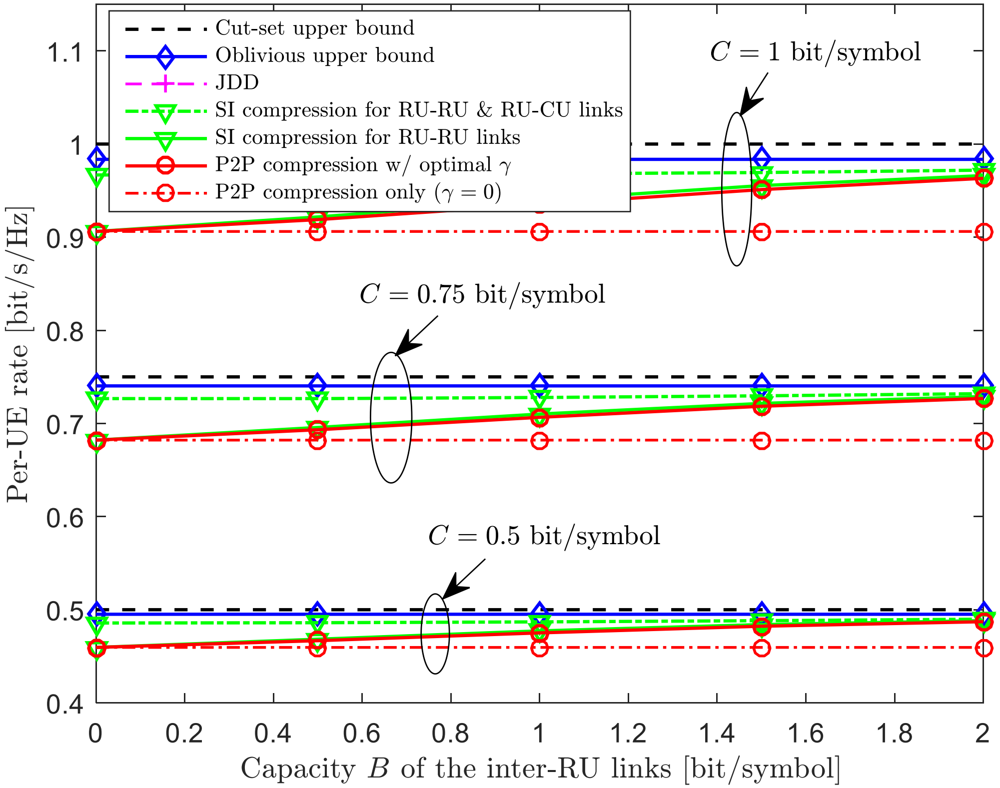


– With INP, the performance approaches upper bound as B increases.

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

Numerical Example

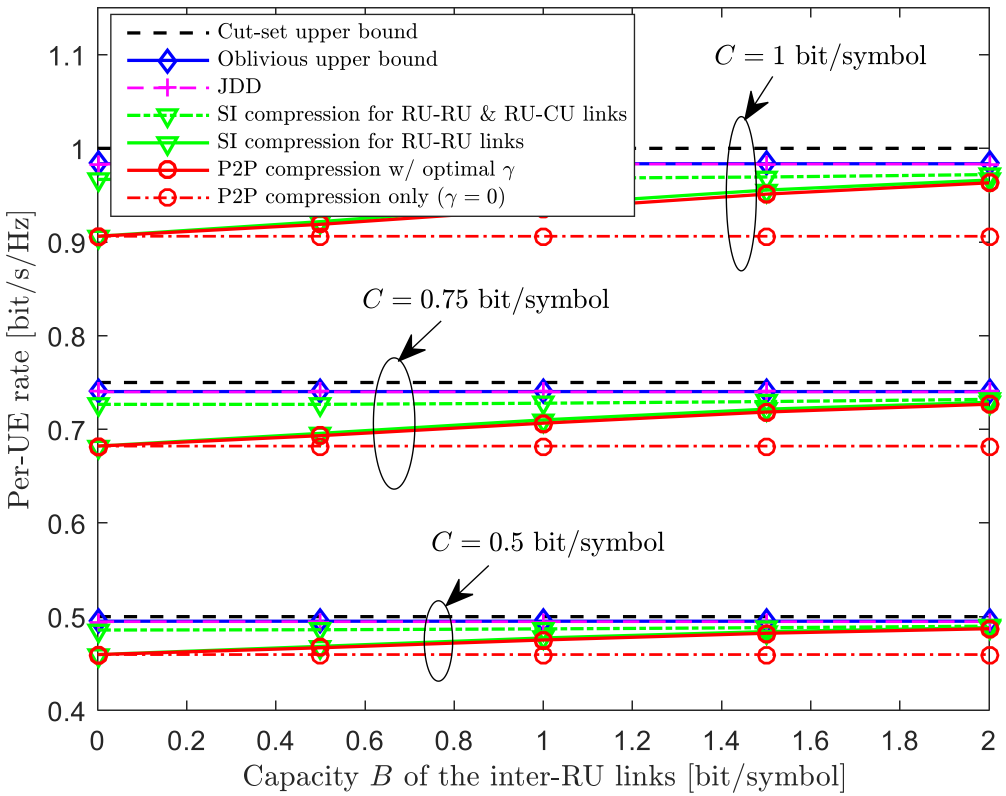
- Per-UE rate versus RU-RU capacity B
  - $N = 3$, $\text{SNR} = 20$ dB, $\alpha = 0.7$



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

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.

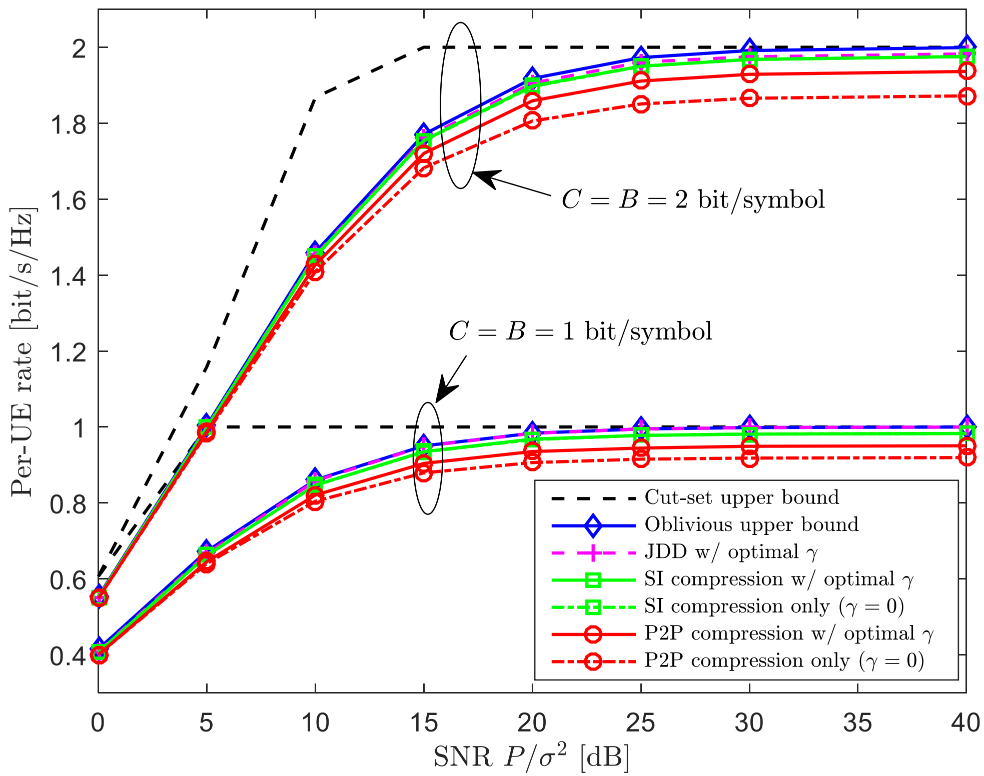
– Leveraging SI for RU–RU link provides a slight sum–rate gain.

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

- JDD further improves the sum-rate performance.
(This is the optimal oblivious processing [Aguerri et al:arXiv].)

Numerical Example

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

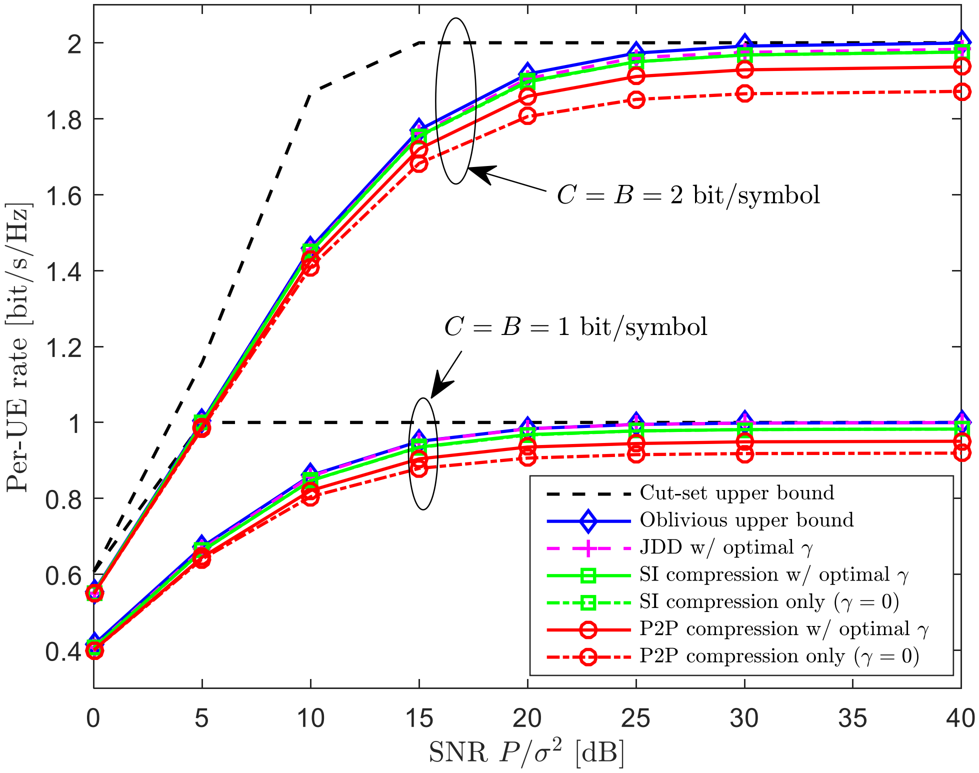


- In low-to-intermediate SNR regime, the gap to cutset upper bound is still large.

Numerical Example

Technion Israel Institute of Technology

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



- In low-to-intermediate SNR regime, the gap to cutset 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

Technion Israel Institute of Technology

- Introduction
- System Model
- Point-to-Point Compression
- Leveraging Side Information
- Joint Decompression and Decoding
- Numerical Examples
- **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

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
  - Possible optimality of non-oblivious processing also for interconnected radio units, ala: [Aguerri, Zaidi, Caire and Shamai arXiv:1701.07237, Jan. 2017]
  - 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][Bidokhti et al, ISIT2017]

Concluding Remarks

- Future work (ctd')
  - C-RAN uplink set-ups with fading channels
  - Downlink of C-RAN (Oblivious and Non-oblivious schemes) [Wang et al IT, Aug 2018]
    - Possibly with edge processing or edge caching

Thank you!

References

[Shamai et al:JWCC] S. Shamai, O. Somekh and B. M. Zaidel, “Multi-cell communications: An information theoretic perspectives,” *Proc. Joint Workshop Comm. Coding*, Domini, Italy, Oct. 2004.

[Somekh et al:TIT] O. Somekh, B. Zaidel and S. Shamai (Shitz), "Sum rate characterization of joint mulitple-cell-site processing," *IEEE Trans. Inf. Theory*, vol. 53, no. 12, pp. 4473-4497, Dec. 2007.

[Simeone et al:TIT] O. Simeone, O. Somekh, H. V. Poor and S. Shamai, “Local base station cooperation via finite-capacity links for the uplink of linear cellular networks,” *IEEE Trans. Inf. Theory*, vol. 55, no. 1, pp. 190-204, Jan. 2009.

[dCoso-Simoens] A. d. Coso and S. Simoens, “Distributed compression for MIMO coordinated networks with a backhaul constraint,” *IEEE Trans. Wireless Comm.*, vol. 8, no. 9, pp. 4698-4709, Sep. 2009.

[Sanderovich et al:TIT] A. Sanderovich, O. Somekh, H. V. Poor and S. Shamai (Shitz), "Uplink macro diversity with limited backhaul cellular networks," *IEEE Trans. Inf. Theory*, vol. 55, no. 8, pp. 3457-3478, Aug. 2009.

References

[Yu-Sharma] C. Yu and G. Sharma, “Distributed estimation and coding: A sequential framework based on a side-information decomposition,” *IEEE Trans. Sig. Proc.*, vol. 59, no. 2, pp. 759-773, Feb. 2011.

[Hoydis et al:TSP] J. Hoydis, M. Kobayashi and M. Debbah, “Optimal channel training in uplink network MIMO systems," *IEEE Trans. Sig. Proc.*, vol. 59, no. 6, pp. 2824-2833, Jun 2011.

[Lim et al:TIT] S. H. Lim, Y.-H. Kim, A. E. Gamal and S.-Y. Chung, "Noisy network coding," *IEEE Trans. Inf. Theory*, vol. 57, no. 5, pp. 3132-3152, May 2011.

[CPRI] Ericsson AB, Huawei Technologies, NEC Corporation, Alcatel Lucent and Nokia Siemens Networks, “Common public radio interface (CPRI): interface specification,” CPRI specification v5.0, Sep. 2011.

[China] China Mobile, C-RAN: The Road Towards Green RAN, White Paper, ver. 2.5, China Mobile Research Institute, Oct. 2011.

[Segel-Weldon] J. Segel and M. Weldon, “Lightradio portfolio-Technical overview,” Technology White Paper 1, Alcaltel-Lucent.

References

[Simeone et al:FnT] O. Simeone, N. Levy, A. Sanderovich, O. Somekh, B. M. Zaidel, H. V. Poor and S. Shamai, “Cooperative wireless cellular systems: An information-theoretic view,” *Foundations and Trends in Comm. Inf. Theory*, vol. 8, nos. 1-2, 2011, pp. 1-177, Now Publishers, 2012.

[IDC] Integrated Device Technol. Inc., “Front-haul compression for emerging C-RAN and small cell networks,” Apr. 2013.

[Park et al:SPL] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Joint decompression and decoding for cloud radio access networks,” *IEEE Signal Processing Letters*, vol. 20, no. 5, pp. 503-506, May 2013.

[Hong-Caire] S.-N. Hong and G. Caire, “Compute-and-forward strategies for cooperative distributed antenna systems,” *IEEE Trans. Inf. Theory*, vol. 59, no. 9, pp. 5227-5243, Sep. 2013.

[Zhou-Yu:JSAC] L. Zhou and W. Yu, “Uplink multicell processing with limited backhaul via per-base-station successive interference cancellation,” *IEEE Journ. Sel. Areas Comm.*, vol. 31, no. 10, pp. 1981-1993, Oct. 2013.

References

[Andrews et al:JSAC] J. G. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. C. K. Soong and J. C. Zhang, “What will 5G be?” *IEEE Journ. Sel. Areas Comm., Special Issue on 5G Communication Systems*, vol. 32, no. 6, pp. 1065-1082, Sep. 2014.

[Park et al:SPM] S.-H. Park, O. Simeone, O. Sahin and S. Shamai, “Fronthaul compression for cloud radio access networks: Signal processing advances inspired by network information theory,” *IEEE Sig. Proc. Mag.*, vol. 31, no. 6, pp. 69-79, Nov. 2014.

[Aguerri-Zaidi] I. E. Aguerri and A. Zaidi, “Lossy compression for compute-and-forward in limited backhaul uplink multicell processing,” arXiv:1602.08714, Feb. 2016.

[Simeone et al:JCN] O. Simeone, A. Maedar, M. Peng, O. Sahin and W. Yu, “Cloud radio access network: Virtualizing wireless access for dense heterogeneous systems,” *Journ. Comm. Networks*, vol. 18, no. 2, pp. 135-149, Apr. 2016.

[Zhou et al:TIT] Y. Zhou, Y. Xu, W. Yu and J. Chen, “On the optimal fronthaul compression and decoding strategies for uplink cloud radio access networks,” *IEEE Trans. Inf. Theory*, vol. 62, no. 12, pp. 7402-7418, Dec. 2016.

References

[Aguerri-Zaidi-Caire-Shamai:arXiv17] I. E. Aguerri, A. Zaidi, G. Caire and S. Shamai (Shitz), "On the Capacity of Cloud Radio Access Networks with Oblivious Relaying," arXiv:1701.07237, Jan. 2017.

[Wu et al:arXiv] X. Wu, L. P. Barnes and A. Ozgur, "The capacity of the relay channel," arXiv:1701.02043, Jan. 2017.

[Wigger et al:TIT] M. Wigger, R. Timo and S. Shamai (Shitz), "Conferencing in Wyner's Asymmetric Interference Network: Effect of Number of Rounds," *IEEE Trans. Inf. Theory*, vol. 63, no. 2, pp. 1199-1226, Feb. 2017.

[Bidokhti et al, ISIT2017] S. S. Bidokhti, G. Kramer and S. Shamai (Shitz), "Capacity bounds on the downlink of symmetric, multi-relay, single receiver C-RAN networks," in *Proc. IEEE ISIT 2017*, Aachen, Germany, Jun. 2017.

[Wang et al IT, Aug 2018] C.-Y. Wang, M. Wiger and A. Zaidi, "On achievability for downlink cloud radio access networks with base station cooperation," *IEEE Trans. Inf. Thoery*, vol. 64, No. 8, pp. 5726-5742, Aug. 2018

Abstract

Shlomo Shamai

The Andrew and Erna Viterbi Faculty of Electrical Engineering

Technion-Israel Institute of Technology

"On Uplink Cloud Radio Access Networks With Interconnected Radio Units,"

We address the achievable sum-rate for the cloud radio access network (C-RAN) uplink 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 compression options, leveraging side information are also provided. Insights into the advantages of inter-RU communications follow some numerical examples highlighting the performance gap to the associated sum-rate upper bounds.

Joint work with Seok-Hwan Park (Chonbuk National University, Korea) and Osvaldo Simeone (King's College London).

This research was supported by the European Union's Horizon 2020 Research And Innovation Programme under grant agreement no. 694630.