On Uplink Cloud Radio Access Networks With Interconnected Radio Units

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Outline

- Introduction
- System Model
- Point-to-Point Compression
- Leveraging Side Information
- Joint Decompression and Decoding
- Numerical Examples
- Concluding Remarks
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  - Low-cost deployment of BSs [China][Segel-Weldon]
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- Effective interference mitigation via joint baseband processing [Shamai et al:JWCC][Somekh et al:TIT]
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  - Transfer **quantized** IQ baseband samples
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**Key challenges: Effective transfer of quantized IQ samples**

- Standard technique: CPRI [CPRI]
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  - Standard technique: CPRI [CPRI]
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 \( (0.002 \text{ ppm}) \), delay \( (5\mu s) \)
Sample-wise quantization (CPRI)
Sample-wise quantization (CPRI)

Vector quantization

Vector quantization (1)

\[ Y_i(1) \]

\[ Y_i(n) \]

Time index

Time domain

RU \( i \)

\[ C_i \text{ bits} \]

\[ nC_i \text{ bits} \]
Conventional source coding

[ElGamal-Kim, Ch. 3]

\[
Y \rightarrow Q(\ ) \rightarrow C \rightarrow Q^{-1}(\ ) \rightarrow \hat{Y}
\]

\(Q(\)\): Compression encoder;
\(Q^{-1}(\)\): Compression decoder.
Conventional source coding

[ElGamal-Kim, Ch. 3]

test channel: \( p(\hat{Y} | Y) \)

\[ Y \xrightarrow{Q()} C \xrightarrow{Q^{-1}()} \hat{Y} \]

\( Q() \): Compression encoder;
\( Q^{-1}() \): Compression decoder.
**Source Coding Results**

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

  \[ p(\hat{Y} | Y) \]

  An equivalent Gaussian test channel

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

  \( \omega = \mathbb{E}[|Q|^2] \):
  Quantization noise power

  \( Y \rightarrow Q(\ ) \rightarrow C \rightarrow Q^{-1}(\ ) \rightarrow \hat{Y} \)

  **Q( ):** Compression encoder;
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Conventional source coding

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

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

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

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

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

• Vector quantization in time domain

![Fronthaul Compression Diagram]

- **State-of-the-Art:** C-RAN
  - \( \omega_1 : I(Y_1; \hat{Y}_1) \leq C_1 \)
  - \( \omega_2 : I(Y_2; \hat{Y}_2) \leq C_2 \)
  - \( \omega_{NR} : I(Y_{NR}; \hat{Y}_{NR}) \leq C_{NR} \)

C-RAN (Centralized Radio Access Network) is a key technology in 5G and beyond, offering significant benefits in terms of energy efficiency, reduced CAPEX/OPEX, and enhanced spectral efficiency.
Distributed source coding with side information
[ElGamal-Kim, Ch. 12]

test channel: \( p(\hat{Y} | Y) \)

\[
\begin{array}{c}
Y \\
\rightarrow Q( ) \\
\rightarrow C \\
\rightarrow Q^{-1}( ) \\
\rightarrow \hat{Y}
\end{array}
\]

\( Z \) (correlated with \( Y \))

\( Q( ) \): Compression encoder;
\( Q^{-1}( ) \): Compression decoder.
Distributed source coding with side information

[ElGamal-Kim, Ch. 12]

An equivalent Gaussian test channel

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

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

$$\omega : I(Y; \hat{Y} | Z) \leq C$$
Distributed source coding with side information

[ElGamal-Kim, Ch. 12]

Distributed source coding

\[ Q(\cdot) : \text{Compression encoder; } \]
\[ Q^{-1}(\cdot) : \text{Compression decoder.} \]

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

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

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

\( p(\hat{Y} \mid Y) \)

An equivalent Gaussian test channel

\( Y \)
\( Y \)
\( Z \)
\( \hat{Y} \)
\( C \)
\( \hat{Y} \)

(correlated with \( Y \))

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State-of-the-Art: C-RAN

- **Distributed fronthaul compression**
  

\[ y_{\pi(1)}^{ul} \]
\[ y_{\pi(2)}^{ul} \]
\[ y_{\pi(N_R)}^{ul} \]

\[ \hat{y}_{\pi(1)}^{ul} \]
\[ \hat{y}_{\pi(2)}^{ul} \]
\[ \hat{y}_{\pi(N_R)}^{ul} \]

\[ \pi \] denotes a permutation of RUs’ indexes.
Distributed fronthaul compression


\[ \text{Con}_{\pi(1)} : I(Y_{\pi(1)} ; \hat{Y}_{\pi(1)}) \leq C_{\pi(1)} \]

\[ \text{Con}_{\pi(2)} : I(Y_{\pi(2)} ; \hat{Y}_{\pi(2)} | \hat{Y}_{\pi(1)}) \leq C_{\pi(2)} \]

\[ \vdots \]

\[ \text{Con}_{\pi(N_R)} : I(Y_{\pi(N_R)} ; \hat{Y}_{\pi(N_R)} | \hat{Y}_{\pi(1)}, \ldots, \hat{Y}_{\pi(N_R-1)}) \leq C_{\pi(N_R)} \]

\[ \pi \] denotes a permutation of RUs’ indexes.
Joint decompression and decoding (JDD)


equivalent to what is latter known as: Noise Network Coding [Lim et al:TIT]
Numerical example for Wyner uplink model with $C = 4$ bit/symbol
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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
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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

- 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 \( Z_i \sim N(0, \sigma^2) \),
  - \( \alpha \): Inter-cell channel gain with \( \alpha \in [0,1] \).

<Example for \( N = 3 \)>
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

\[
Y_i = X_i + \alpha X_{[i-1]} + Z_i, \\
\text{where } Y_i: \text{Rx signal RU} \ i, \\
X_i: \text{Tx signal of UE} \ i, \\
Z_i: \text{Noise at RU} \ i \text{ with } Z_i \sim N(0, \sigma^2), \\
\alpha: \text{Inter-cell channel gain with } \alpha \in [0,1].
\]
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 $i$
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    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
  $$\text{SNR} = \frac{P}{\sigma^2}.$$
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 $i$

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

\[ \hat{Y}_{B,i} = Y_{i} + Q_{B,i}, \]
with quantization noise
\[ Q_{B,i} \sim N(0, \omega_{B,i}) \]
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

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

![Diagram](image_url)
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 $\hat{Y}_{c,1}, \hat{Y}_{c,2}, \ldots, \hat{Y}_{c,N}$. 

![Diagram of CU block diagram with decompression and signal flow]

- Without side information
- With WZ-like side information

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

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

\[
\begin{bmatrix}
\hat{Y}_{C,1} \\
\hat{Y}_{C,2} \\
\vdots \\
\hat{Y}_{C,N}
\end{bmatrix}
= 
\begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_N
\end{bmatrix}
X + 
\begin{bmatrix}
Z_1 \\
Z_2 \\
\vdots \\
Z_N
\end{bmatrix}
+ 
\begin{bmatrix}
Q_{B,1} \\
Q_{B,2} \\
\vdots \\
Q_{B,N}
\end{bmatrix}
+ 
\begin{bmatrix}
Q_{C,1} \\
Q_{C,2} \\
\vdots \\
Q_{C,N}
\end{bmatrix},
\]

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

\( \mathbf{H}_Z = \mathbf{I} + \gamma\mathbf{E}_1 \),

\( \mathbf{H}_Q = \gamma\mathbf{E}_1 \),

(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 $R_{\text{sum}}$ 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 $\lambda_{k,l}$: $l$th 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
  - $\omega_B$ : quantization noise power for RU-RU links
  - $\omega_C$ : quantization noise power for RU-CU links
  - $\gamma$ : combining coefficient for in-network processing
Design Space

• Optimization variables
  • $\omega_B$ : quantization noise power for RU-RU links
  • $\omega_C$ : quantization noise power for RU-CU links
  • $\gamma$ : combining coefficient for in-network processing

• Objective function
  • Sum-rate $R_{\text{sum}}$
Design Space

- **Optimization variables**
  - $\omega_B$ : quantization noise power for RU-RU links
  - $\omega_C$ : quantization noise power for RU-CU links
  - $\gamma$ : combining coefficient for in-network processing

- **Objective function**
  - Sum-rate $R_{\text{sum}}$

- **Constraints**
  - Capacity $B$ of RU-RU links
  - Capacity $C$ of RU-CU links
Design Space

- **Optimization variables**
  - $\omega_B$ : quantization noise power for RU-RU links
  - $\omega_C$ : quantization noise power for RU-CU links
  - $\gamma$ : combining coefficient for in-network processing

- **Objective function**
  - Sum-rate $R_{\text{sum}}$

- **Constraints**
  - Capacity $B$ of RU-RU links
  - Capacity $C$ of RU-CU links

Modeled differently depending on decompression strategy
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In this strategy, the quantized signals \( \hat{Y}_{B,i} \) and \( \hat{Y}_{C,i} \) are decompressed without leveraging side information.

Constraints on \( \omega_B \) for RU-RU links [ElGamal-Kim, Ch. 3]

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

Constraints on \( \omega_C \) for RU-CU links [ElGamal-Kim, Ch. 3]

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

- Sum-rate maximization problem (P1)

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

s.t.
\[
\frac{1}{2} \log_2 \left( 1 + \frac{P(1 + \alpha^2) + \sigma^2}{\omega_B} \right) \leq B,
\]
\[
\frac{1}{2} \log_2 \left( 1 + \frac{\left( \gamma^2 \alpha^2 + (\gamma + \alpha)^2 + 1 \right) P + \gamma^2 \omega_B + (1 + \gamma^2) \sigma^2}{\omega_C} \right) \leq C.
\]

- Not easy to solve the problem due to the non-convexity.
At optimal point, the capacity constraints should be tight.

Without loss of optimality, we can set

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

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

Therefore, the optimal value for (P1) can be found via one-dimensional search over the coefficient \( \gamma \).
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.
Decompression of \( \hat{Y}_{B,i} \) at RU \([i + 1]\):

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

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

- Leveraging side information \( Y_{[i+1]} \)
- Constraint on \( \omega_B \) [ElGamal-Kim, Ch. 10]

\[
I(Y_i; \hat{Y}_{B,i} | Y_{[i+1]}) = \frac{1}{2} \log_2 \left( 1 + \frac{E[Y_i^2 | Y_{[i+1]}]}{\omega_B} \right) \leq B, \quad \text{with} \quad E[Y_i^2 | Y_{[i+1]}] = (1 + \alpha^2)P + \sigma^2 - \frac{\alpha^2P^2}{(1 + \alpha^2)P + \sigma^2}.
\]
Decompression of $\hat{Y}_{C,1}, \hat{Y}_{C,2}, \ldots, \hat{Y}_{C,N}$ at CU

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

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

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

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

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

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

\[
= \left( \gamma + \alpha \right) P + \gamma \alpha (\gamma + \alpha) P + \gamma \sigma^2 \left[ (\gamma + \alpha) P + \gamma \alpha (\gamma + \alpha) P + \gamma \sigma^2 \right]^2
\]

\[
- \left( \gamma^2 \alpha^2 + (\gamma + \alpha)^2 + 1 \right) P + \gamma^2 \omega_B + (1 + \gamma^2) \sigma^2 + \omega_{C,i-1}.
\]
Sum-rate maximization problem (P2)

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

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

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

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

The optimization can be similarly tackled as for (P1).

i.e., one-dimensional search with respect to \(\gamma\).
At optimal point, the capacity constraints should be tight.

Without loss of optimality, we can set

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

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

\[
\omega_{C,i} = \beta_C \left( \left( \gamma_i^2 \alpha^2 + (\gamma_i + \alpha)^2 + 1 \right) P + \gamma_i^2 \omega_B + (1 + \gamma_i^2)\sigma^2 \right)
\]

\[
\left( \frac{\left[ (\gamma + \alpha)P + \gamma \alpha(\gamma + \alpha)P + \gamma \sigma^2 \right]^2}{\left( \gamma^2 \alpha^2 + (\gamma + \alpha)^2 + 1 \right) P + \gamma^2 \omega_B + (1 + \gamma^2)\sigma^2 + \omega_{C,i-1}} \right), \quad i \in \mathcal{N} \setminus \{1\},
\]

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 \( \gamma \).
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 (JDD)

- Achievable sum-rate under JDD for given $\omega_B$, $\omega_C$, $\gamma$ [Sanderovich et al: TIT] [Lim et al: TIT]

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

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

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

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

$H_{X,s}$, $H_{Z,s}$, $H_{Q,s}$: Submatrices of $H_X$, $H_Z$, $H_Q$ with rows in $\mathcal{S}$ removed.
**Problem Description**

- **Sum-rate maximization problem (P3)**

\[
\begin{align*}
\text{maximize} & \quad R_{\text{sum}} \\
\text{s.t.} & \quad R_{\text{sum}} \leq |S| \left( C - \tilde{g}_C(\omega_B, \omega_C, \gamma) \right) + f_{C,S}(\omega_B, \omega_C, \gamma), \quad S \subseteq \mathcal{N}, \\
& \quad \frac{1}{2} \log_2 \left( 1 + \frac{E[Y_i^2 | Y_{[i+1]}]}{\omega_B} \right) \leq B, \quad i \in \mathcal{N},
\end{align*}
\]
Sum-rate maximization problem (P3)

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

- We propose to perform one-dimensional search w.r.t. \( \gamma \).
- For given \( \gamma \), optimizing \( \omega_B \) and \( \omega_C \) is a difference-of-convex (DC) problem.
  - Thus, suboptimal solution of \( \omega_B \) and \( \omega_C \) for given \( \gamma \) can be found via concave convex procedure (CCCP) approach.
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For reference, we consider the Cut-Set upper bound on $R_{\text{sum}}$ as

$$R_{\text{sum}} \leq \min \{ NC, R_{\text{full}} \},$$

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

$$R_{\text{full}} = I(\{X_i\}_{i \in \mathcal{N}}; \{Y_i\}_{i \in \mathcal{N}})$$

$$= \frac{1}{2} \log_2 \det \left( \mathbf{I} + P \left( \sigma^2 \mathbf{H}_Z \mathbf{H}_Z^T \right)^{-1} \mathbf{H}_X \mathbf{H}_X^T \right).$$
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.

Enabling full RU cooperation

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, $\alpha = 0.7$

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

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  - $N = 3$, 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 $B$. 

![Graph showing Per-UE rate versus RU-RU capacity $B$.]
**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. (This is the optimal oblivious processing [Aguerri et al:arXiv].)
Numerical Example

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

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

![Graph showing the relationship between Per-UE rate and SNR for different values of $C = B$ bit/symbol.](image)
Numerical Example

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

- 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]
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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:
  - 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:
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


References


References


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"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.

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