Wireless Networks via the Cloud: An Information Theoretic View

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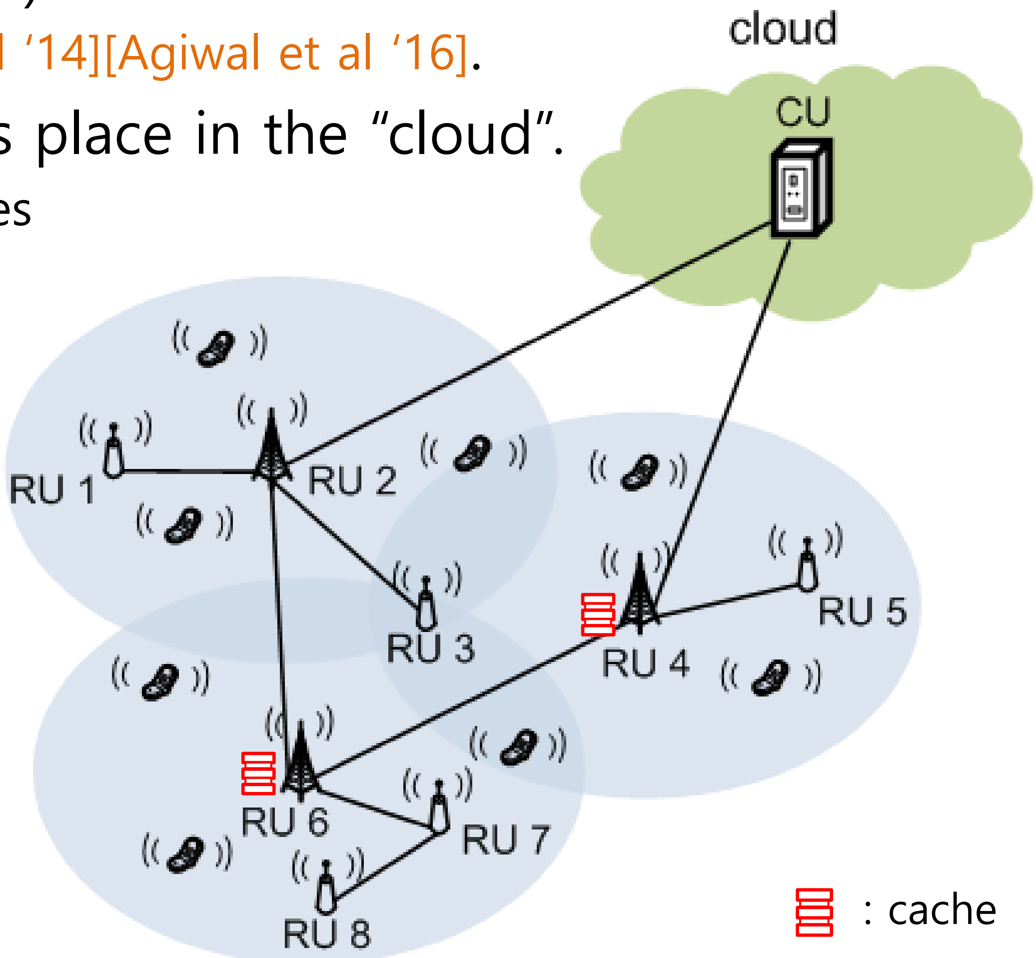
Outline

Cloud/Fog Radio Access Networks

- Base Stations (BSs), macro/pico, operate as radio units (RUs) [Alcatel-Lucent][China][Rost et al ‘14][Agiwal et al ‘16].
- Baseband processing takes place in the “cloud”.
  - Baseband processing includes encoding/decoding of the messages of Mobile Stations (MSs), (i.e., User Equipment (UEs)).
- Fronthaul links carry complex (IQ) baseband signals.
- Network utilization of low data traffic instances for caching.



Cloud Radio Access Networks

Advantages:

- Low-cost deployment of BSs
- Effective interference mitigation via joint baseband processing

Key challenge: Effective transfer of the IQ signals on the fronthaul links [Andrews et al JSAC'14]

Cloud Radio Access Networks

- Common public radio interface (CPRI) standard based on analog-to-digital (ADC)/digital-to-analog converter (DAC) [CPRI][IDC]

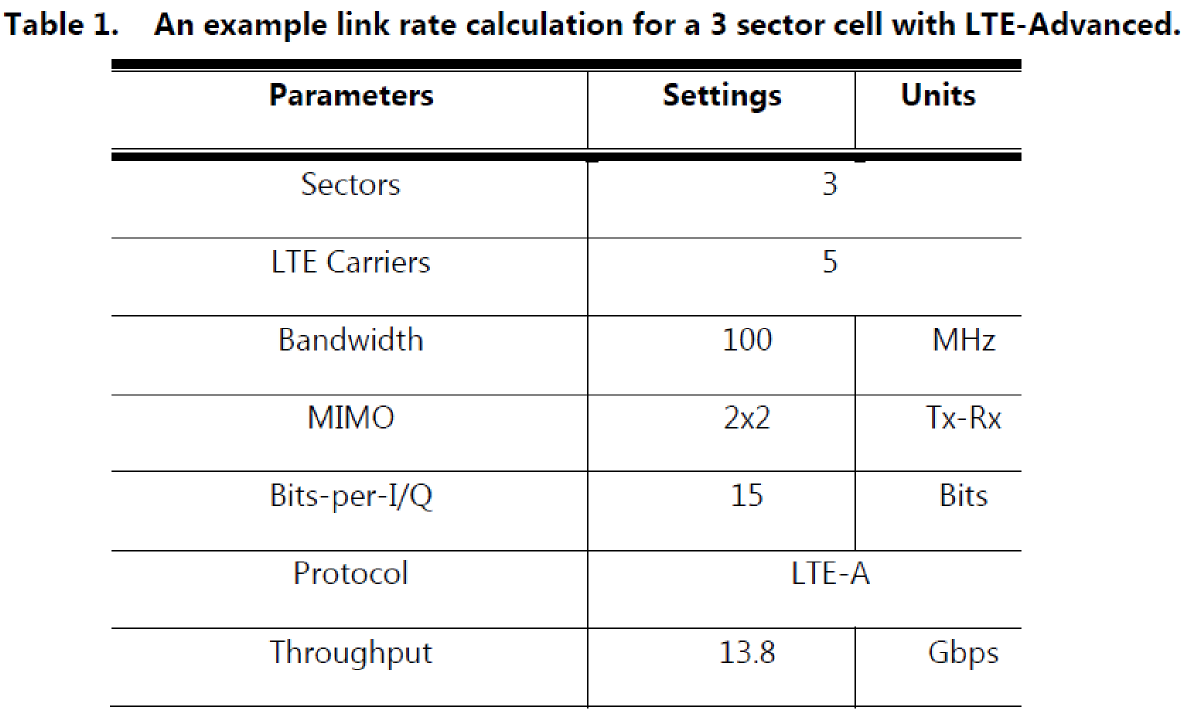


Table 1. An example link rate calculation for a 3 sector cell with LTE-Advanced.

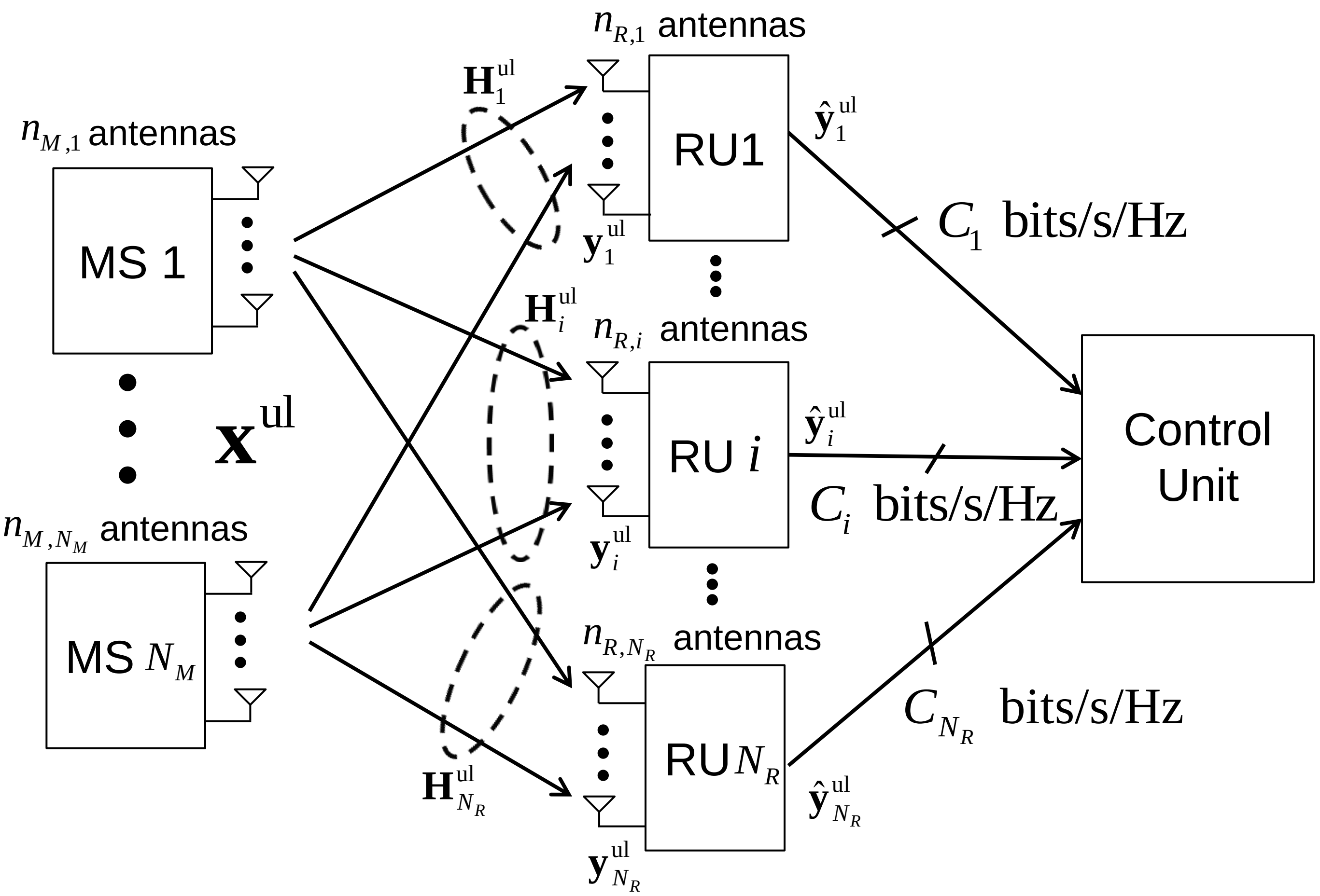
Parameters	Settings	Units
Sectors	3	
LTE Carriers	5	
Bandwidth	100	MHz
MIMO	2x2	Tx-Rx
Bits-per-I/Q	15	Bits
Protocol	LTE-A	
Throughput	13.8	Gbps

… Need for fronthaul compression

- “Death by Starvation?: backhaul and 5G,” [Lundqvist, CTN-Sep. 2015]

Outline

Basic Settings



Basic Settings

- Assuming flat-fading channel, the received signal at RU i is given by

$$\mathbf{y}_i^{\mathrm{ul}} = \mathbf{H}_i^{\mathrm{ul}} \mathbf{x}^{\mathrm{ul}} + \mathbf{z}_i^{\mathrm{ul}}, \quad i \in \mathcal{N}_R$$

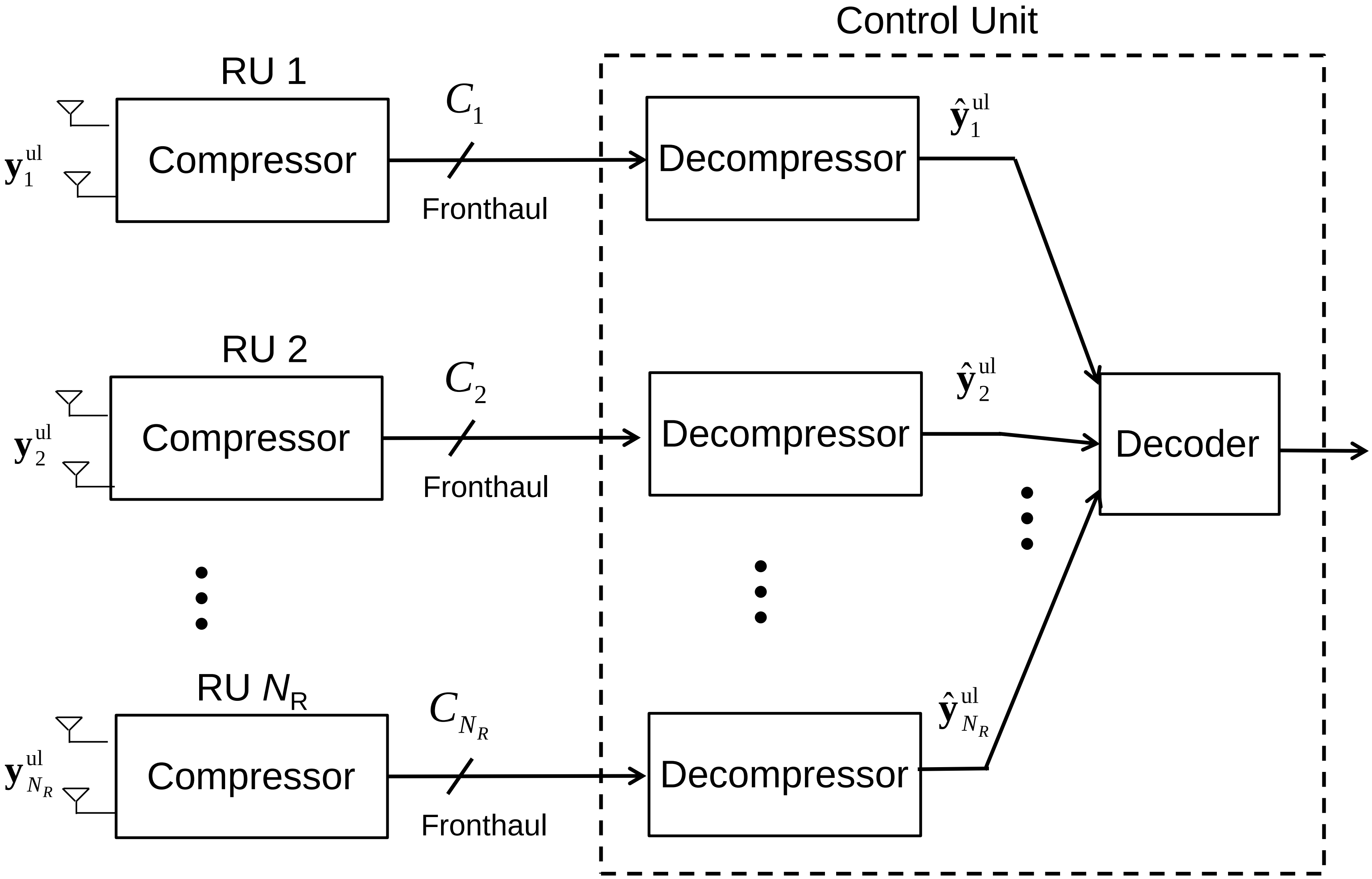
where $\mathbf{H}_i^{\mathrm{ul}} = \left[\mathbf{H}_{i,1}^{\mathrm{ul}}, \cdots, \mathbf{H}_{i,N_M}^{\mathrm{ul}} \right]$: channel matrix toward to RU i ;

$\mathbf{x}^{\mathrm{ul}} = \left[\mathbf{x}_1^{\mathrm{ul}\,H}, \cdots, \mathbf{x}_{N_R}^{\mathrm{ul}\,H} \right]^H$: vector of symbols transmitted by all MSs;

$\mathbf{z}_i^{\mathrm{ul}} \sim \mathcal{CN}(\mathbf{0}, \mathbf{\Omega}_{\mathbf{z}_i^{\mathrm{ul}}})$: noise vector at RU i .

- The fronthaul capacity C_i is normalized to the bandwidth of the uplink channel.
  - For any coding block of n symbols, nC_i bits can be transmitted on the i th fronthaul link.

Point-to-Point Compression



Point-to-Point Compression

- A standard way of modeling the compression at RU i is to adopt the Gaussian direct “test channel” [ElGamal-Kim ’11, Ch. 3]

$$\hat{\mathbf{y}}_i^{\mathrm{ul}} = \mathbf{y}_i^{\mathrm{ul}} + \mathbf{q}_i^{\mathrm{ul}},$$

where $\mathbf{q}_i^{\mathrm{ul}} \sim \mathcal{CN}(\mathbf{0}, \mathbf{\Omega}_i^{\mathrm{ul}})$ represents the quantization noise.

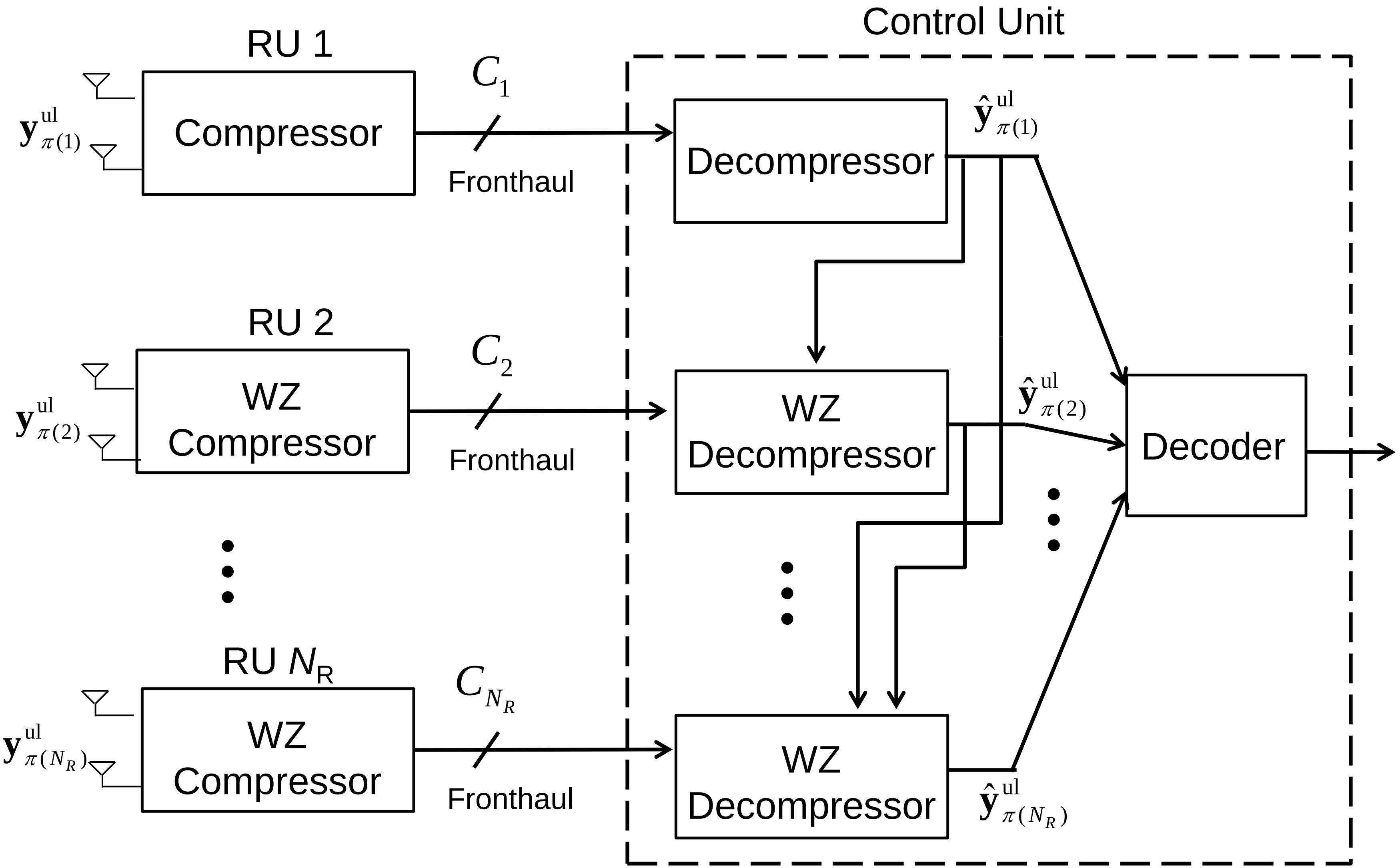
- If the fronthaul capacity C_i satisfies

$$I(\mathbf{y}_i^{\mathrm{ul}}; \hat{\mathbf{y}}_i^{\mathrm{ul}}) \leq C_i,$$

it is possible to design a compression strategy that realizes the given quantization error covariance $\mathbf{\Omega}_i^{\mathrm{ul}}$.

Distributed Fronthaul Compression

[Sanderovich et al ’09] [dCoso-Simoens ’09] [Zhou-Yu ’11]



$\pi : \mathcal{N}_R \rightarrow \mathcal{N}_R$ denotes a permutation of RUs’ indexes where $\mathcal{N}_R \triangleq \{1,\ldots,N_R\}$.

Distributed Fronthaul Compression

[Sanderovich et al '09] [dCoso-Simoens '09] [Zhou-Yu '11]

- Using Wyner-Ziv compression, a given quantization error matrix $\mathbf{\Omega}^{\text{ul}}_{\pi(i)}$ is attainable if the fronthaul capacity $C_{\pi(i)}$ satisfies

$$I(\mathbf{y}^{\text{ul}}_{\pi(i)};\hat{\mathbf{y}}^{\text{ul}}_{\pi(i)} \mid \hat{\mathbf{y}}^{\text{ul}}_{\pi(1)},\hat{\mathbf{y}}^{\text{ul}}_{\pi(2)},\ldots,\hat{\mathbf{y}}^{\text{ul}}_{\pi(i-1)}) \leq C_{\pi(i)}.$$

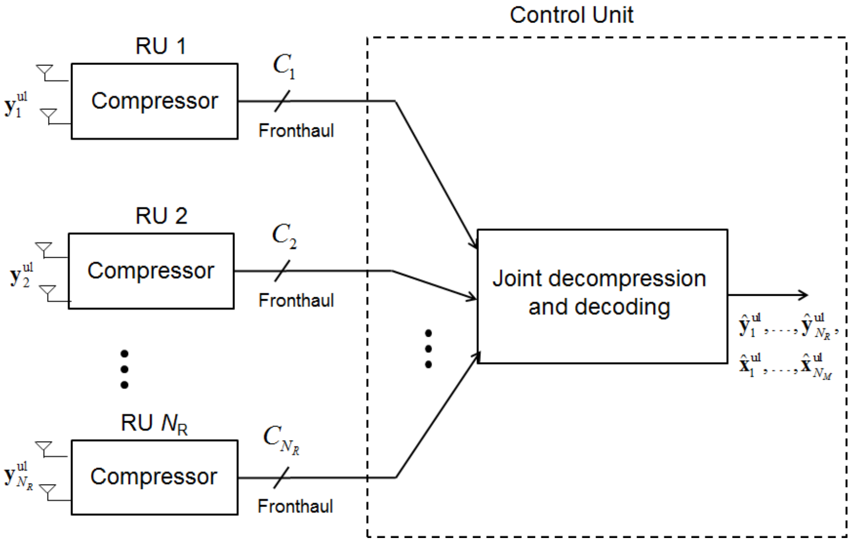
- After the quantized IQ signals $\hat{\mathbf{y}}^{\text{ul}}_1,\ldots,\hat{\mathbf{y}}^{\text{ul}}_{N_R}$ are recovered, the CU then performs joint decoding of the signal $\mathbf{x}^{\text{ul}}$ sent by all MSs.
  - The uplink sum-rate is given by

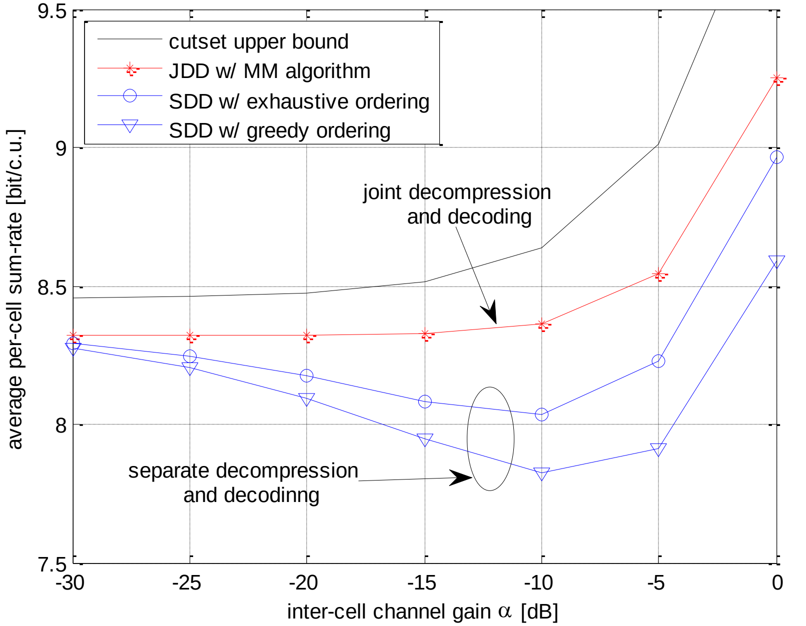
$$R^{\text{ul}}_{\text{sum}} = I(\mathbf{x}^{\text{ul}};\hat{\mathbf{y}}^{\text{ul}}_1,\ldots,\hat{\mathbf{y}}^{\text{ul}}_{N_R}).$$

Distributed Fronthaul Compression

[Sanderovich et al ’09] [dCoso-Simoens ’09] [Zhou-Yu ’11]

- Joint decompression and decoding
  [Sanderovich et al ‘09][Lim et al ‘11][Yassaee-Aref ‘11]
  - Potentially larger rates can be achieved with joint decompression and decoding (JDD) at the central unit [Sanderovich et al ‘08][Sanderovich et al ‘09].
    - Now often seen as an instance of noisy network coding [Lim et al ‘11].
    - Optimal oblivious processing [Aguerri et al ‘17].





Achievable rate [Sanderovich et al ‘09][Hong-Caire ‘15]:

$$R_{\text{sum}} = \min_{\mathcal{S}\subseteq\mathcal{N}_{\mathcal{B}}} \left\{ \sum_{j\in\mathcal{S}} \left(C_j - I(\mathbf{y}_j;\hat{\mathbf{y}}_j\,|\,\mathbf{x}) \right) + I(\mathbf{x};\hat{\mathbf{y}}_{\mathcal{S}}) \right\}.$$

Numerical results in 3-cell uplink [Park et al SPL ‘13]
(SDD: Separate decompression and decoding)

Distributed Fronthaul Compression

[Sanderovich et al ’09] [dCoso-Simoens ’09] [Zhou-Yu ’11]

- Sum-rate maximization problem with fronthaul capacity constraints is generally challenging.
- In [Park et al TVT’13], a block-coordinate optimization approach was proposed for successive WZ decompression case.
    - One optimizes the covariance matrices $\mathbf{\Omega}^{\mathrm{ul}}_{\pi(1)},\ldots,\mathbf{\Omega}^{\mathrm{ul}}_{\pi(N_R)}$ following the same order π employed for decompression.
    - At the ith step, for fixed (already optimized) covariances $\mathbf{\Omega}^{\mathrm{ul}}_{\pi(1)},\ldots,\mathbf{\Omega}^{\mathrm{ul}}_{\pi(i-1)}$, the covariance $\mathbf{\Omega}^{\mathrm{ul}}_{\pi(i)}$ is obtained by solving

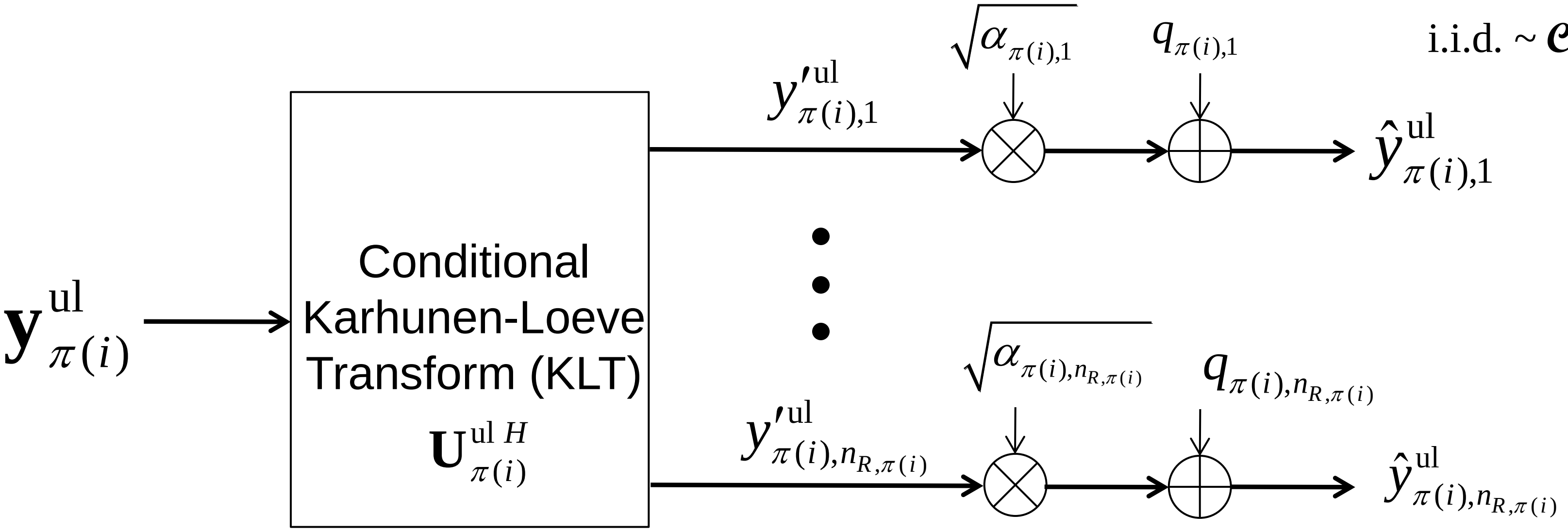
$$\underset{\mathbf{\Omega}^{\mathrm{ul}}_{\pi(i)}\succeq\mathbf{0}}{\text{maximize}}\ \ I(\mathbf{x}^{\mathrm{ul}};\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(i)}\,|\,\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(1)},\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(2)},\ldots,\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(i-1)})$$

$$\text{s.t.}\qquad I(\mathbf{y}^{\mathrm{ul}}_{\pi(i)};\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(i)}\,|\,\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(1)},\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(2)},\ldots,\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(i-1)})\leq C_{\pi(i)}.$$

Distributed Fronthaul Compression

[Sanderovich et al ’09] [dCoso-Simoens ’09] [Zhou-Yu ’11]

- Optimal WZ compressor [dCoso-Simoens ’09]



$q_{\pi(i),1},\ldots,q_{\pi(i),n_{R,\pi(i)}}$

i.i.d. $\sim \mathcal{CN}(0,1)$.

  - Unitary transform $\mathbf{U}^{\mathrm{ul}\,H}_{\pi(i)}$ decorrelates the received signal streams when conditioned on the side information signals $\hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(1)}, \hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(2)}, \ldots, \hat{\mathbf{y}}^{\mathrm{ul}}_{\pi(i-1)}$.
  - Stream-wise multiplication by $\sqrt{\alpha_{\pi(i),1}},\ldots,\sqrt{\alpha_{\pi(i),n_{R,\pi(i)}}}$ represents the compression rate allocation among the streams.
  - Statistical independence among quantization noises $q_{\pi(i),1},\ldots,q_{\pi(i),n_{R,\pi(i)}}$ implies that the signals are compressed separately.

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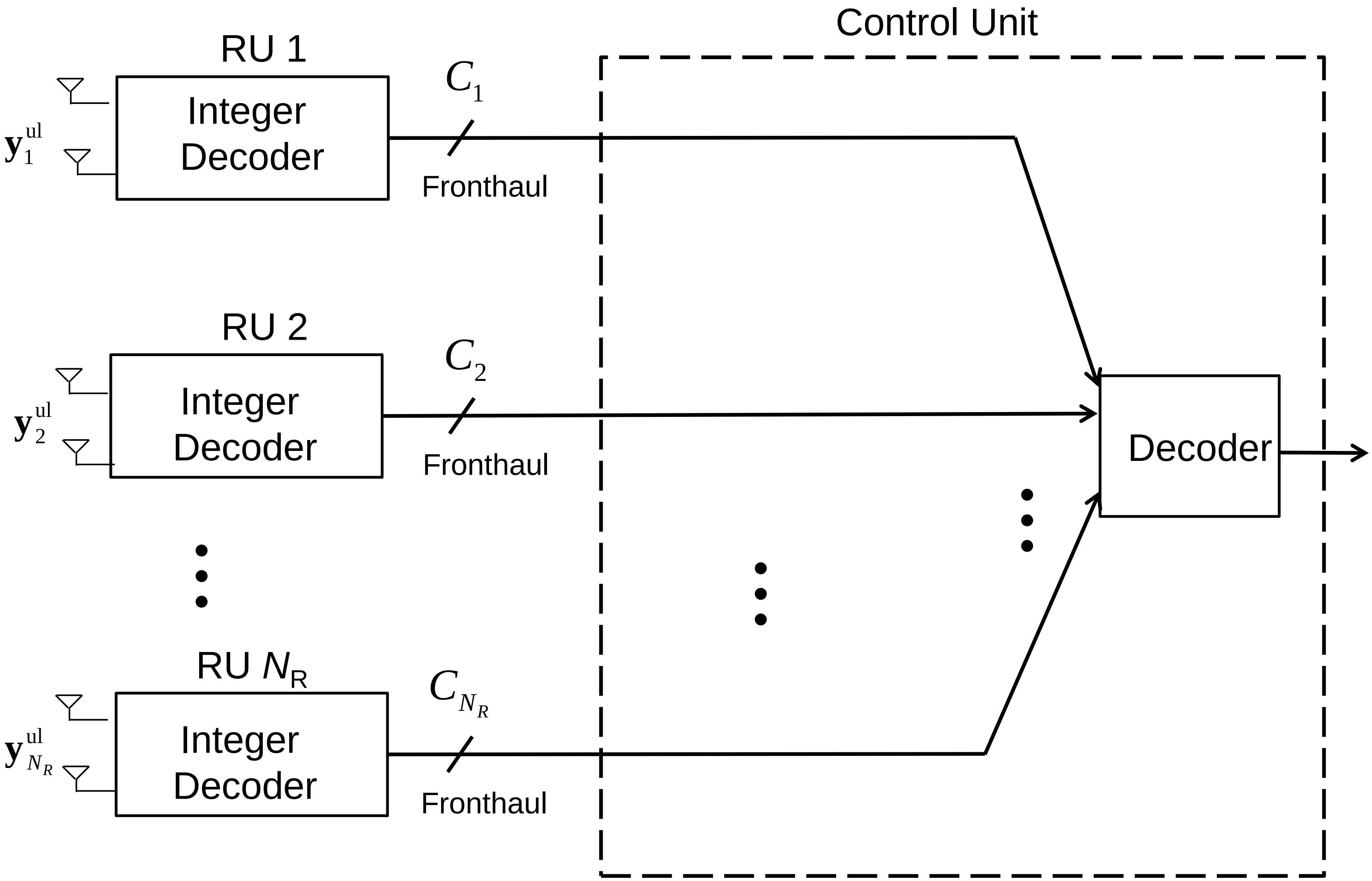
Compute-and-Forward

[Nazer et al ’09] [Hong and Caire ’11]



Compute-and-Forward

[Nazer et al ’09] [Hong and Caire ’11]

- Compute-and-forward (CoF) [Nazer et al ‘09]
  - The same codebook is used both for channel encoding at all MSs and for quantization at RUs.
  - Each RU decodes an appropriate (modulo-)sum, with integer weights, of the codewords transmitted by MSs.
    - And then sends a bit stream on the fronthaul link that identifies the decoded codeword within the lattice code.
  - Upon receiving a sufficient number of linear combinations, the CU can invert the resulting linear system and recover the transmitted codewords.
  - For single-antenna uplink system with $N_M = N_R$ and $C_1 = \ldots = C_{N_R} = C$, achievable rate per MS is given by

$$R_{\text{per-MS}} = \min\left\{C, \min_{l \in \mathcal{L}} R\left(\mathbf{h}_l, \mathbf{a}_l, \text{SNR}\right)\right\}$$

where

$$R(\mathbf{h}, \mathbf{a}, \text{SNR}) = \max\left\{\log\left(\frac{\text{SNR}}{\mathbf{a}^H\left(\text{SNR}^{-1}\mathbf{I} + \mathbf{h}\mathbf{h}^H\right)^{-1}\mathbf{a}}\right), 0\right\};$$

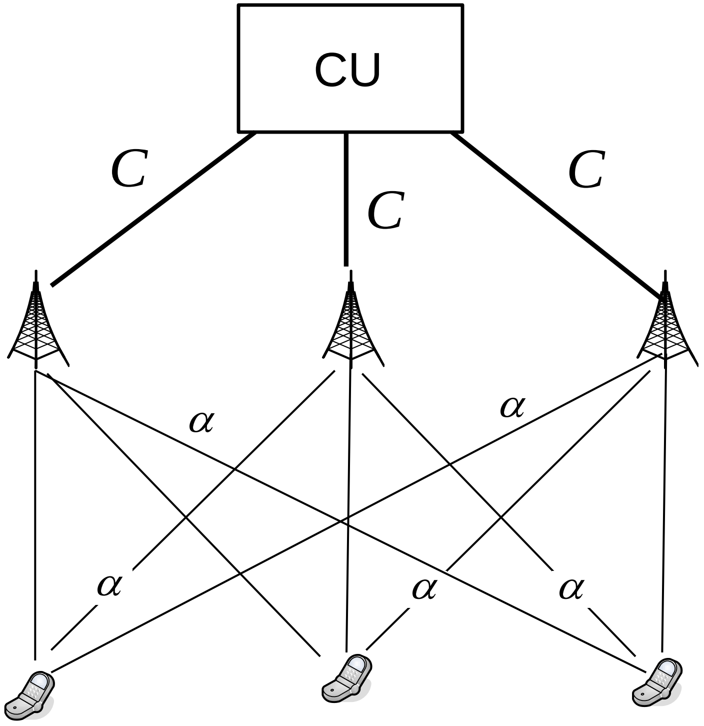
Integer penalty: The signal received at each RU is sum with *non-integer weights* of the codewords transmitted by MSs.

$\mathbf{h}_l$: channel vector toward RU l;

$\mathbf{a}_l$: target integer vector for RU l.

Numerical Example

- Three-cell SISO circular Wyner model



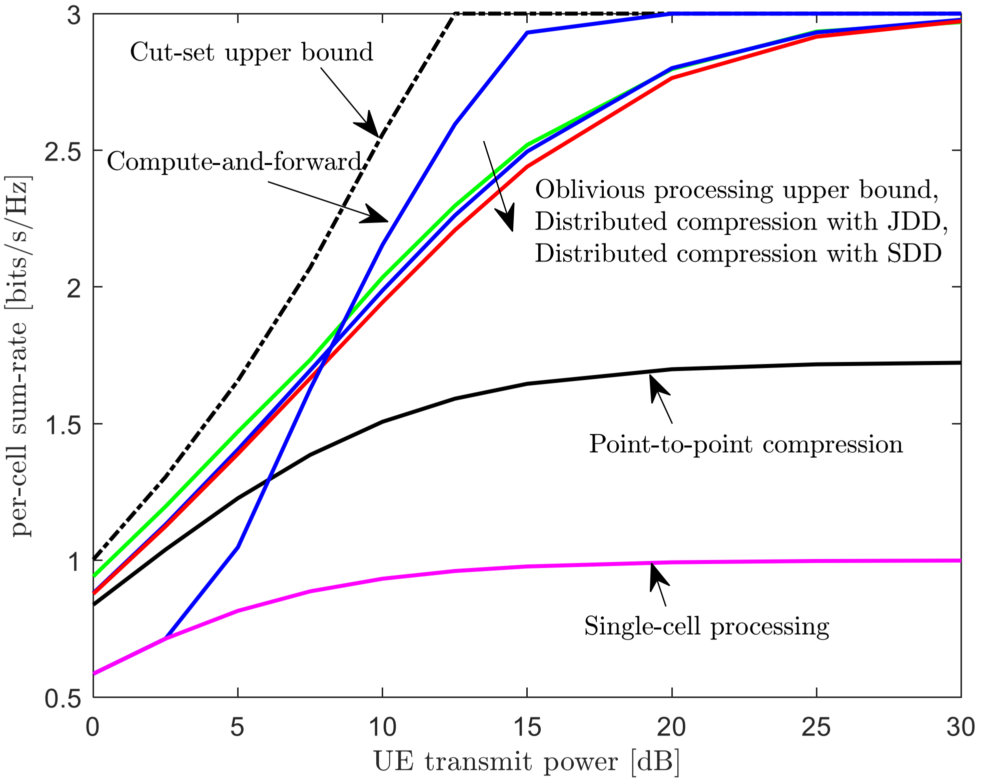
- Each cell contains a single-antenna and a single-antenna RU.
- Inter-cell interference takes place only between adjacent cells.
- The intra-cell and inter-cell channel gains are given by 1 and α, respectively.
- All RUs have a fronthaul capacity of C

Numerical Example

- Compare the following schemes
  - Single-cell processing
    - Each RU decodes the signal of the in-cell MS by treating all other MSs' signals as noise.
  - Point-to-point fronthaul compression
    - Each RU compresses the received baseband signal and the quantized signals are decompressed in parallel at the control unit.
  - Distributed fronthaul compression [dCoso-Simoens '09]
    - Each RU performs Wyner-Ziv coding on the received baseband signal and the quantized signals are successively recovered at the control unit.
    - Joint Decompression and Decoding (noisy network coding [Sanderovich et al '08])
  - Compute-and-forward [Hong-Caire '11]
    - Each RU performs structured coding.
  - Oblivious processing upper bound
    - RUs cooperate and optimal compression is done over $3C$ fronthaul link.
  - Cutset upper bound [Simeone et al '12]

Numerical Example

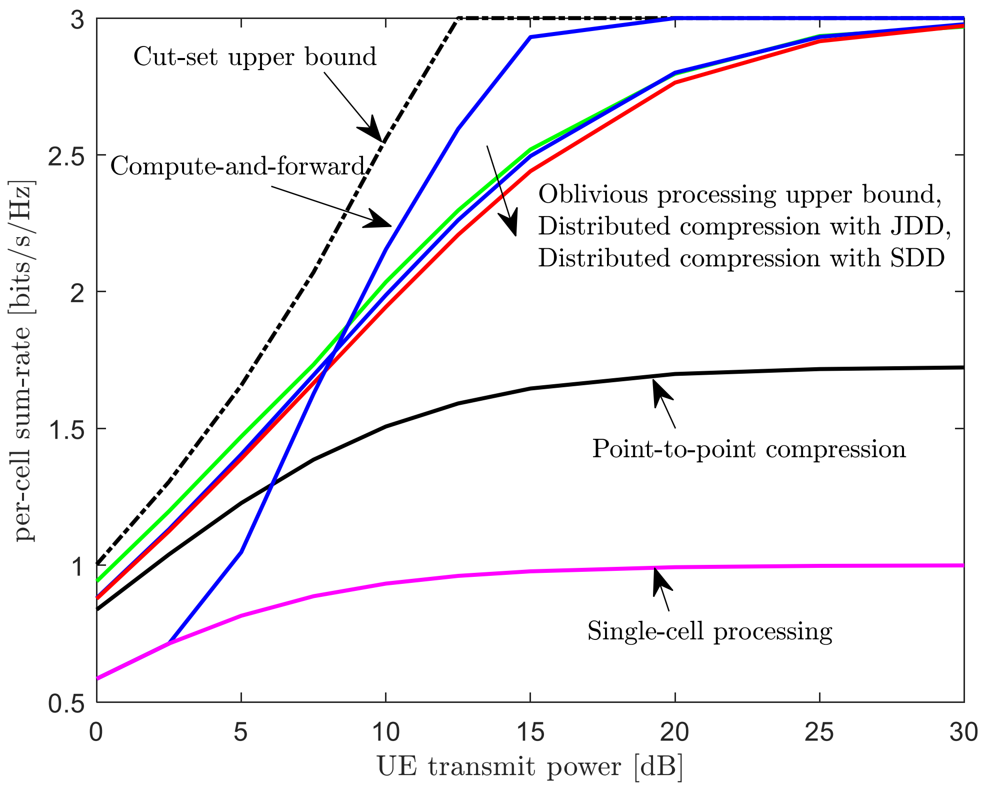
$\alpha = 1/\sqrt{2}$ and $C = 3$ bit/s/Hz



- The performance advantage of distributed compression over point-to-point compression increases as SNR grows larger.
    - At high SNR, the correlation of the received signals at RUs becomes more pronounced.
- Compute-and-Forward
    - At low SNR, its performance coincides with single-cell processing.
        - RUs tend to decode trivial combinations.
    - At high SNR, the fronthaul capacity is the main performance bottleneck, so CoF shows the best performance.

Numerical Example

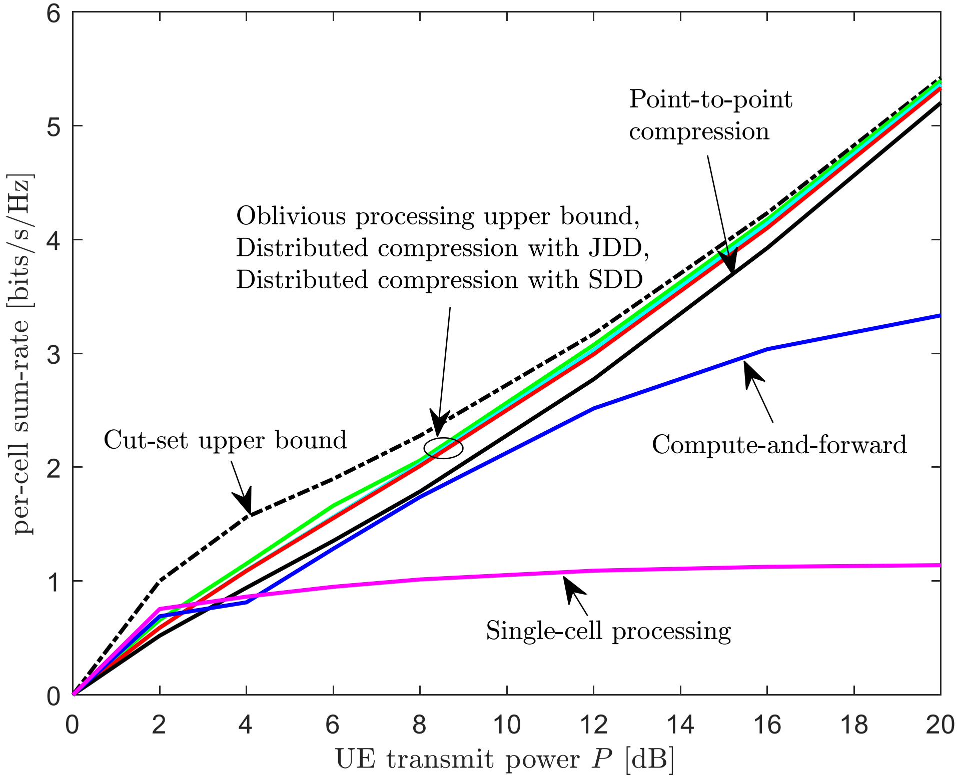
$\alpha = 1/\sqrt{2}$ and $C = 3$ bit/s/Hz



- Distributed compression
    - Joint decompression and decoding does not provide much gain compared to separate decompression and decoding.
    - Optimality of joint decompression and decoding in symmetric case [Aguerri et al ‘17].

Numerical Example

$\alpha = 1/\sqrt{2}$ and $C = 5\log_{10} P$ bit/s/Hz



- When C increases as log(snr), CoF is not the best for high SNR.
  - i.e., if C does not limit the performance, the oblivious compression technique will be advantageous than CoF.

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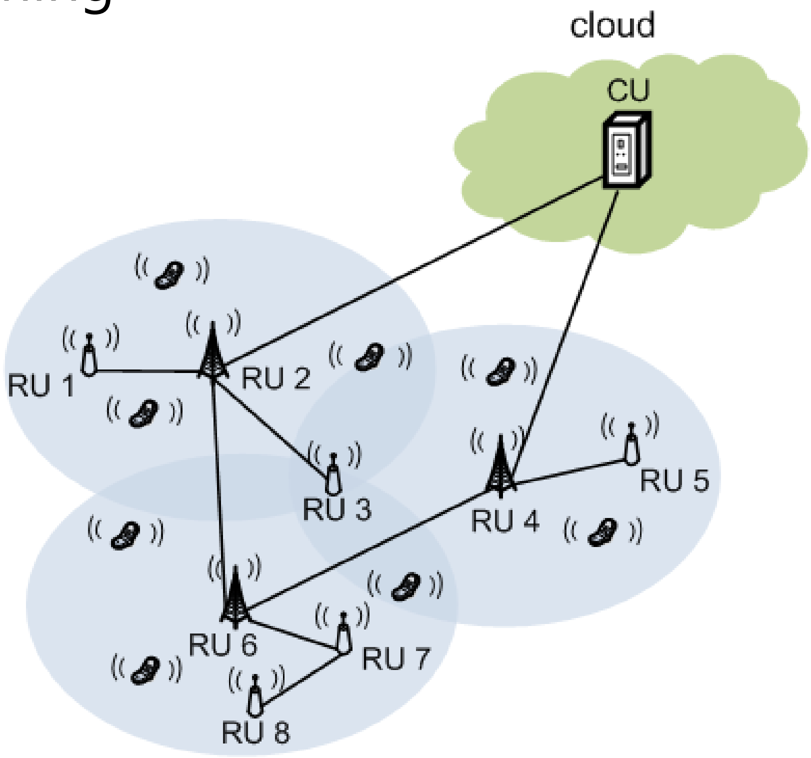
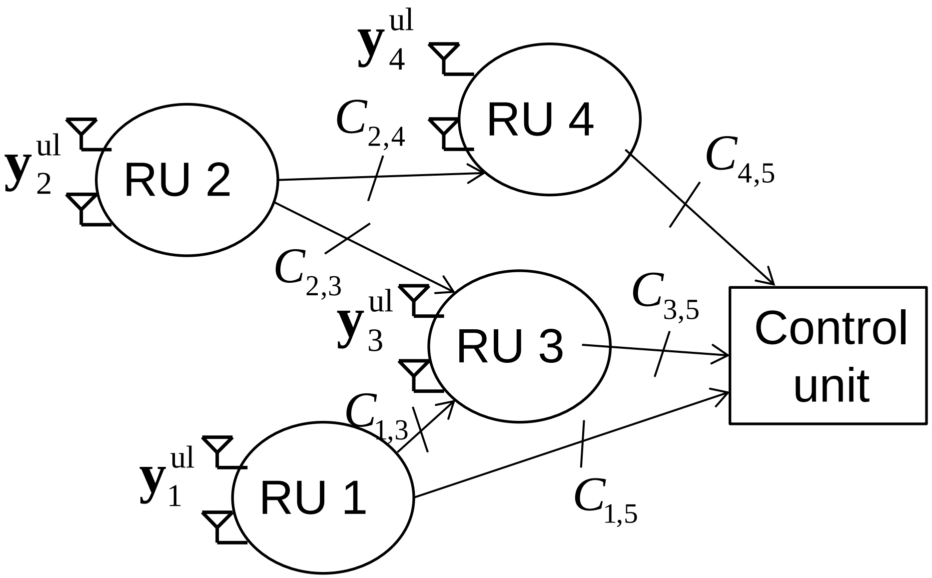
Cloud Radio Access Networks

- In multihop fronthaul networks, each RU may have multiple incoming and outgoing fronthaul links.
- For example, RU 6 in the figure has two incoming and single outgoing links.
- Two different operations, *routing* and *in-network processing*, were compared in [Park et al TVT'15].

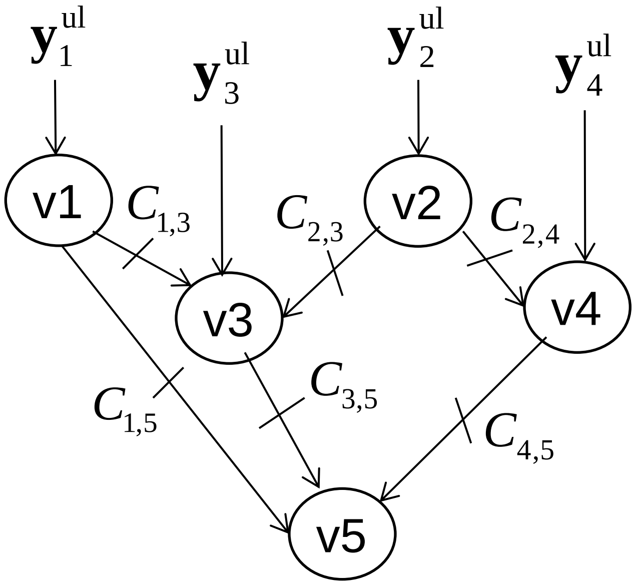


Directed Acyclic Graph

- Multihop fronthaul network modeled as a directed acyclic graph (DAG) [Koetter-Medard '03]

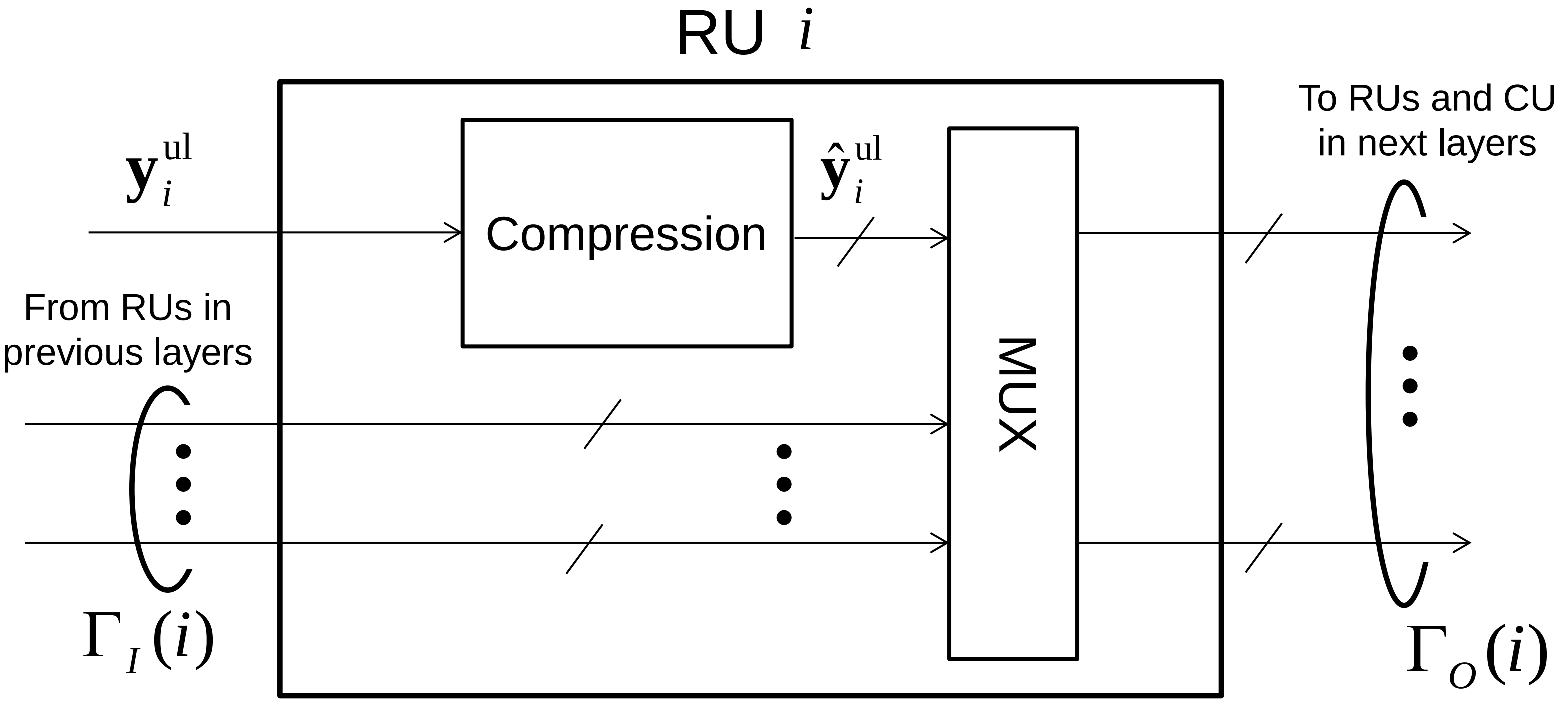


Fronthaul network



An equivalent DAG

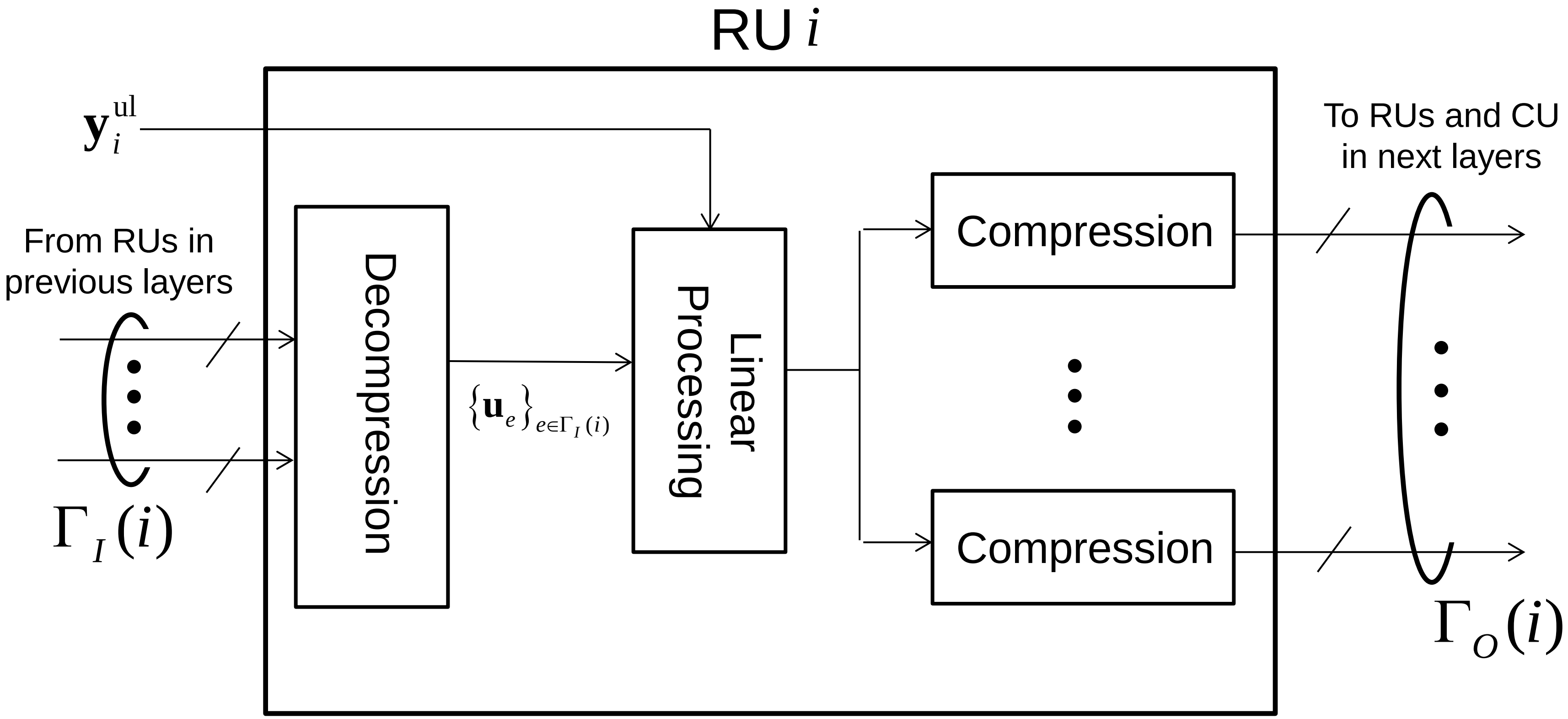
Routing



- The bits received on the incoming links are simply forwarded on the outgoing links without any addition processing.
- This approach requires the optimization of standard flow variables that define the allocation of fronthaul capacity to different bit streams.
  - In [Park et al TVT'15], the problem was addressed via the Majorization Minimization (MM) algorithm [Beck-Teboulle '11].

In-Network Processing

[Park et al TVT‘15]



- In a dense deployment of RUs, an RU may be connected to a large number of nearby RUs, all of which receive correlated baseband signals.
- It is possible to combine the correlated baseband signals at the RU in order to reduce redundancy.

In-Network Processing

[Park et al TVT‘15]

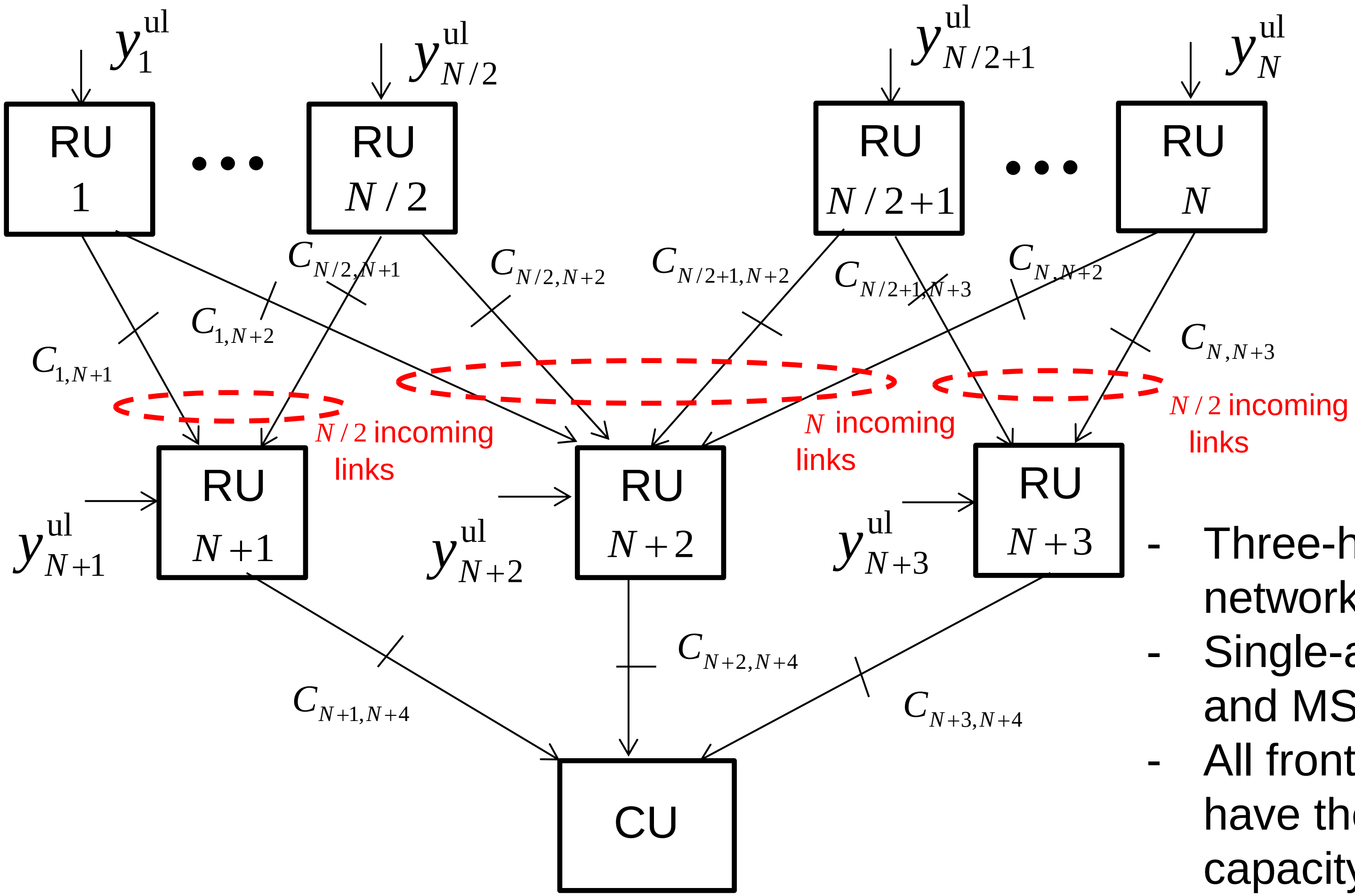
- In in-network processing, the RU must first decompress the received bit streams.

- The decompressed baseband signals are linearly processed, along with the IQ signal received locally by the RU.

- The in-network processed signal must be recompressed before being sent on the outgoing fronthaul links.
  - The effect of the resulting quantization noise must be counterbalanced by the advantage of in-network processing.

- The optimization of both routing and in-network processing was addressed in [Park et al TVT’15].

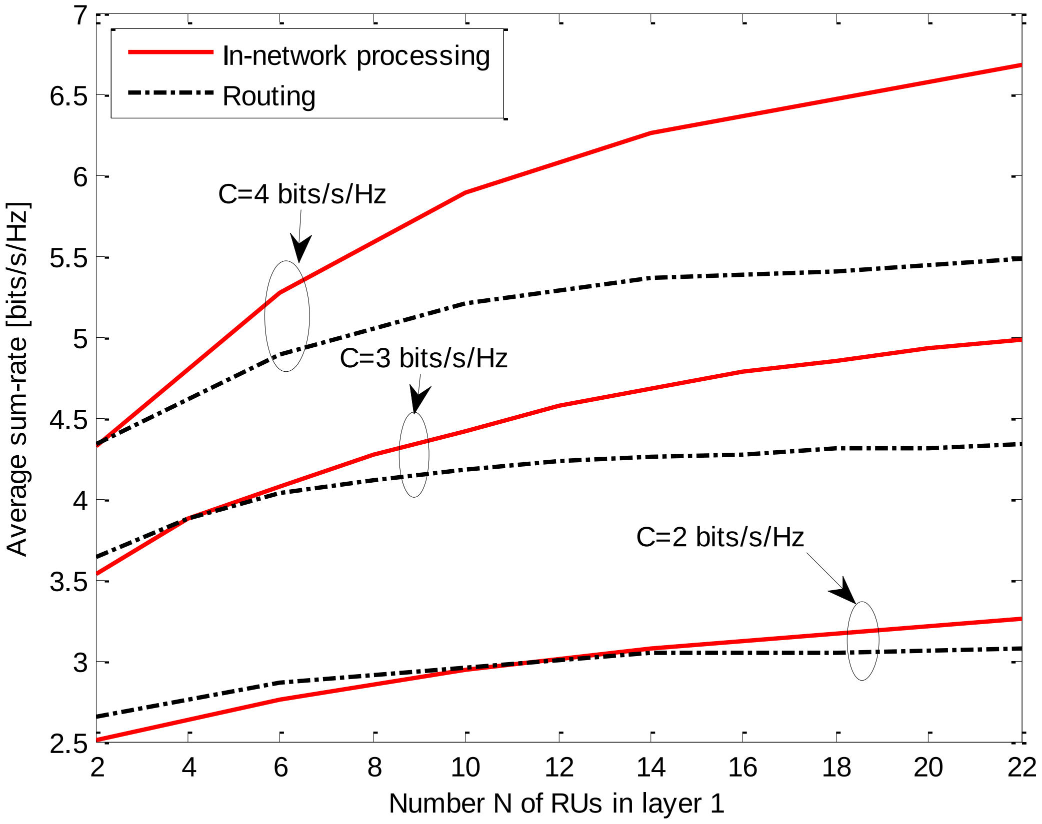
Numerical Example



- Three-hop fronthaul network
- Single-antenna RUs and MSs
- All fronthaul links have the same capacity C.
- i.i.d. Rayleigh fading channels with unit power

Numerical Results

4 MSs, average received per-antenna SNR of 20 dB



- The performance gain of in-network processing over routing becomes more pronounced as the number N of RUs in the first layer increases.

- As the density of the RUs' deployment increases, it is desirable for each RU in layer 2 perform in-network processing.

- In-network processing is more advantageous when the fronthaul links have larger capacity, as the distortion introduced by the recompression step becomes smaller.

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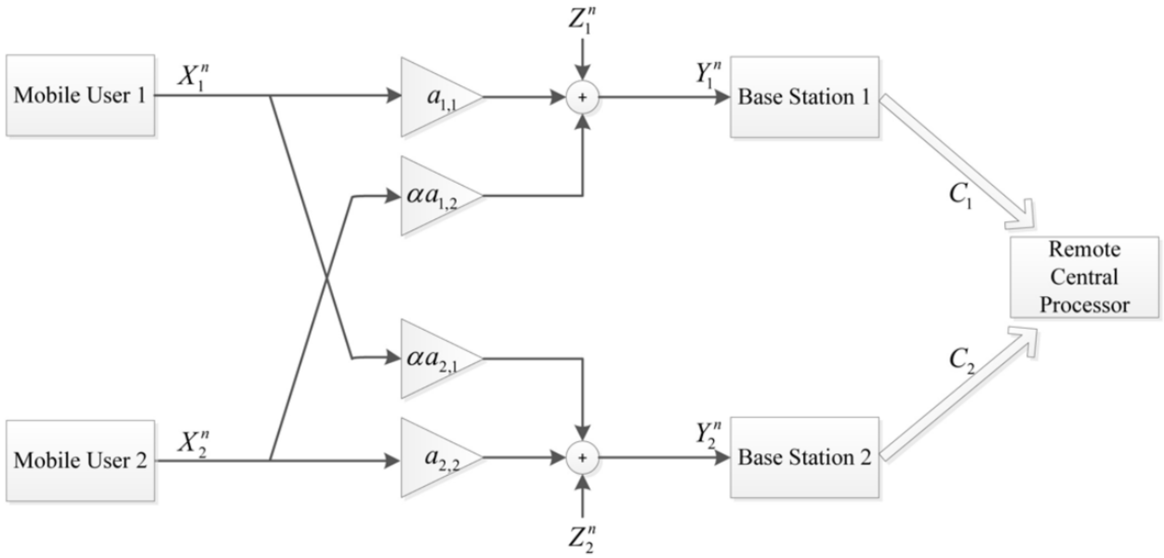
Variable Backhaul Connectivity

[Karasik et al TWC‘13]



- Wireless uplink channel is subject to fading.
- Fronthaul links’ capacity are subject to random fluctuations, i.e.,

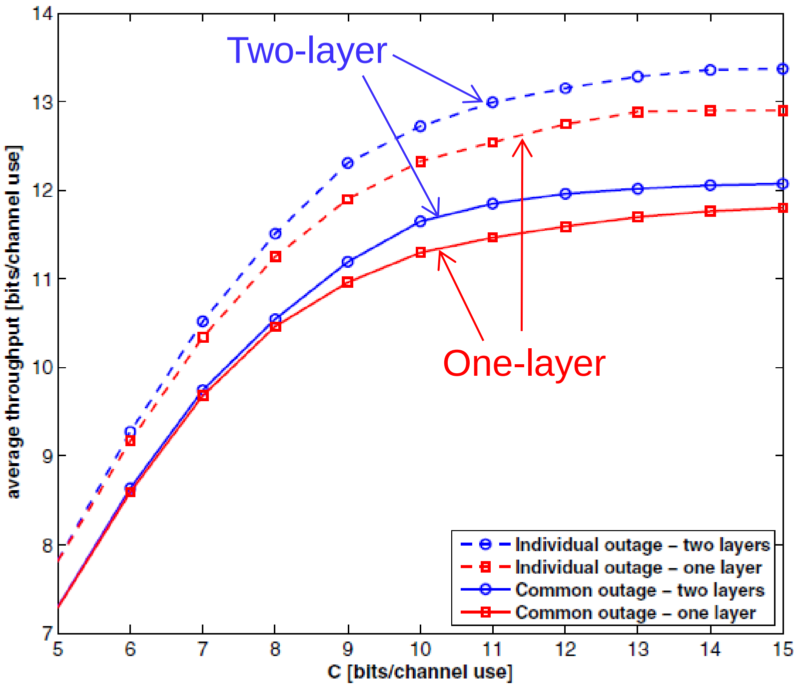
$$C_j = \begin{cases} C, & \text{with probability } p \\ C + \Delta C, & \text{with probability } 1 - p \end{cases}$$

- Only receiver-side CSI, i.e.,
  - Fading channel gains are known only to BSs and cloud.
  - Fronthaul connectivity is known only to cloud.

Variable Backhaul Connectivity

[Karasik et al TWC'13]

- To enable variable-rate transmission from users to cloud, an achievable scheme is proposed that levereages
  - Broadcast coding approach (at users, as in, e.g., [Shamai-Steiner TIT'03] [Verdu-Shamai TIT'10])
  - Layered distributed compression (at BSs, as in, e.g., [Ng et al TIT'12] [Park et al TVT'14])



- For small C, there is no gain in using multi-layer, i.e.,
  - Compression noise dominates the performance.
- As C increases, BC outperforms the single-layer strategy.
  - Due to its robust operation with respect to the uncertainty over fading channels.

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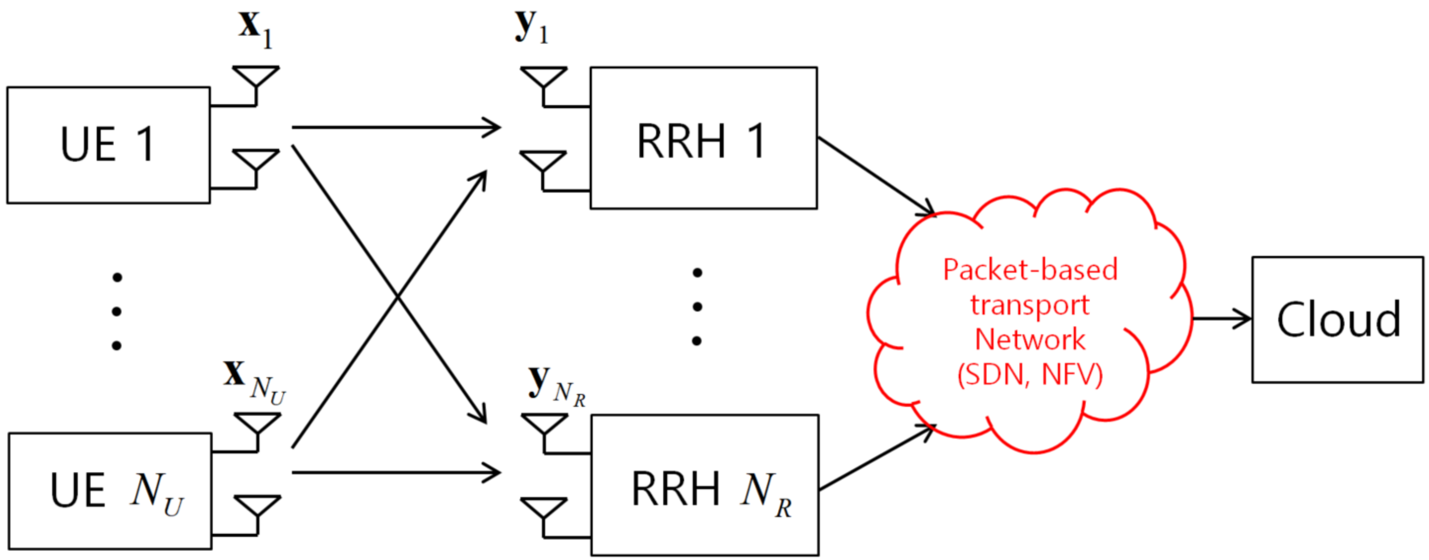
Multiple Description Coding

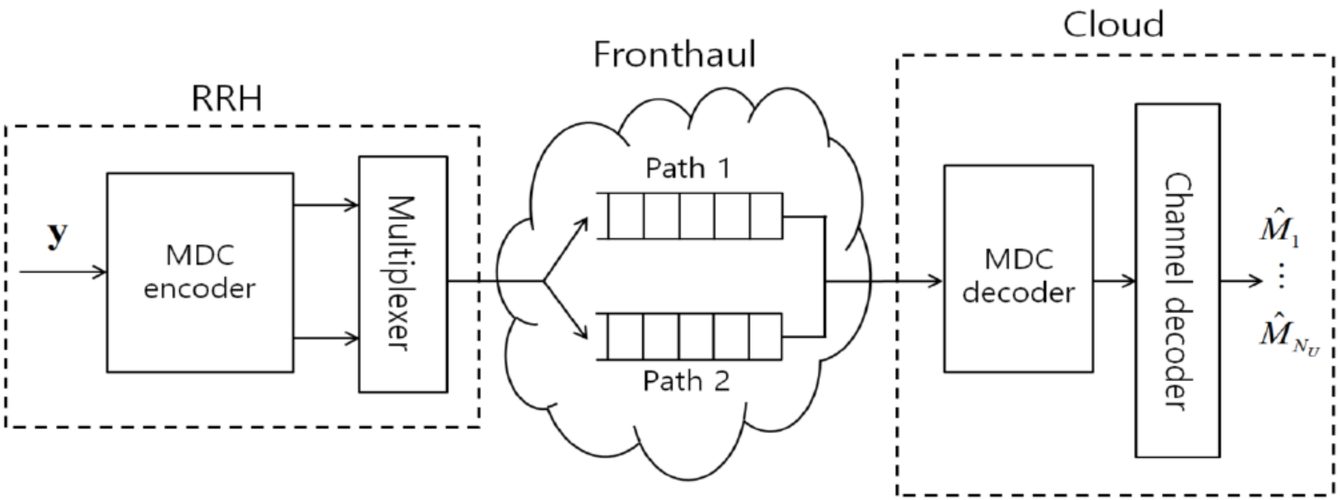
[Park et al Entropy‘19]



- In modern implementations of C-RAN (e.g., eCPRI [eCPRI]), the fronthaul transport network will often be packet-based and it will have a multi-hop architecture.
  - With general-purpose switches using network function virtualization (NFV) and Software-Defined Networking (SDN)
  - It can leverage the wide deployment of Ethernet infrastructure.

Multiple Description Coding

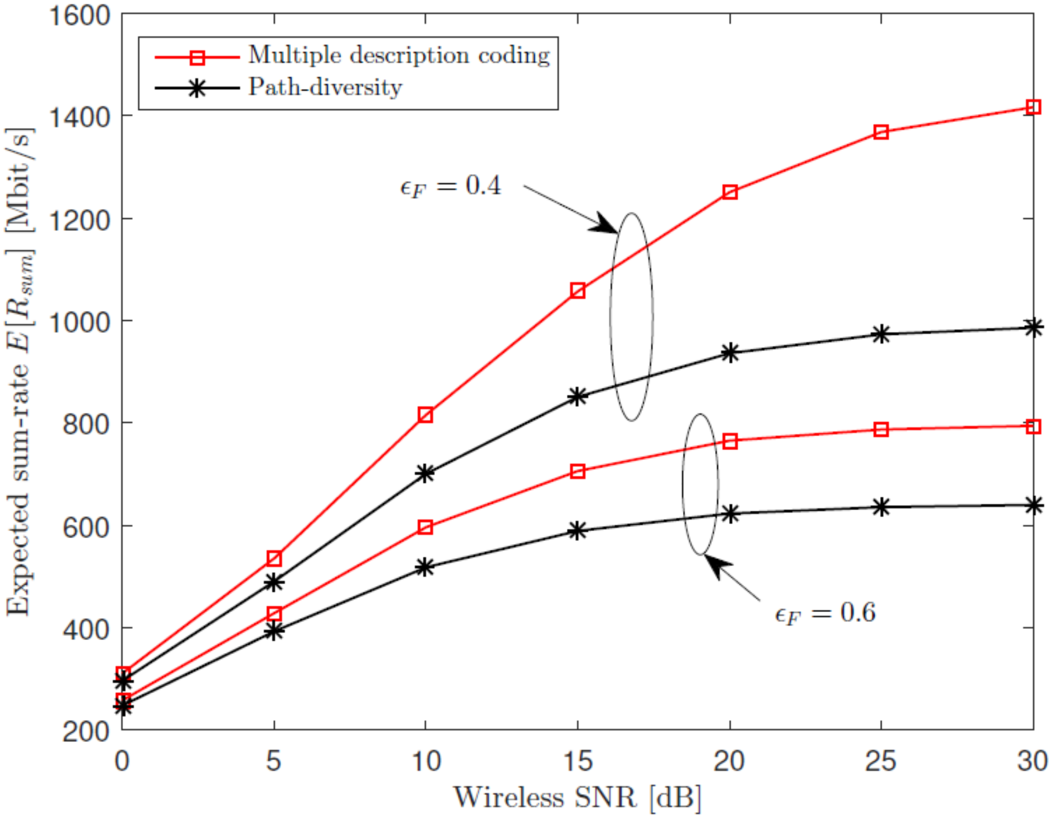
[Park et al Entropy‘19]



- Packet-based multi-hop networks are subject to congestion and packet losses.
- Traditional path diveristy can successfully reduce the packet loss probability.
  - However, the performance remains the same regardless of the number of timely reception of packets.
- To better use the multiple routes in packet-based fronthaul networks, variable-rate transmission is proposed in [Park et al Entropy ‘19] based on
  - Multiple Description Coding (MDC) directly on the level of baseband signals [Alastic et al TIT ‘01]
  - Broadcast Coding (BC) at users [Shamai-Steiner TIT’03][Verdu-Shamai TIT’10]

Multiple Description Coding

[Park et al Entropy‘19]



(ϵ_F: packet error probability)

- The MDC scheme shows a larger gain over the path diversty (PD) scheme at high SNR.
  - As the SNR increases, the overall performance becomes limited by the quantization noise distortion which is smaller for MDC than for PD.

Outline

- I. Introduction
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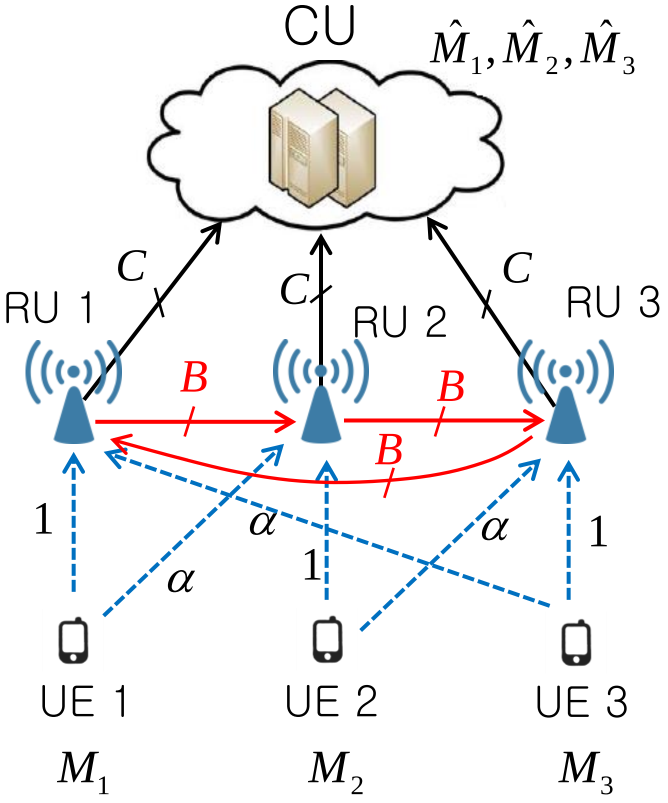
System Model

- C-RAN with inter-connected RUs, Wyner-type example

  [Shama et al ITA ‘17]

  - N pairs of RU-UE ($\mathcal{N} = \{1, 2, \ldots, N\}$)



<Example for $N = 3$ >

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

Oblivious Processing at RUs

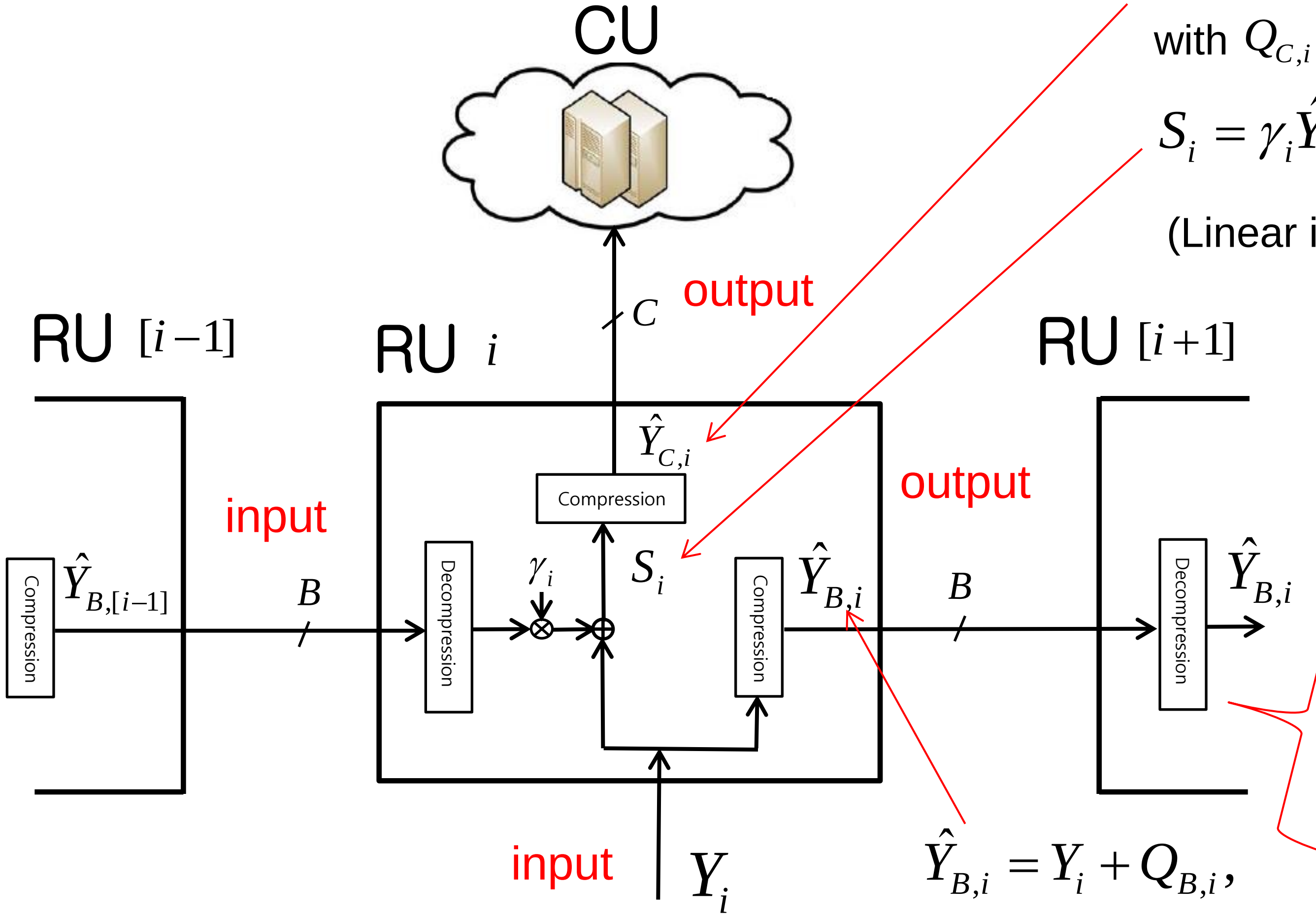
- In-network processing (INP) at RU i

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

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

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

(Linear is optimal.)



Without side information

With WZ-like side information

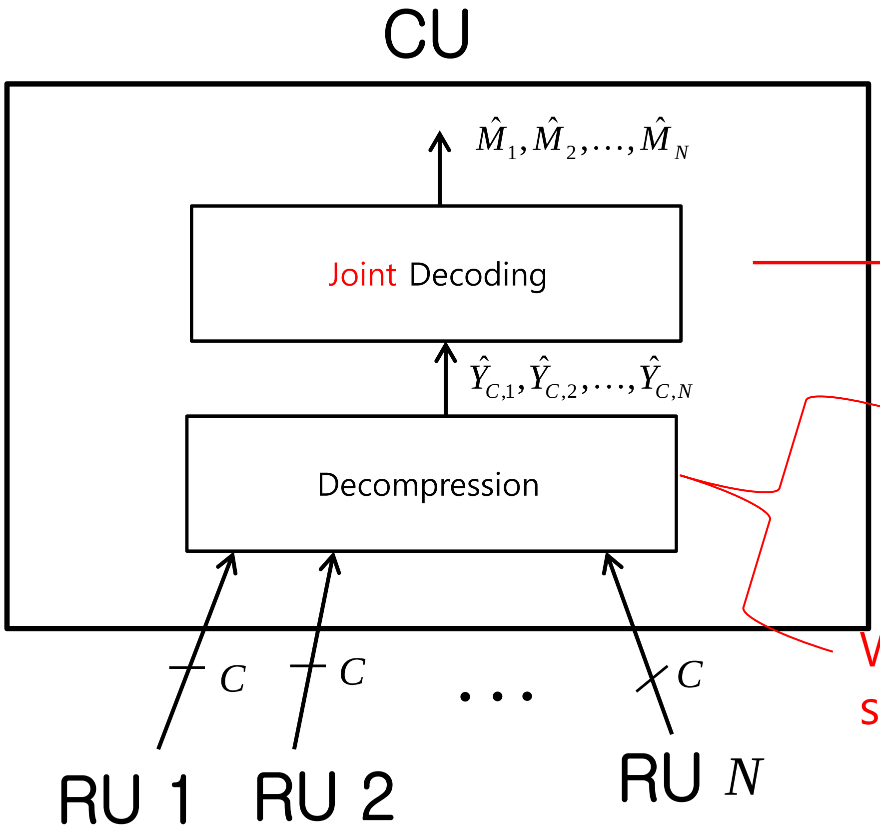
$\hat{Y}_{B,i} = Y_i + Q_{B,i}$,

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

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



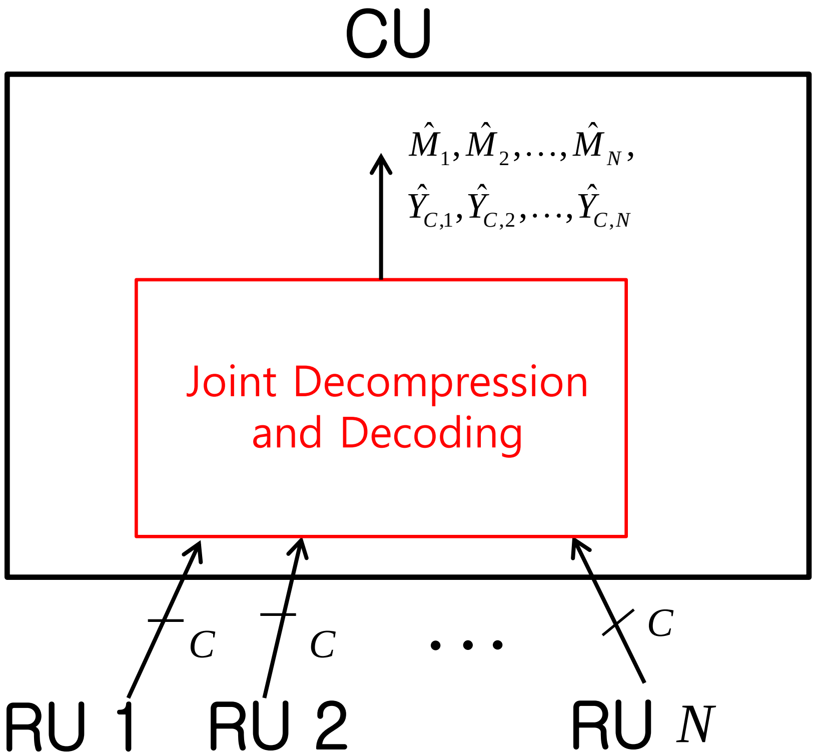
$$R_{\text{sum}} = \sum_{i\in\mathcal{N}} R_i$$
$$= I\left(\{X_i\}_{i\in\mathcal{N}}; \{\hat{Y}_{C,i}\}_{i\in\mathcal{N}}\right)$$

Without
side information

With WZ-like
side information

Joint Decompression and Decoding

- Joint decompression and decoding (JDD) [Sanderovich et al '09][Lim et al '11][Yassaee-Aref '11]
  - JDD at CU can potentially improve the performance [Sanderovich et al '08][Sanderovich et al '09].
    - Optimal oblivious processing [Aguerri et al '17].



Upper Bounds

- Cut-Set upper bound $R_{\text{cut-set}}$

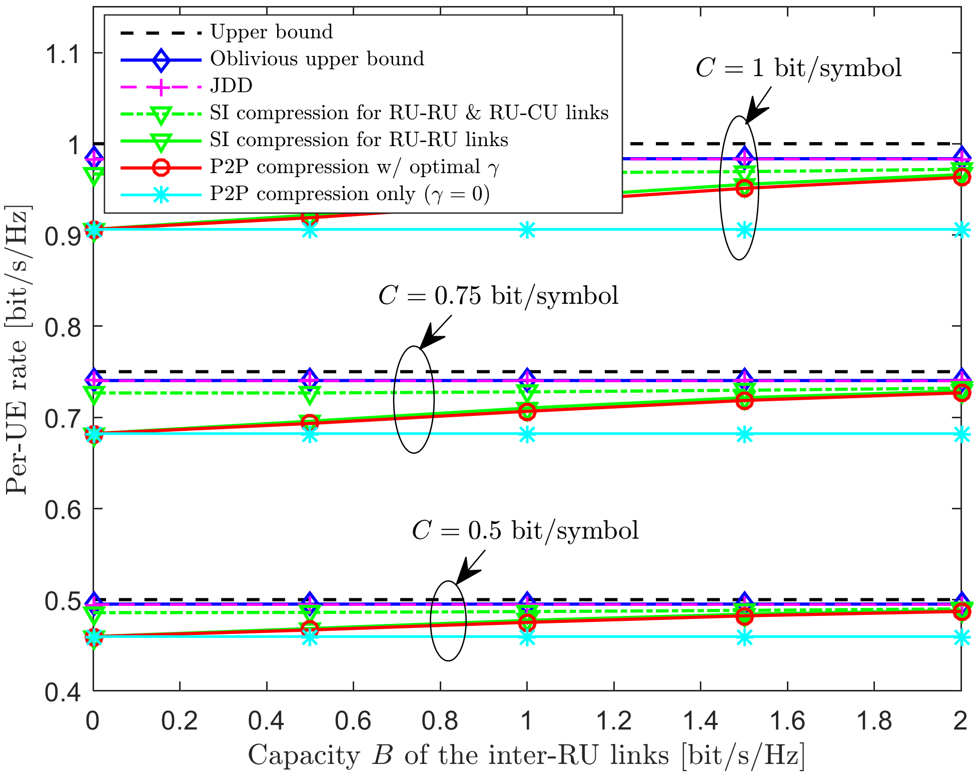
$$R_{\text{cut-set}} = \min\left\{NC,\, R_{\text{full}}\right\},$$

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

- Oblivious upper bound $R_{\text{oblv-UB}}$
    - $R_{\text{oblv-UB}}$ is the rate achievable when the RUs are colocated and connected to the CU with capacity NC.

Numerical Example

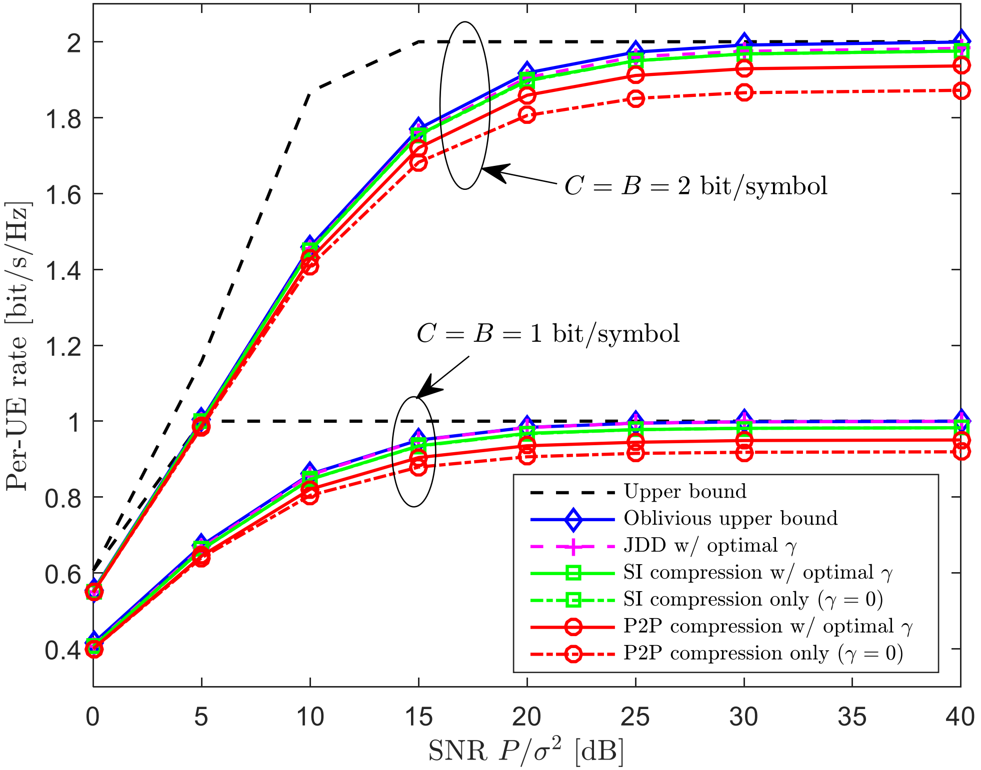
- Per-UE rate versus RU-RU capacity B
  - $N = 3$, $\text{SNR} = 20$ dB, $\alpha = 0.7$



- 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.
  - Its performance is very close to oblivious upper bound.

Numerical Example

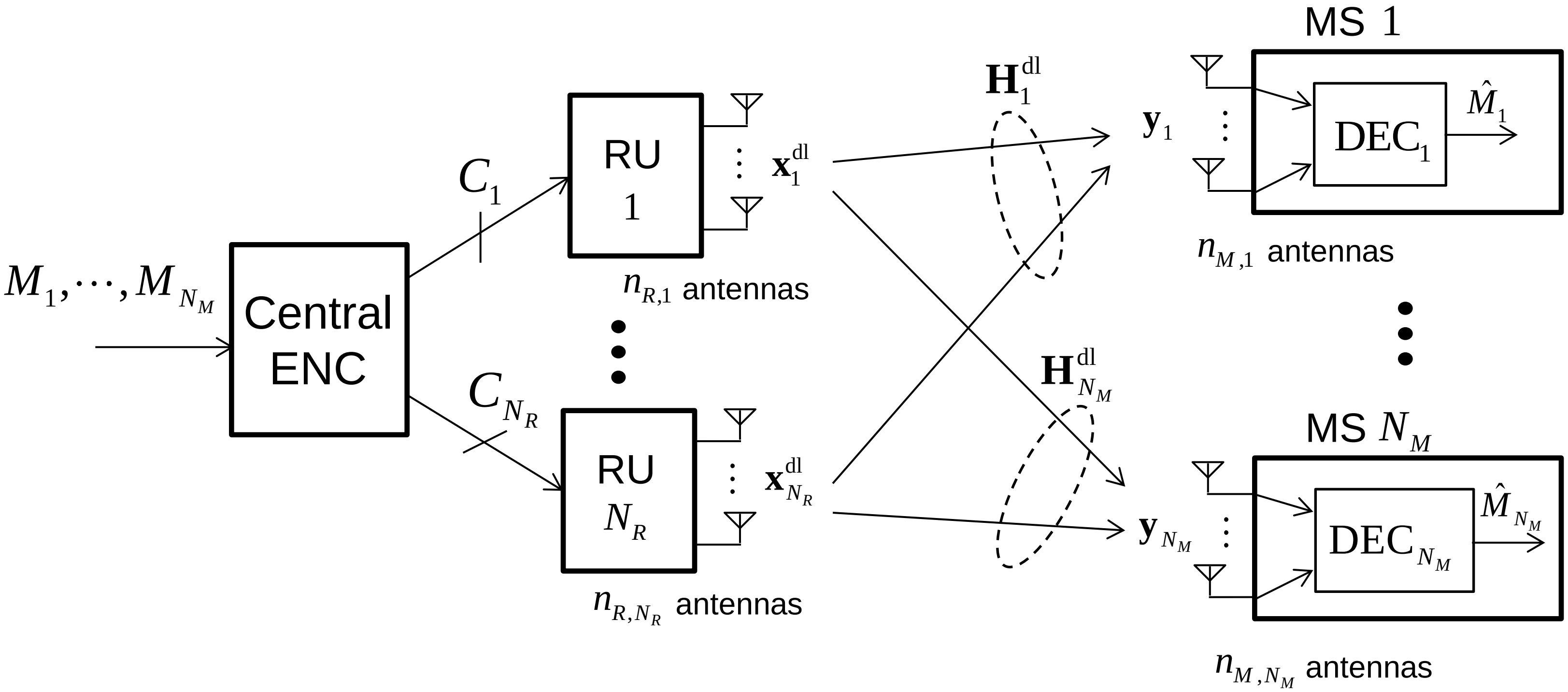
- Per-UE rate versus SNR P/σ^2
  - $N=3,\ \alpha=0.7,\ C=B\in\{1,2\}$



- 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 '17]

Outline

System Model



System Model

- The signal $\mathbf{y}_k^{\mathrm{dl}}$ received by MS k in the downlink

$$\mathbf{y}_k^{\mathrm{dl}} = \mathbf{H}_k^{\mathrm{dl}\,H}\mathbf{x}^{\mathrm{dl}} + \mathbf{z}_k^{\mathrm{dl}},$$

where

$\mathbf{x}^{\mathrm{dl}} = [\mathbf{x}_1^{\mathrm{dl}} \ \ldots \ \mathbf{x}_{N_R}^{\mathrm{dl}}]^T$: vector of symbols transmitted by all RUs;

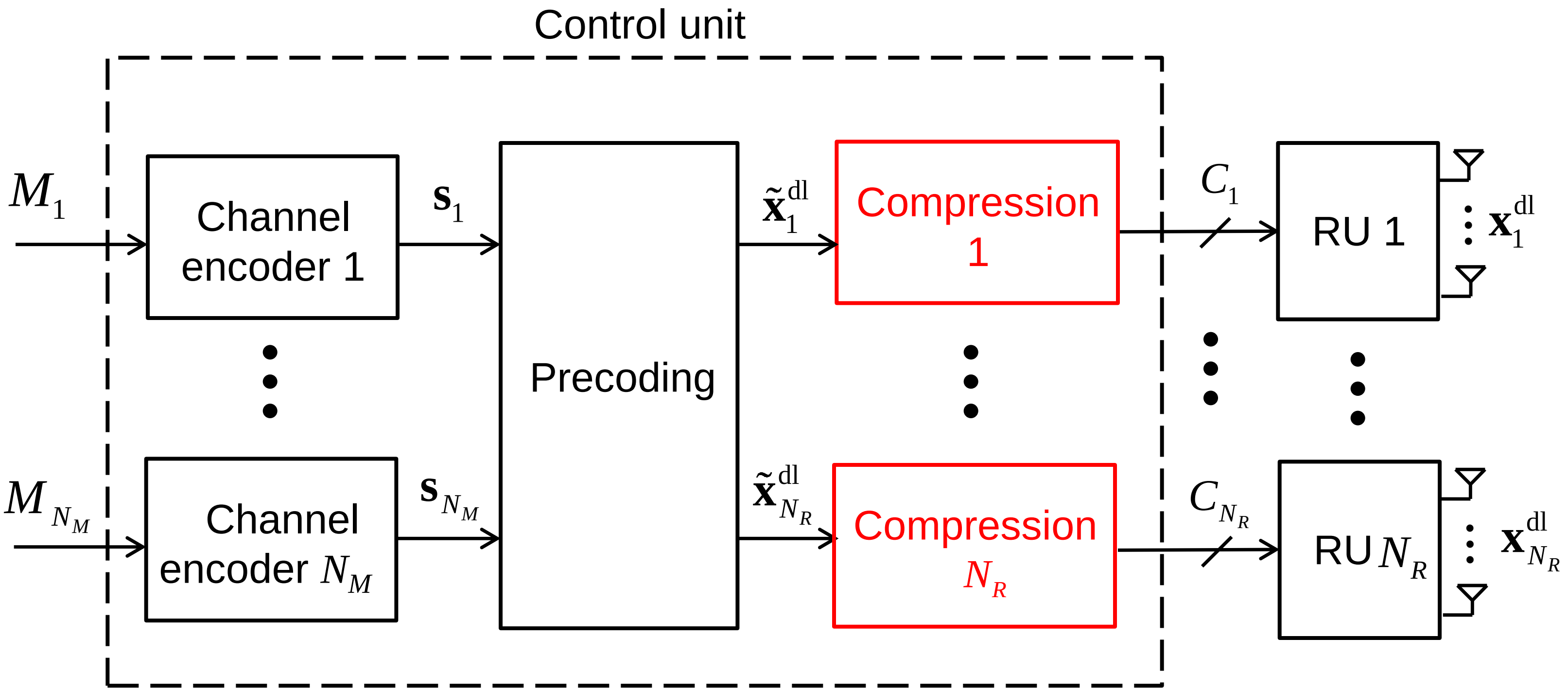
$\mathbf{z}_k^{\mathrm{dl}} \sim \mathcal{CN}(\mathbf{0}, \mathbf{\Omega}_{\mathbf{z}_i^{\mathrm{dl}}})$: noise and interference arising from the other clusters;

$\mathbf{H}_k^{\mathrm{dl}}$: channel vector from all RUs toward MS k.

- Per-RU power constraint: $E\left\|\mathbf{x}_1^{\mathrm{dl}}\right\|^2 \leq P_{R,i}, \ i \in \{1, \ldots, N_R\}.$

Point-to-Point Compression

[Simeone et al ‘09]

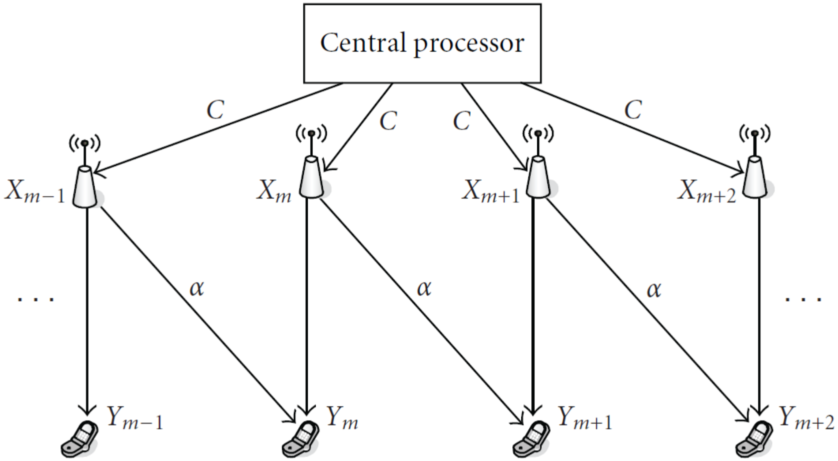


Baseband signals for different RUs are separately compressed.

- For precoding, both linear precoding [Huh et al ‘10] and non-linear dirty-paper coding [Costa ‘83] can be considered.

Asymmetric Wyner model Downlink: Independent Compression

- Compressed dirty-paper coding (CDPC) [Simeone et al '09]



System model

Quantization is performed at the central unit using the forward test channel

$$X_m = \tilde{X}_m + Q_m,$$

where $\tilde{X}_m$: DPC precoding output,

Q_m: quantization noise with $Q_m \sim \mathcal{CN}(0, P/2^C)$,

m: cell-index, thus Q_m is independent over the index m.

- With constrained backhaul links, we obtain a modified broadcast channel (BC) with the added quantization noises.

- Per-cell sum-rate

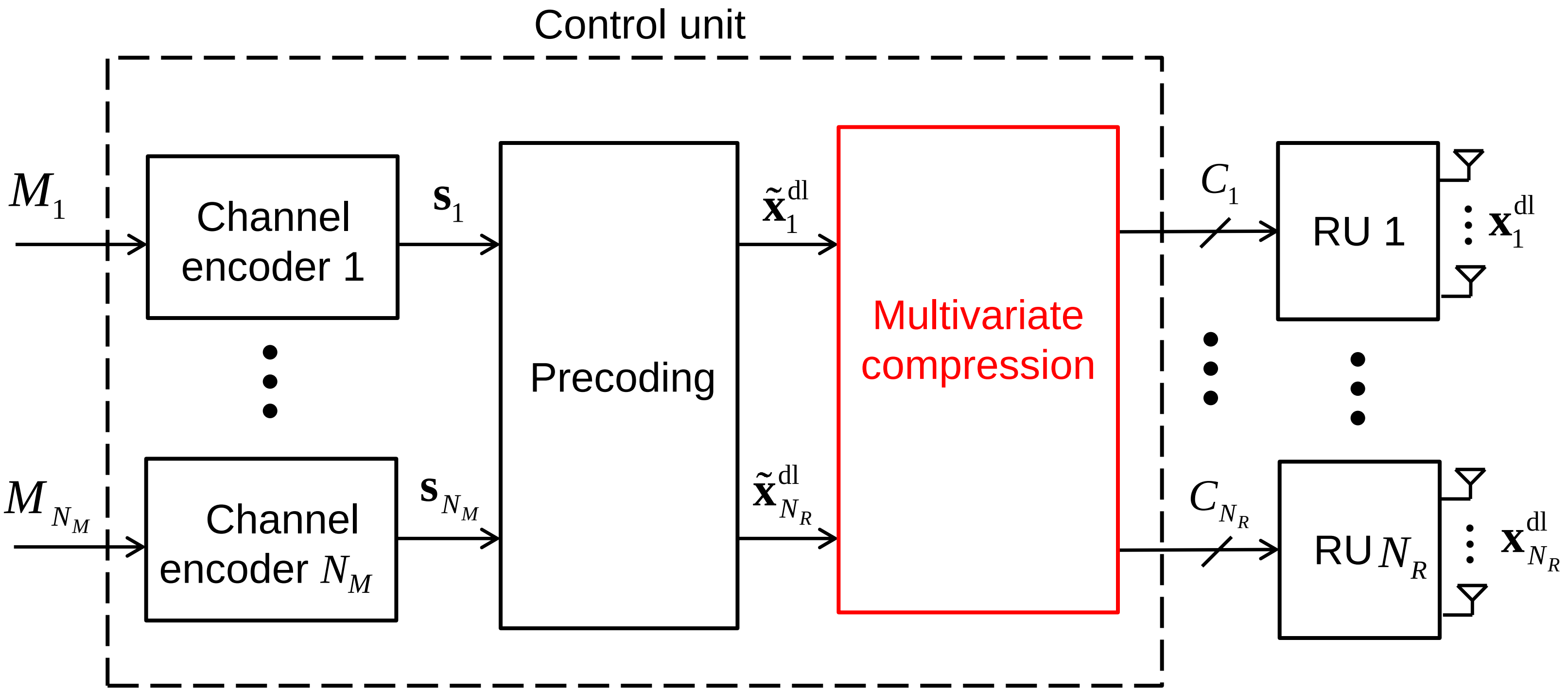
$$R_{\text{per-cell}} = \log\left(\frac{1+(1+\alpha^2)\tilde{P}+\sqrt{1+2(1+\alpha^2)\tilde{P}+(1-\alpha^2)^2\tilde{P}^2}}{2}\right)$$

where $\tilde{P}$ is the effective SNR at the MSs decreased from P to

$$\tilde{P} = \frac{P}{\left(1+(1+\alpha^2)P\right)/(2^C-1)+1}.$$

Multivariate Compression

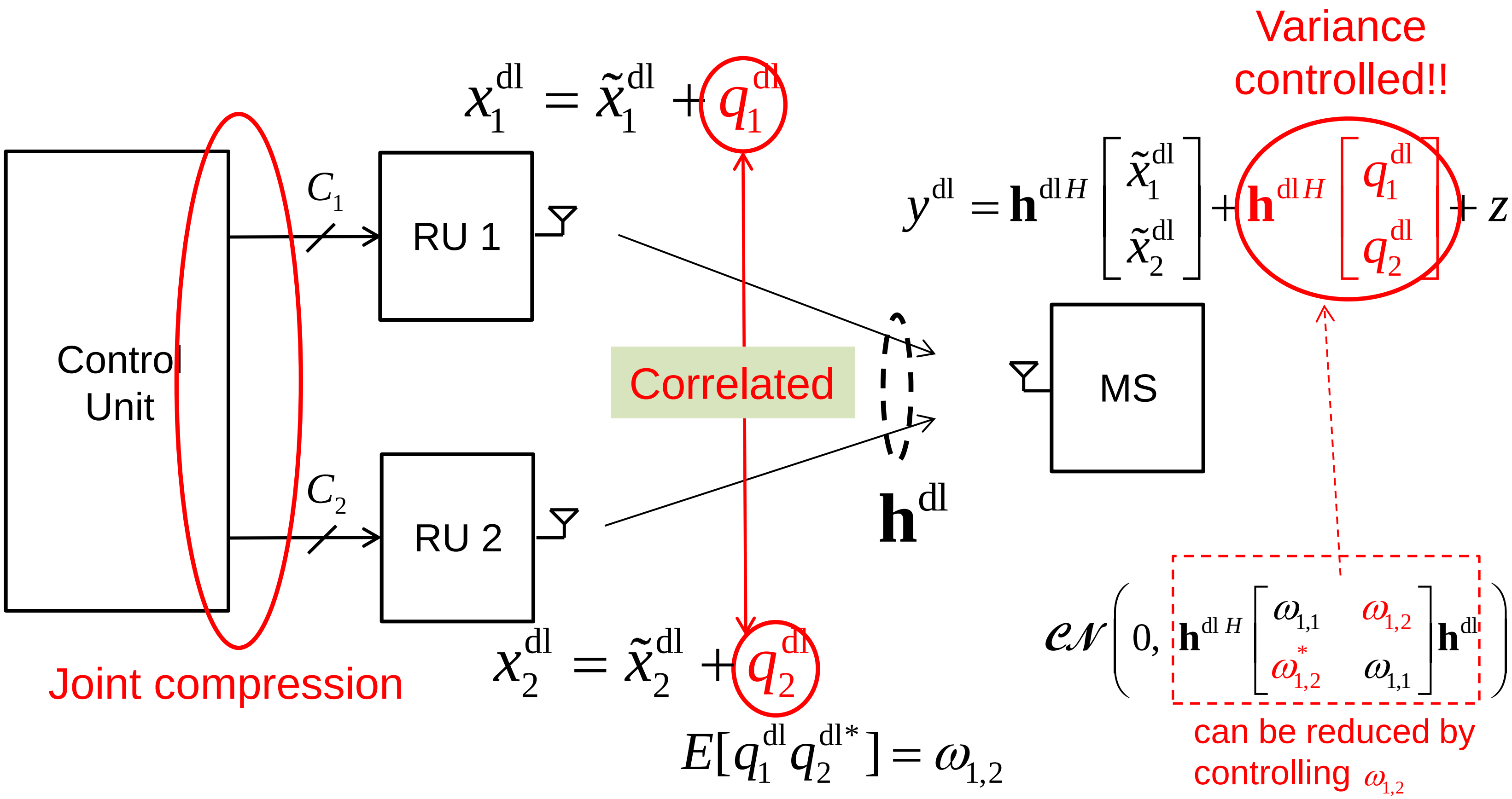
[Park et al TSP‘13]



Baseband signals for different RUs are jointly compressed.

Multivariate Compression

- Multivariate compression produces compressed signals with correlated quantization noises
- Noise correlation enables finer control of effect quantization at the MSs



$$x_1^{\mathrm{dl}} = \tilde{x}_1^{\mathrm{dl}} + q_1^{\mathrm{dl}}$$

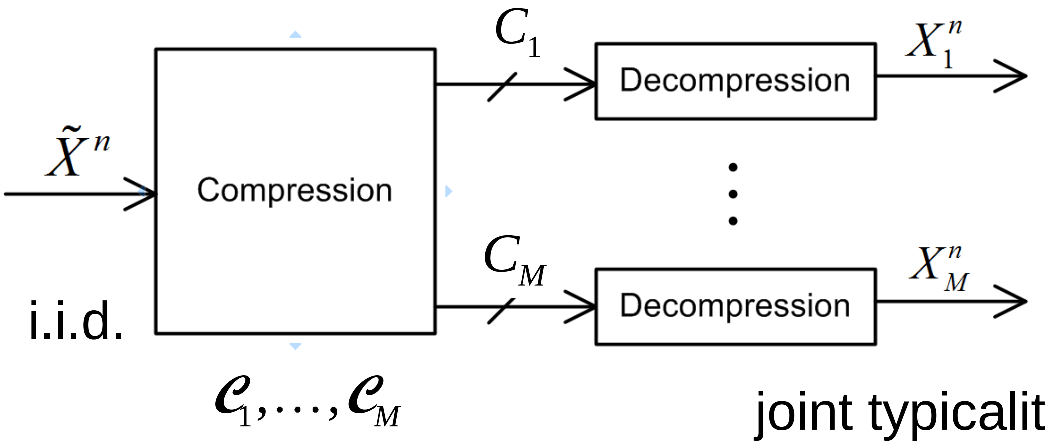
$$x_2^{\mathrm{dl}} = \tilde{x}_2^{\mathrm{dl}} + q_2^{\mathrm{dl}}$$

$$E[q_1^{\mathrm{dl}} q_2^{\mathrm{dl}*}] = \omega_{1,2}$$

$$y^{\mathrm{dl}} = \mathbf{h}^{\mathrm{dl}\,H} \begin{bmatrix} \tilde{x}_1^{\mathrm{dl}} \\ \tilde{x}_2^{\mathrm{dl}} \end{bmatrix} + \mathbf{h}^{\mathrm{dl}\,H} \begin{bmatrix} q_1^{\mathrm{dl}} \\ q_2^{\mathrm{dl}} \end{bmatrix} + z$$

$$\mathcal{CN}\left(0, \mathbf{h}^{\mathrm{dl}\,H} \begin{bmatrix} \omega_{1,1} & \omega_{1,2} \\ \omega_{1,2}^{*} & \omega_{1,1} \end{bmatrix} \mathbf{h}^{\mathrm{dl}}\right)$$

Multivariate Compression Lemma



joint typicality wrt

$$p(\tilde{x}, x_1, \ldots, x_M) = p(\tilde{x})\, p(x_1, \ldots, x_M \mid \tilde{x})$$

$$\sum_{i \in \mathcal{S}} h(X_i) - h\left(X_{\mathcal{S}} \mid \tilde{X}\right) \leq \sum_{i \in \mathcal{S}} C_i, \text{ for all } \mathcal{S} \subseteq \{1, \cdots, M\}$$

[ElGamal-Kim ’11, Ch. 9]

Multivariate Compression

- Linear precoding (DPC treated in a similar way)

- Gaussian test channel:

$$\mathbf{x}_i^{\text{dl}} = \tilde{\mathbf{x}}_i^{\text{dl}} + \mathbf{q}_i^{\text{dl}}, \qquad \mathbf{q}_i^{\text{dl}} \sim \mathcal{CN}(\mathbf{0}, \mathbf{\Omega}_{i,i}^{\text{dl}}), \quad i \in \mathcal{N}_R$$

- The compressed signal $\mathbf{x}^{\text{dl}} = \left[\mathbf{x}_1^{\text{dl}\,H}, \cdots, \mathbf{x}_{N_R}^{\text{dl}\,H}\right]^H$ is given as

$$\mathbf{x}^{\text{dl}} = \mathbf{A}\mathbf{s} + \mathbf{q}^{\text{dl}},$$

with $\mathbf{q}^{\text{dl}} = \left[\mathbf{q}_1^{\text{dl}\,H}, \cdots, \mathbf{q}_{N_R}^{\text{dl}\,H}\right]^H \sim \mathcal{CN}(\mathbf{0}, \mathbf{\Omega}^{\text{dl}})$ and

$$\mathbf{\Omega}^{\text{dl}} = \begin{bmatrix} \mathbf{\Omega}_{1,1}^{\text{dl}} & \mathbf{\Omega}_{1,2}^{\text{dl}} & \cdots & \mathbf{\Omega}_{1,N_R}^{\text{dl}} \\ \mathbf{\Omega}_{2,1}^{\text{dl}} & \mathbf{\Omega}_{2,2}^{\text{dl}} & \cdots & \mathbf{\Omega}_{2,N_R}^{\text{dl}} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{\Omega}_{N_R,1}^{\text{dl}} & \mathbf{\Omega}_{N_R,2}^{\text{dl}} & \cdots & \mathbf{\Omega}_{N_R,N_R}^{\text{dl}} \end{bmatrix}$$

(Independent compression is a special case with $\mathbf{\Omega}_{i,j}^{\text{dl}} = \mathbf{0},\ i \neq j \in \mathcal{N}_R$.)

Optimization

- Weighted sum-rate maximization

$$\underset{\mathbf{A},\boldsymbol{\Omega}^{\mathrm{dl}}\geq\mathbf{0}}{\text{maximize}} \quad \sum_{k=1}^{N_M} w_k f_k\left(\mathbf{A},\boldsymbol{\Omega}^{\mathrm{dl}}\right) \qquad (1a)$$

$$\text{s.t.} \quad g_{\mathcal{S}}\left(\mathbf{A},\boldsymbol{\Omega}^{\mathrm{dl}}\right)\leq\sum_{i\in\mathcal{S}}C_i,\ \text{ for all }\ \mathcal{S}\subseteq\mathcal{N}_R, \qquad (1b)$$

$$\mathrm{tr}\left(\mathbf{E}_i^H\mathbf{A}\mathbf{A}\mathbf{E}_i+\boldsymbol{\Omega}_{i,i}^{\mathrm{dl}}\right)\leq P_i,\ \text{ for all }\ i\in\mathcal{N}_R. \qquad (1c)$$

where $f_k\left(\mathbf{A},\boldsymbol{\Omega}^{\mathrm{dl}}\right)=I\left(\mathbf{s}_k;\mathbf{y}_k^{\mathrm{dl}}\right)$

$$=\log\det\left(\mathbf{I}+\mathbf{H}_k^{\mathrm{dl}}(\mathbf{A}\mathbf{A}^H+\boldsymbol{\Omega}^{\mathrm{dl}})\mathbf{H}_k^{\mathrm{dl}\,H}\right)-\log\det\left(\mathbf{I}+\mathbf{H}_k^{\mathrm{dl}}\left(\sum_{l\neq k}\mathbf{A}_l\mathbf{A}_l^H+\boldsymbol{\Omega}^{\mathrm{dl}}\right)\mathbf{H}_k^{\mathrm{dl}\,H}\right),$$

$$g_{\mathcal{S}}\left(\mathbf{A},\boldsymbol{\Omega}^{\mathrm{dl}}\right)=\sum_{i\in\mathcal{S}}h\left(\mathbf{x}_i^{\mathrm{dl}}\right)-h\left(\mathbf{x}_{\mathcal{S}}^{\mathrm{dl}}\,|\,\tilde{\mathbf{x}}^{\mathrm{dl}}\right)$$

$$=\sum_{i\in\mathcal{S}}\log\det\left(\mathbf{E}_i^H\mathbf{A}\mathbf{A}^H\mathbf{E}_i+\boldsymbol{\Omega}_{i,i}^{\mathrm{dl}}\right)-\log\det\left(\mathbf{E}_{\mathcal{S}}^H\boldsymbol{\Omega}^{\mathrm{dl}}\mathbf{E}_{\mathcal{S}}\right)\leq\sum_{i\in\mathcal{S}}C_i.$$

- Difference-of-convex (DC) problem: Local optimum via MM algorithm

[Beck-Teboulle '11]

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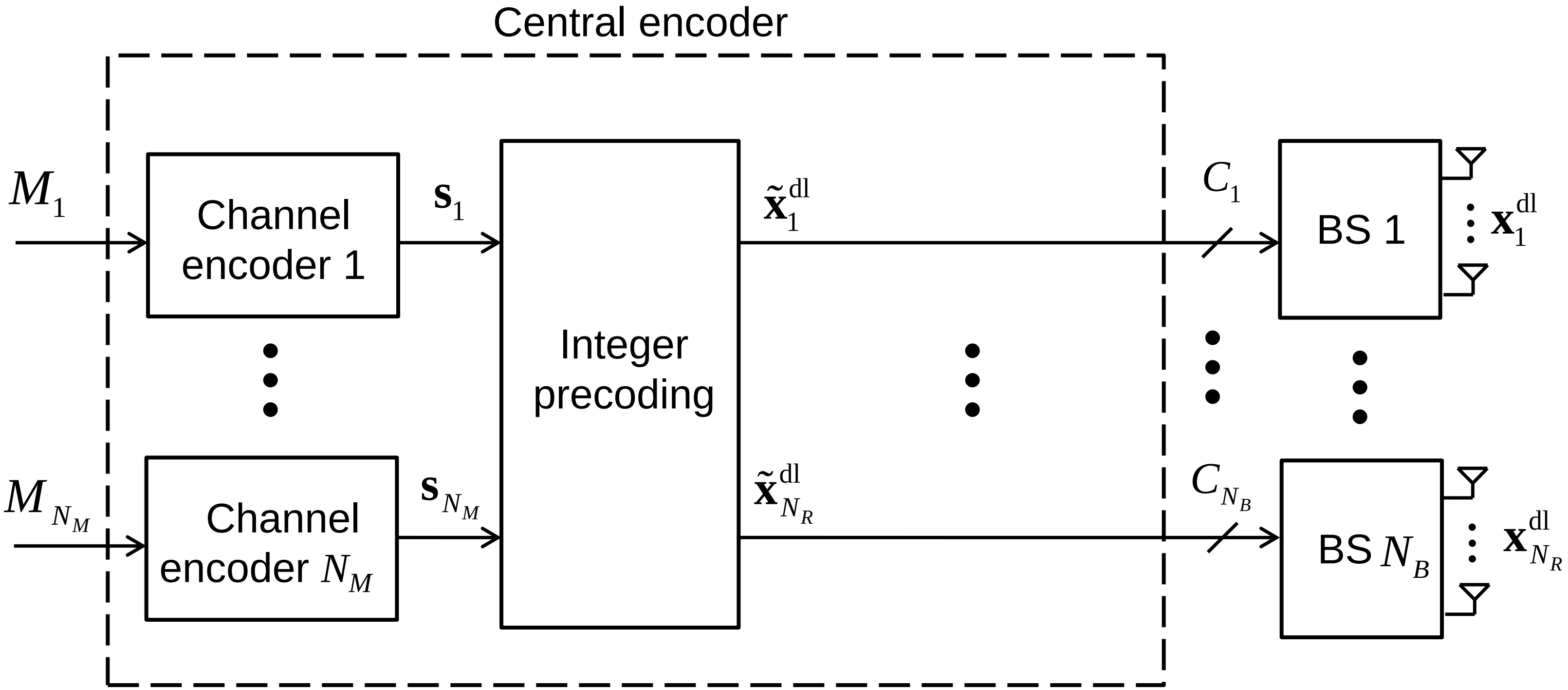
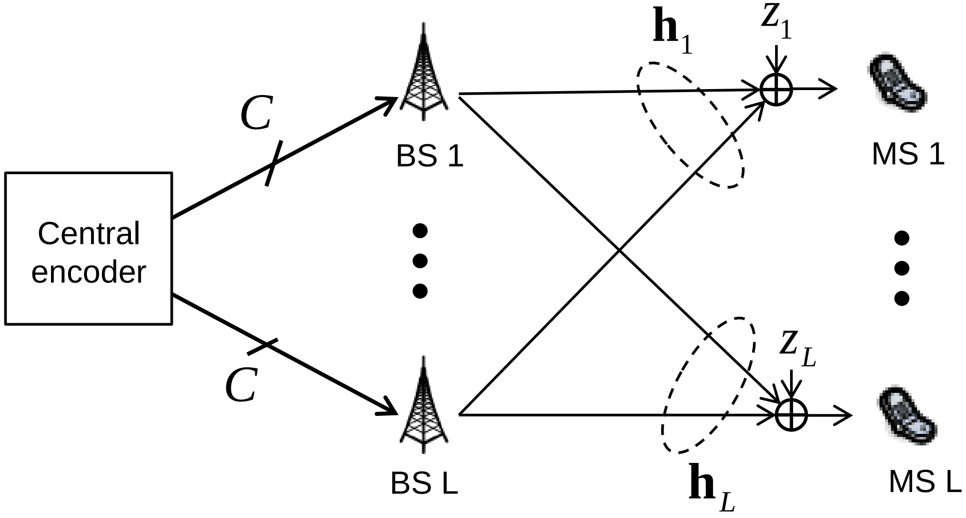
Structured Coding

- Reverse compute-and-forward (RCoF) [Hong-Caire '13]



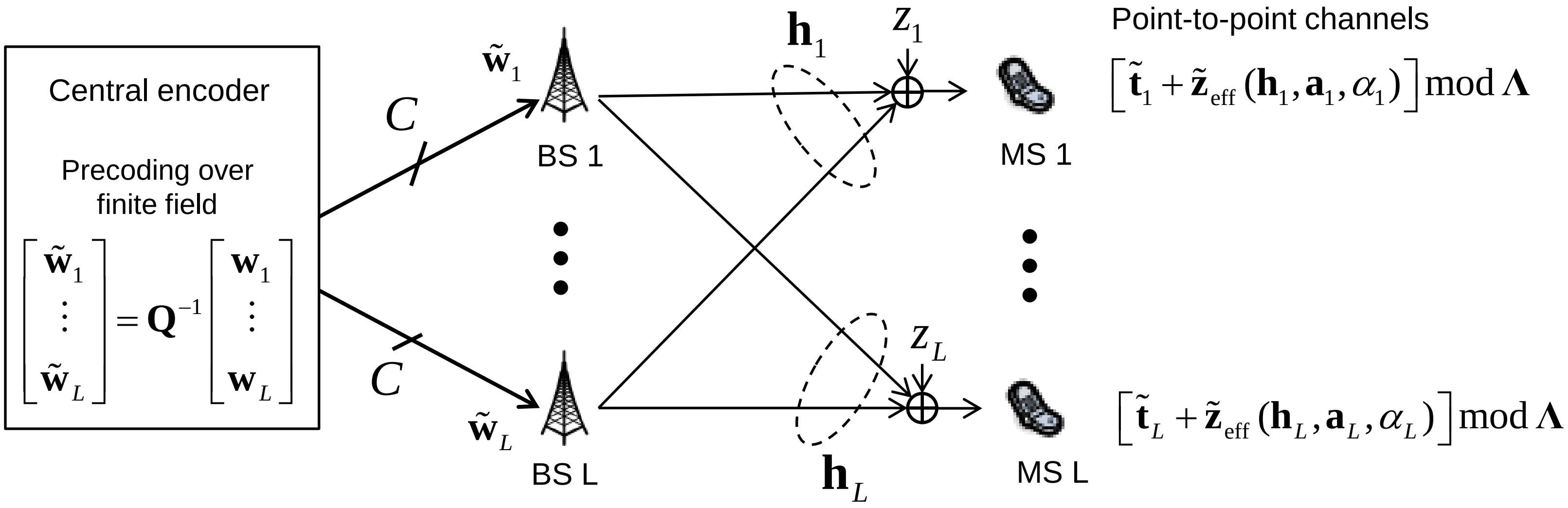
Structured Coding

- Reverse compute-and-forward (RCoF) [Hong-Caire '13]
  - Downlink counterpart of the compute-and-forward (CoF) scheme proposed for the uplink in [Nazer et al '09].
    - Exchange the role of BSs and MSs and use CoF in reverse direction.
  - System model
    - $N_B = N_M = L,\ C_i = C$ for all $i \in \mathcal{L} = \{1, \cdots, L\}$.



Structured Coding

- Reverse compute-and-forward (RCoF) [Hong-Caire '13] (ctd')



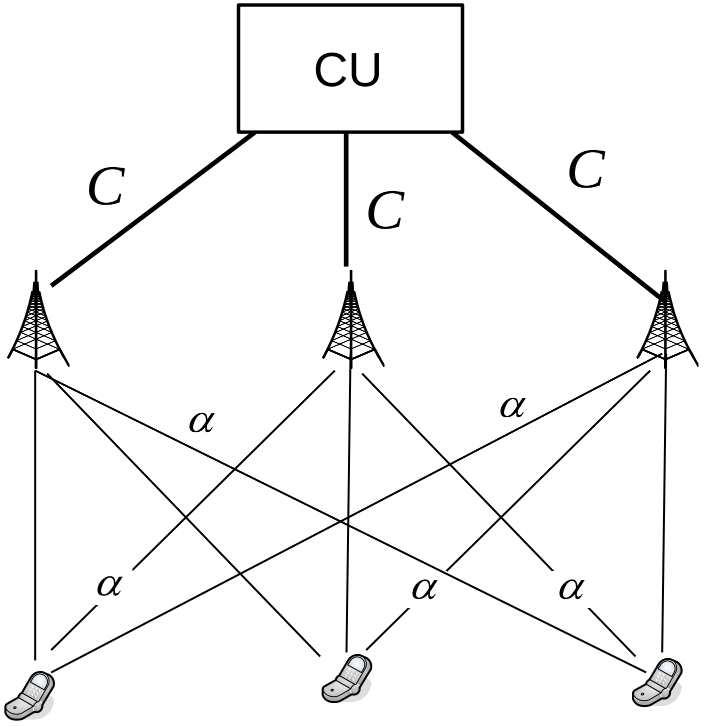
  - The same lattice code is used by each BS.
  - Each MS k estimates a function $\hat{\mathbf{w}}_k = \sum_{j=1}^{L} a_{k,j}\tilde{\mathbf{w}}_j$ by decoding on the lattice code.
  - Achievable rate per MS is given by

$$R_{\text{per-MS}} = \min\left\{C, \min_{l\in\mathcal{L}} R\left(\mathbf{h}_l,\mathbf{a}_l,\mathrm{SNR}\right)\right\} \quad \text{where} \quad R\left(\mathbf{h},\mathbf{a},\mathrm{SNR}\right) = \max\left\{\log\left(\frac{\mathrm{SNR}}{\mathbf{a}^H\left(\mathrm{SNR}^{-1}\mathbf{I}+\mathbf{h}\mathbf{h}^H\right)^{-1}\mathbf{a}}\right),0\right\}$$

Integer penalty

Numerical Example

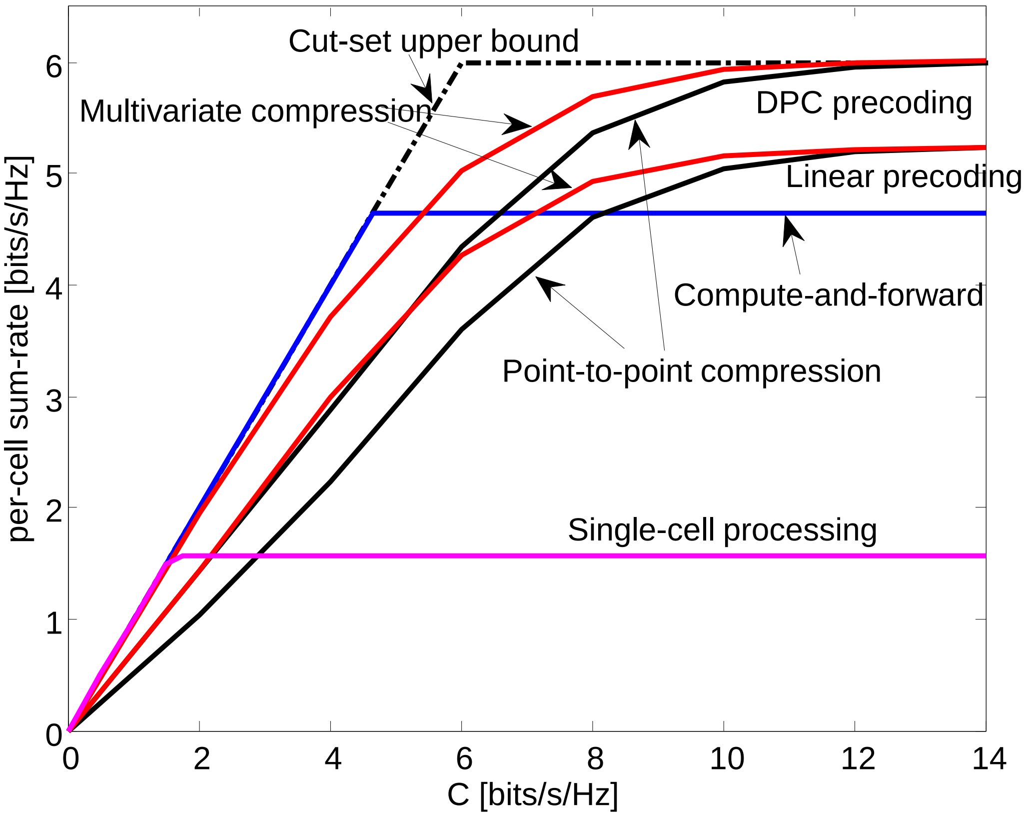
- Three-cell SISO circular Wyner model



- Each cell contains one single-antenna RU and one single-antenna MS.
- Inter-cell interference takes place only between adjacent cells.
- The intra-cell and inter-cell channel gains are given by 1 and α, respectively.
- All RUs have a fronthaul capacity of C.

Numerical Example

$P = 20$ dB and $\alpha = 0.5$



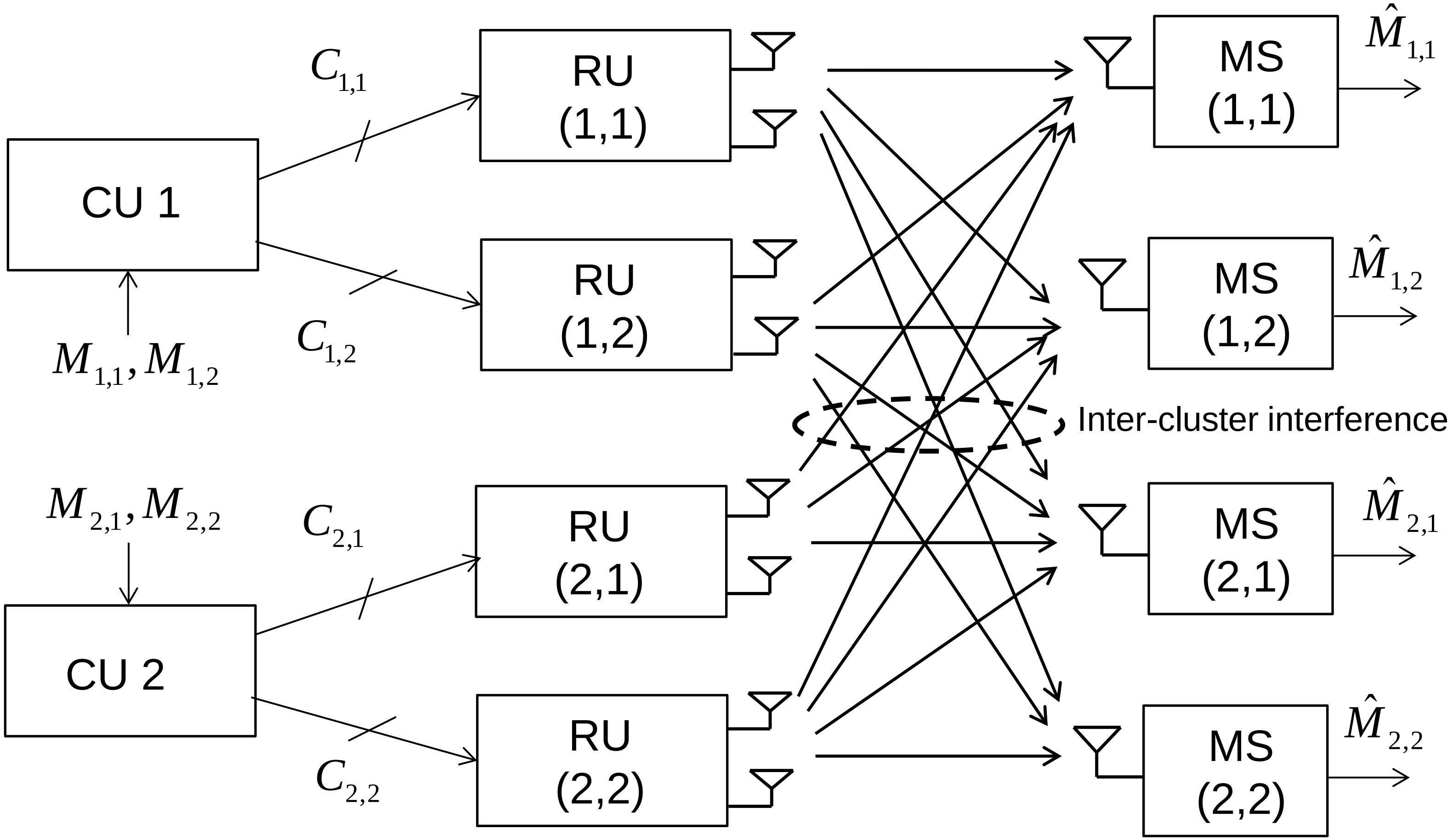
- Multivariate compression is significantly advantageous for both linear and DPC precoding.
- RCoF remains the most effective approach in the regime of moderate fronthaul capacity C, although multivariate compression allows to compensate for most of the rate loss of standard DPC precoding in the low-fronthaul regime.
- The curve of RCoF flattens before the others do, since it is limited by the integer approximation penalty when the fronthaul capacity is large enough.

Outline

Inter-Cluster Multivariate Fronthaul Design

[Park et al WCL‘14]

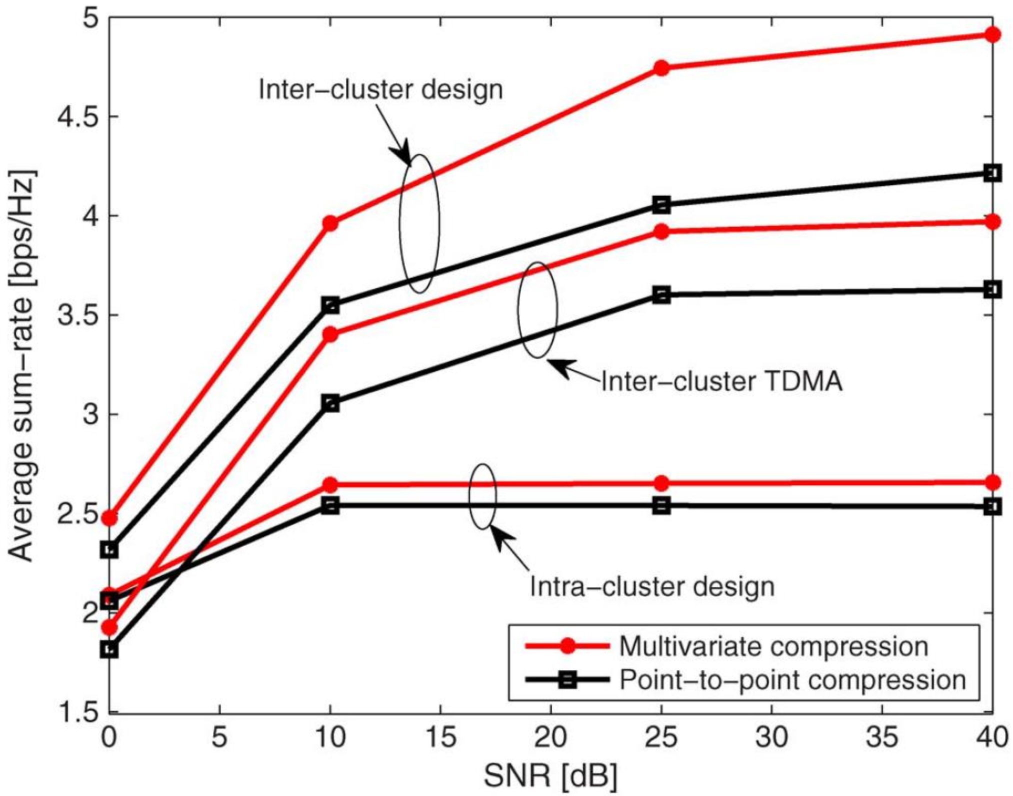
- An illustration of the downlink of multi-cluster cloud radio access network



Inter-Cluster Multivariate Fronthaul Design

[Park et al WCL‘14]

- Problem of maximizing weighted sum-rate across multiple clusters is a DC problem.
  - The MM approach can be applied to obtain a stationary point [Park et al WCL‘14].



Two clusters, two RUs and UEs per cluster,
single-antenna at RUs and UEs and fronthaul capacity of 2 bps/Hz

- Baseline schemes:
  - Inter-cluster TDMA
    : Activate only a single cluster
  - Intra-cluster design
    : Each cluster is designed assuming there is no incoming and outgoing inter-cluster interference signals.
- Inter-cluster design provides significant gains compared to inter-cluster TDMA and intra-cluster design.
- Advantage of multivariate compression is most pronounced for inter-cluster design.

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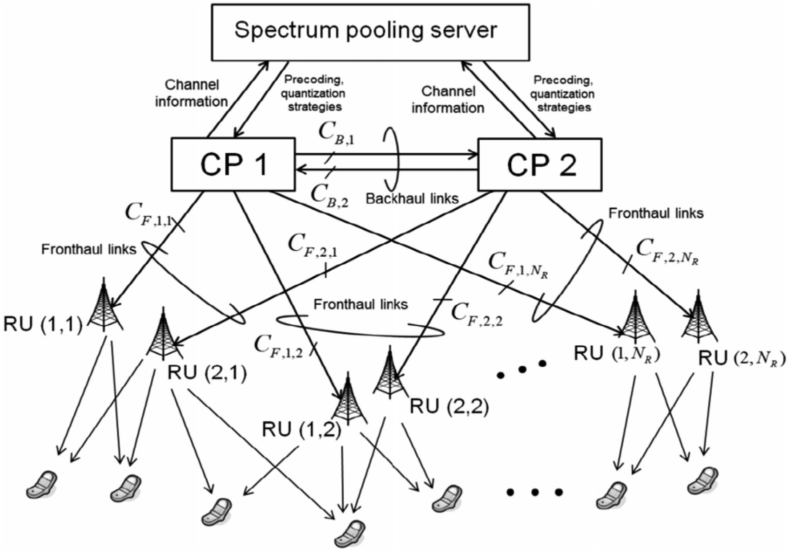
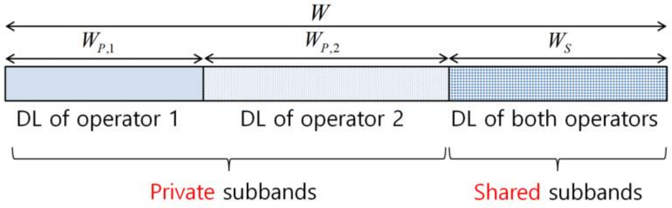
Multi-Tenant C-RAN

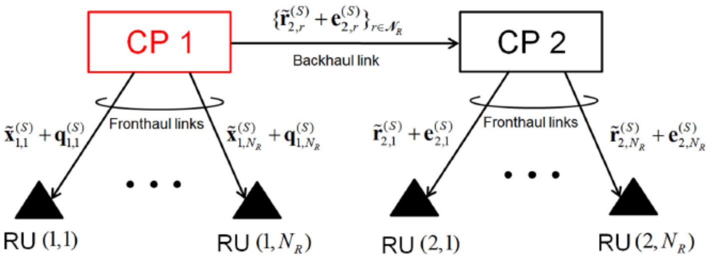
[Park et al TVT‘18]



<Downlink of multi-tenant C-RAN>



<Band splitting for downlink trans.>

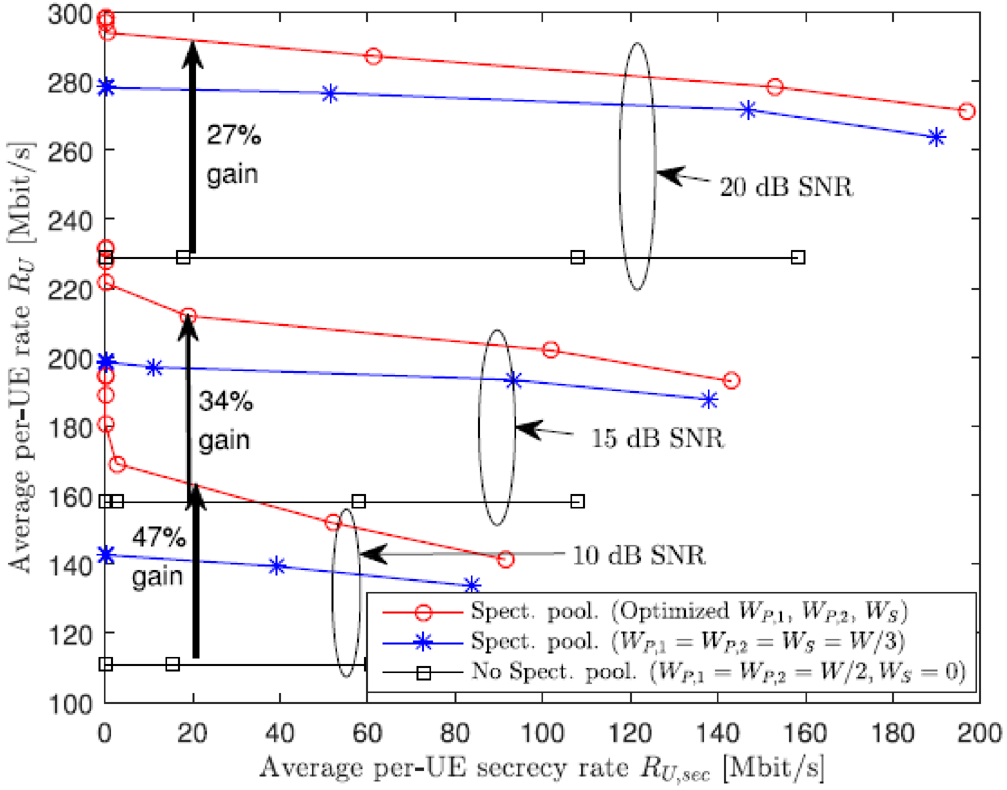


<Operation of CP 1 on shared subband>

- Spectrum pooling among multiple network operators
  - Energing technique for meeting the rapidly increasing traffic demands over the available scarce spectrum resources [Khan et al CM’11][Boccardi et al CM’16].
- In [Park et al TVT’18], centralized joint optimization of multi-tenant C-RAN was addressed.
  - Specifically, inter-operator privacy constraints were imposed.

Multi-Tenant C-RAN

[Park et al TVT‘18]

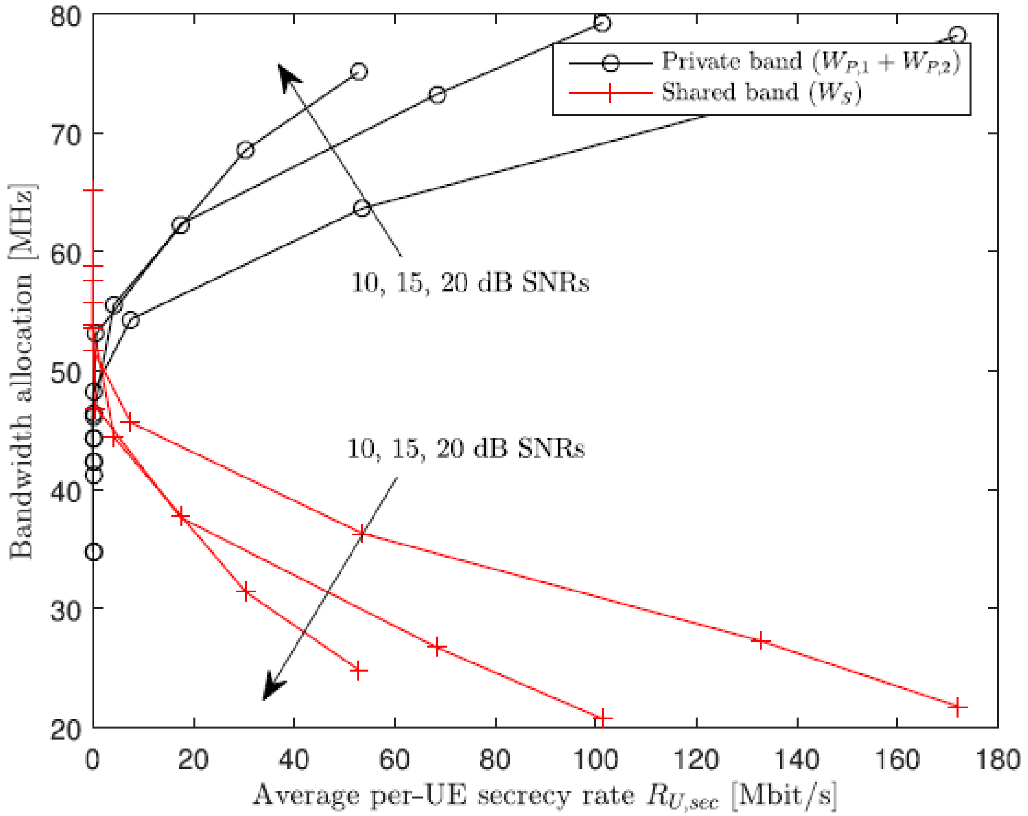


<Advantages of optimized spectrum pooling>

- Proposed optimized multi-tenant C-RAN achieves a significantly improved rate-privacy trade-off.
- The gain from inter-operator cooperation becomes more significant at lower SNR levels.
- Ex) To guarantee per-UE secrecy rate of 20 Mbps, the proposed multi-tenant C-RAN achieves a gain of 47% at 10 dB SNR with respect to traditional C-RAN.

Multi-Tenant C-RAN

[Park et al TVT‘18]

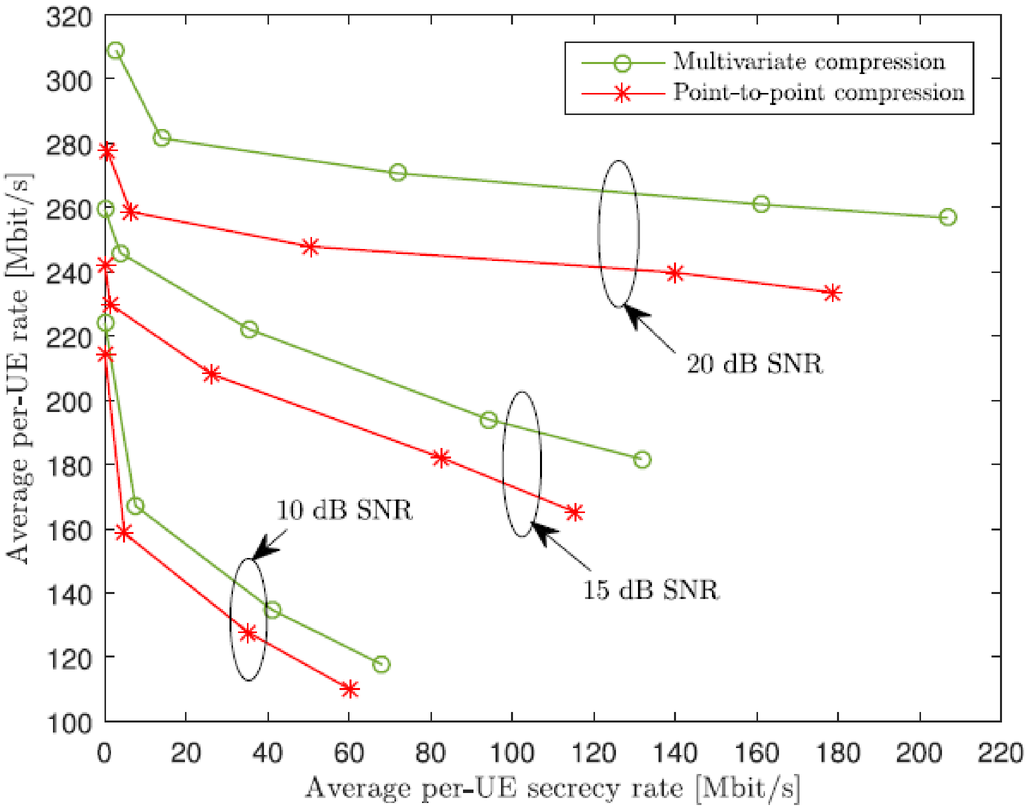


<Optimized bandwidth allocation>

- As the SNR decreases, more spectrum resources are allocated to the shared subband to leverage the opportunity of inter-operator cooperation.
    - This coincides with the above observation, i.e., the impact of inter-operator cooperation is more pronounced in lower SNR regime.

Multi-Tenant C-RAN

[Park et al TVT‘18]



<Advantages of multivariate compression>

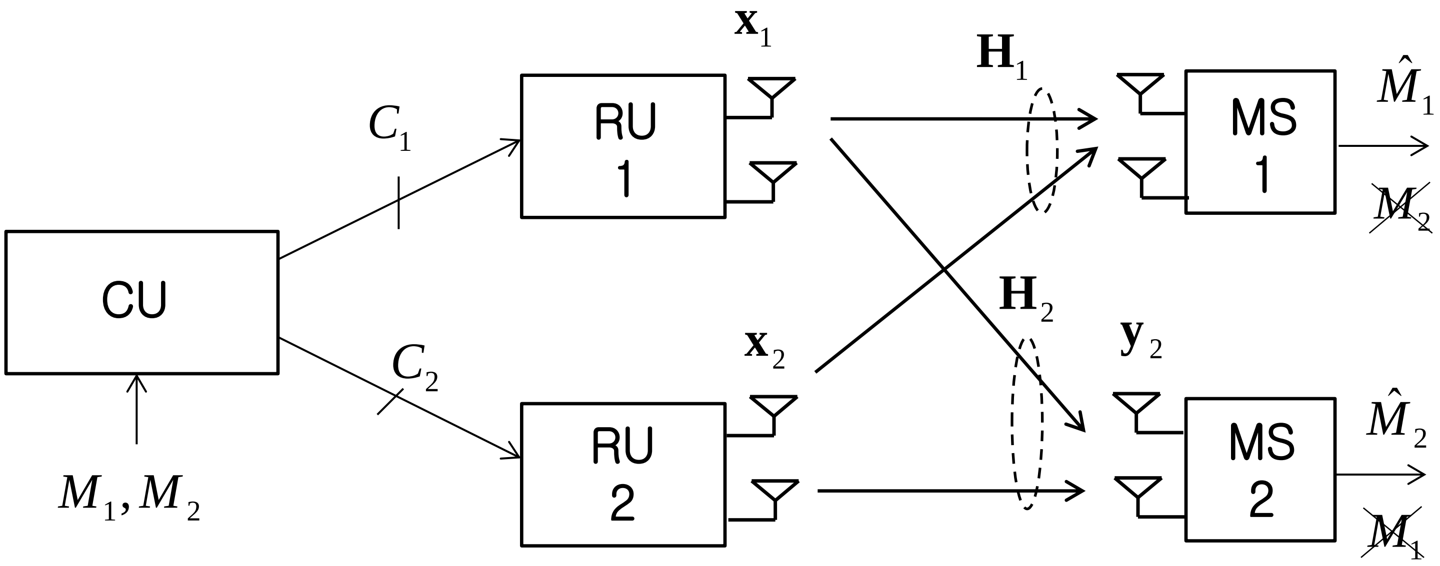
- The figure shows that multivariate compression is instrumental in improving the trade-off between inter-operator cooperation and privacy.
    - The accrued performance gain increases with the SNR, since the performance degradation due to quantization is masked by the additive noise when the SNR is small.

Outline

Fronthaul Quantization as Artificial Noise

[Park et al SPAWC'17]

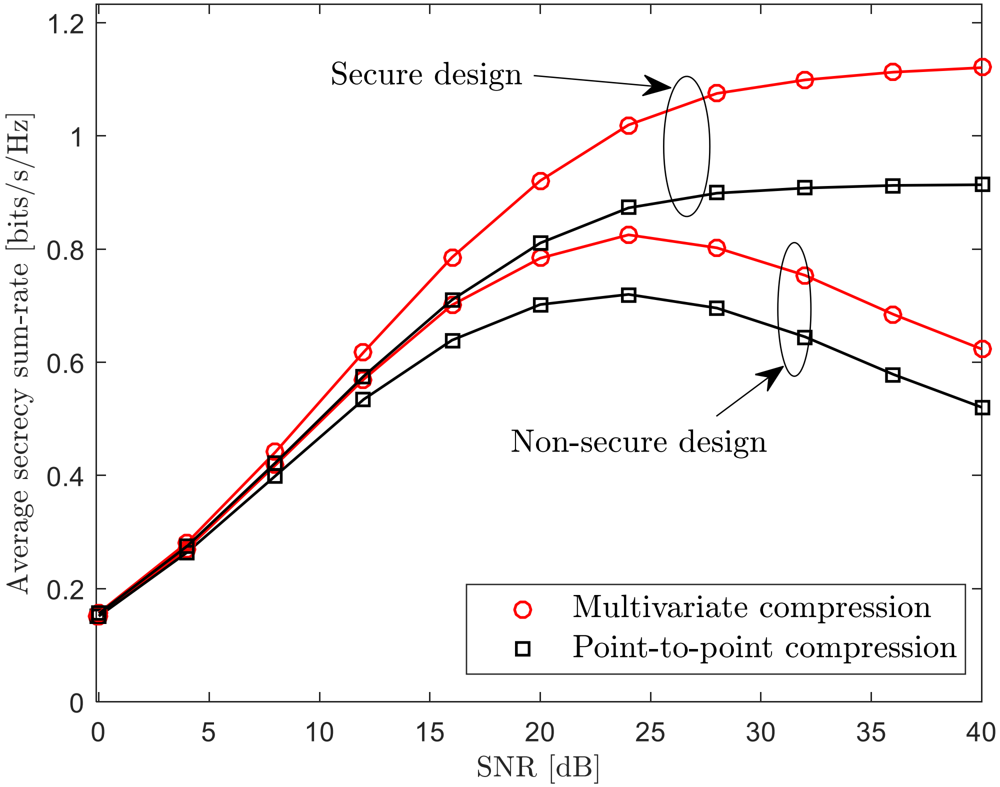
- C-RAN downlink with confidential messages



  - Each message M_k for UE k needs kept secret from the other UEs.
  - In [Park et al SPAWC '17], it was proposed to leverage fronthaul quantization noise as artificial noise.
    - Specifically, multivariate compression is useuful to effectively shape the quantization noise signals of different RUs.

Frontihaul Quantization as Artificial Noise

[Park et al SPAWC‘17]



- The performance of the non-secure design is degraded in the high-SNR regime.
  - due to the enhanced decodability of the messages of the unintended UEs.

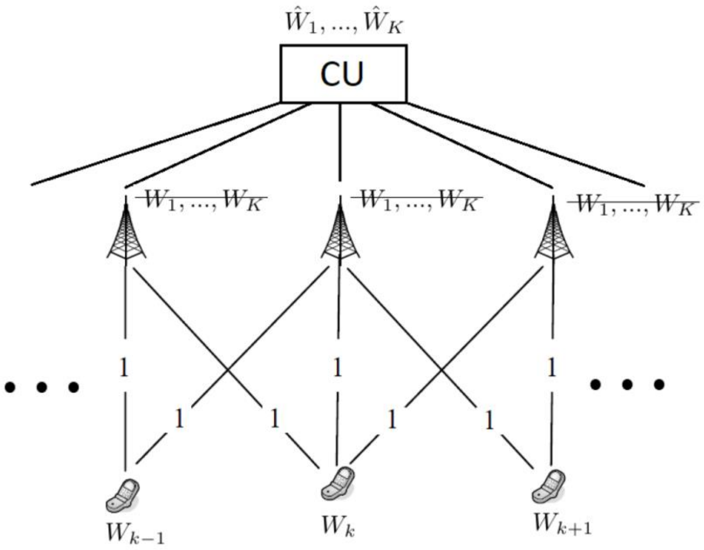
- Multivariate compression yields a significant performance gain that is increasing with SNR.
  - This is because the impact of the quantization noise is more significant when the SNR is large at the UE side.

(Non-secure design: Precoding and fronthaul quantization strategies are designed without considering the secrecy among the UEs.)

C-RAN Uplink With Confidential Messages

[Zeide et al ICSEE‘18]

- Wyner-type K-cell C-RAN uplink with confidential messages



- Each user k wishes to send message W_k to CU guaranteeing secrecy with respect to all RUs.

- Each RU j receives interference only from adjacent RUs, i.e.,

$$Y_j = X_{j-1} + X_j + X_{j+1} + Z_j.$$

- **Two transmission strategies:**
  - Orthogonal transmission: Each user transmits for a fraction $1/K$ of the time with power KP, while the other users are silent.
  - Non-orthogonal transmission: All users simultaneously transmit with power P.

- **Achievable secrecy rates**

Orthogonal transmission:

$$R = \frac{1}{6}\log_2(1+9P) - \frac{1}{6}\log_2(1+3P)$$

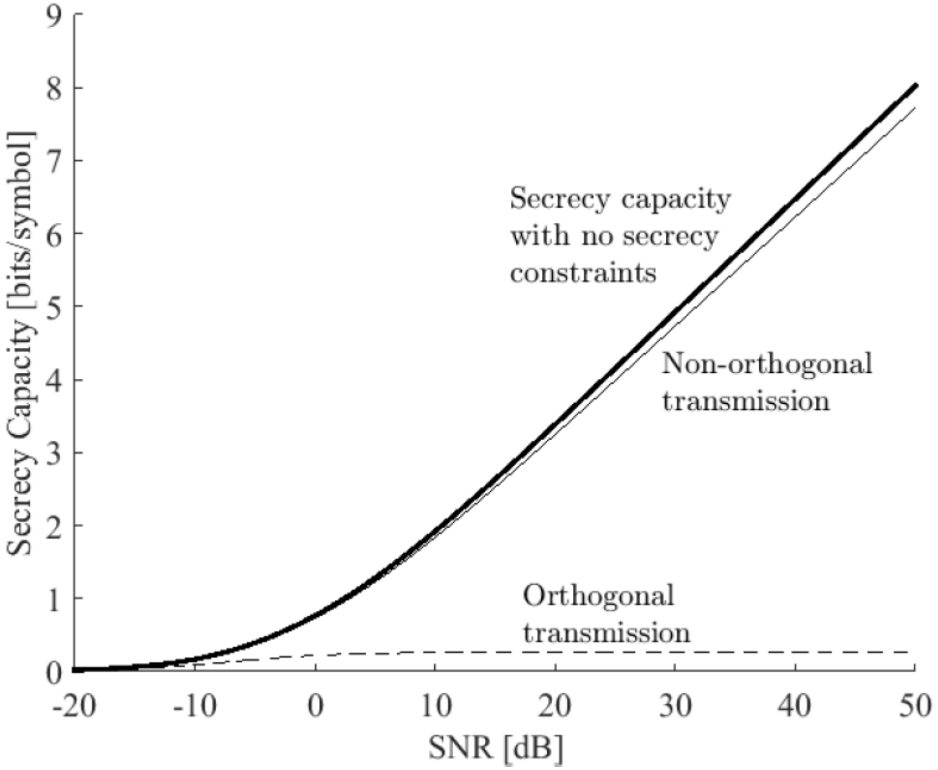
Non-orthogonal transmission ($K \geq 5$):

$$R = \frac{1}{2K}\sum_{k=0}^{K-1}\log_2\left(1+3P+4P\cos\left(2\pi\frac{k}{K}\right)+2P\cos\left(2\pi\frac{2k}{K}\right)\right) - \frac{1}{2K}\log_2(1+3P)$$

C-RAN Uplink With Confidential Messages

[Zeide et al ICSEE'18]

- Wyner-type K-cell C-RAN uplink with confidential messages



<Secrecy rate versus SNR for $K = 30$ >

- For sufficiency large K, non-orthogonal transmission achieves the same DoF as that achieved under no secrecy constraints.
  - This is due to the limited inter-cell interference span in ensuring confidential communication.
- * C-RAN uplink with confidential messages and finite fronhaul capacities

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    - A. Channels with variable backhaul connectivity
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Fog-RAN w/ Edge Caching

- Some pioneering works
  - Receiver-end caching [MAli-Niesen '14][MAli-Niesen '15]
  - Edge-caching (a.k.a. femto-caching) [Golrezaei et al '13]

- Information-theoretic analysis
  - DoF analysis of cache-aided IA [Naderializadeh et al '16]
  - Latency trade-offs in cache-aided wireless networks [Sengupta et al '16]

- Pre-fecthing policy design
  - Coded caching [Ugur et al '15]
  - Fronthaul-aware caching [Xpeng et al '15], mobility-aware caching [Wang et al '16]

- Delivery transmission design
  - Joint design of beamfomring and BSs clustering [Tao et al '16]
  - Hybrid hard-/soft-transfer fronthauling strategy [Park et al '16]

CSI Accuracy, Impact

- Cloud may have a worse CSI quality than the distributed RUs.

- Impact of CSI quality
  - Deterministic worst-case design for uplink [Park et al TVT'13][Park et al TVT'14] and downink [Park et al TSP'13]
  - Broadcast coding and layered compression for unreliable fading and fronthaul links [Karasik et al '13]
  - Joint transfer of CSI and baseband signals for uplink C-RAN [Kang et al TWC'14]
  - Stochastic optimization of precoding and fronthaul compression for the downlink of C-RAN with time-varying channels [Kang et al TVT'16]

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Summarizing/Tutorial References

[1] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Fronthaul compression for cloud radio access networks,” *IEEE Signal Process Mag., Special Issue on Signal Processing for the 5G Revolution*, vol. 31, no. 6, pp. 69-79, Nov. 2014.

[2] J. Wu, Z. Zhang, Y. Hong and Y. Wen, "Cloud Radio Access Network (C-RAN): a Primer,” *IEEE Networks*, vol. 29, no. 1, pp. 35-41, Jan.-Feb. 2015.

[3] M. Peng, C. Wang, V. Lau and H. V. Poor, “Fronthaul-Constrained Cloud Radio Access Networks: Insight and Challenges,” *IEEE Wireless Comm.*, vol. 22, no. 2, pp. 152-160, Apr. 2015.

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

[5] S. Buzzi, I. C-L. I, T. E. Klein and H. V. Poor, "A Survey of Energy-Efficient Techniques for 5G Networks and Challenges Ahead," *IEEE Journ. on Selec. Areas in Commun.*, vol. 34, no. 4, Apr. 2016, pp. 697-709.

[6] M. Agiwal, A. Roy and N. Saxena, “Next generation 5G wireless networks: A comprehensive survey," *IEEE Comm. Surveys & Tutorials*, vol. 18, no. 3, 3rd quart., pp. 1617-1655, 2016.

[7] M. Peng, Y. Sun, X. Li, Z. Mao and C. Wang, "Recent Advances in Cloud Radio Access Networks: System Architectures, Key Techniques, and Open Issues," *IEEE Comm. Surveys & Tutorials*, vol. 18, no. 3, 3rd quart., pp. 2282-2308, 2016.

Summarizing/Tutorial References

[8] W. Yu, B. Dai, P. Patil, Y. Zhou and L. Liu, "Cloud Radio-Access Networks: Capacity, Coding Strategies, and Optimization," *IEEE CTW 2016 IEEE Communication Theory Workshop*, 15-18 May, 2016, Nafplio, Greece. http://www.ieee-ctw.org/ [www.ieee-ctw.org].

[9] O. Simeone, A. Maeder, 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.

[10] R. Tandon and O. Simeone, “Harnessing cloud and edge systems: Towards an information theory of fog radio access networks," *IEEE Comm. Mag.*, vol. 54, no. 8, pp. 44-50, Aug. 2016.

[11] Y. Zhou and Y. Xu, W. Yu and J. Chen, “On the optimal fronthaul compression and decoding strategies for uplink cloud radio access networks,“ arXiv:1608.05768, Aug. 2016.

[12] O. Simeone, S.-H. Park, O. Sahin and S. Shamai (Shitz), "Frontal Compression for C-RAN," Chapter 14 in *Cloud Radio Access Networks: Principles, Technologies, and Applications*, T. Q. S. Quek, M. Peng, O. Simeone, and W. Yu, Eds. Cambridge University Press, Feb. 2017.

[13] A. Zaidi and I. E. Aguerri, “Tutorial: Fronthaul Compression for Cloud Radio Access Networks,” *The Thirteenth Internationl Symposium on Wireless Communication Systems* (*ISWCS ‘16*), Sep. 20-23, 2016, in Poznań, Poland.

Summarizing/Tutorial References

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

[15] Z. Guizani and N. Harmdi, “CRAN, H-CRAN, and F-RAN for 5G systems: Key capabilities and recent advances," *International Journal of Network Management*, pp. 1-22, 2017.

Thank you!

References

References

[Alc-Luc] J. Segel and M. Weldon, “Lightradio portfolio-technical overview,” Technology White Paper 1, Alcatel-Lucent.

[China] China Mobile, “C-RAN: the road towards green RAN,” White Paper, ver. 2.5, China Mobile Research Institute, Oct. 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.

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

[Costa ‘83] M. H. M. Costa, “Writing on dirty paper,” *IEEE Trans. Inf. Theory*, vol. 29, no. 3, pp. 439-441, May 1983.

[Tse-Hanly ‘98] D. N. C. Tse and S. V. Hanly, “Multiaccess fading channels-Part I: polymatroid structure, optimal resource allocation and throughput capacities,” *IEEE Trans. Inf. Theory*, vol. 44, no. 7, pp. 2796-2815, Nov. 1998.

[Alasti et al ‘01] M. Alasti, K. Sayrafian-Pour, A. Ephremides and N. Farvardin, "Multiple description coding in networks with congestion problem," *IEEE Trans. Inf. Theory*, vol. 47, no. 3, pp. 891-902, March 2001.

References

[Viswanath et al ‘02] P. Viswanath, D. Tse and R. Laroia, “Opportunistic beamforming using dumb antennas,” *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp. 1277-1294, Jun. 2002.

[Shamai-Steiner ‘03] S. Shamai (Shitz) and A. Steiner, “A broadcast approach for a single-user slowly fading MIMO channel,” *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2617-2635, Oct. 2003.

[Koetter-Medard ‘03] R. Koetter and M. Medard, “An algebraic approach to network coding,” *IEEE/ACM Trans. Networking*, vol. 11, no. 5, pp. 782-795, Oct. 2003.

[Shamai-Steiner ‘03] S. Shamai (Shitz) and A. Steiner, “A broadcast approach for a single-user slowly fading MIMO channel,” *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2617–2635, Oct. 2003.

[Sanderovich et al ‘08] A. Sanderovich, S. Shamai (Shitz), Y. Steinberg and G. Kramer, “Communication via decentralized processing,” *IEEE Trans. Inf. Theory*, vol. 54, no. 7, pp. 3008-3023, Jul. 2008.

[Simeone et al ‘09] O. Simeone, O. Somekh, H. V. Poor and S. Shamai (Shitz), “Downlink multicell processing with limited-backhaul capacity,” *EURASIP J. Adv. Sig. Proc.*, 2009.

[3GPP-TR-136942] 3GPP TR 36.942 ver. 8.1.0, Rel. 8, Jan. 2009.

References

[dCoso-Ibars] A. d. Coso and C. Ibars, “Achievable rates for the AWGN channel with multiple parallel relays,” *IEEE Trans. Wireless Comm.*, vol. 8, no. 5, pp. 2524-2534, May 2009.

[Nazer et al ‘09] B. Nazer, A. Sanderovich, M. Gastpar and S. Shamai (Shitz), “Structured superposition for backhaul constrained cellular uplink,” in *Proc. IEEE ISIT ‘09*, Seoul, Korea, Jun. 2009.

[Sanderovich et al ‘09] A. Sanderovich, O. Somekh, H. V. Poor and S. Shamai (Shitz), “Uplink macro diversity of limited backhaul cellular network,” *IEEE Trans. Inf. Theory*, vol. 55, no. 8, pp. 3457-3478, Aug. 2009.

[dCoso-Simoens ‘09] 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.

[Marsch-Fettweis ‘09] P. Marsch and G. Fettweis, “On downlink network MIMO under an constrained backhaul and imperfect channel knowledge,” in *proc. IEEE Globecom ‘09*, Honolulu, Hawaii, Nov. 2009.

[Verdu-Shamai ‘10] S. Verdu and S. Shamai (Shitz), “Variable-rate channel capacity,” *IEEE Trans. Inf. Theory*, vol. 56, no. 6, pp. 2651-2667, Jun. 2010.

References

[Huh et al ‘10] H. Huh, H. C. Papadopoulos and G. Caire, “Multiuser MISO transmitter optimization for intercell interference mitigation,” *IEEE Trans. Signal Process.*, vol. 58, no. 8, pp. 4272-4285, Aug. 2010.

[Irmer et al ’11] R. Irmer, H. Droste, P. Marsch, M. Gastpar, G. Fettweis, S. Brueck, H.-P. Mayer, L. Thiele and V. Jungnickel, “Coordinated multipoint: Concepts, performance, and field trial results,” *IEEE Comm. Mag.*, vol. 49, no. 2, pp. 102-111, Feb. 2011.

[Lim et al ‘11] 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.

[Yassaee-Aref ‘11] M. H. Yassaee and M. R. Aref, “Slepian-Wolf coding over cooperative relay networks,” *IEEE Trans. Inf. Theory*, vol. 57, no. 6, pp. 3462-3482, Jun. 2011.

[Hoydis et al ‘11] 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.

[Hong-Caire ‘11] S.-N. Hong and G. Caire, “Quantized compute and forward: A low-complexity architecture for distributed antenna systems,” in *Proc. IEEE ITW ‘11*, Paraty, Brazil, Oct. 2011.

References

[Beck-Teboulle ‘11] A. Beck and M. Teboulle, “Gradient-based algorithms with applications to signal recovery problems,” in *Convex Optimization in Signal Processing and Communications*, Y. Eldar and D. Palomar, eds., pp. 42-88, Cambridge University Press. 2010.

[Khan et al ‘11] A. Khan, W. Kellerer, K. Kozu, and M. Yabusaki, “Network sharing in the next mobile network: TCO reduction, management flexibility, and operational independence,” IEEE Commun. Mag., vol. 49, no. 10, pp. 134–142, Oct. 2011.

[ElGamal-Kim ‘11] A. E. Gamal and Y.-H. Kim, “Network information theory,” Cambridge University Press, 2011.

[Simeone et al ‘12] O. Simeone, N. Levy, A. Sanderovich, O. Somekh, B. M. Zaidel, H. V. Poor and S. Shamai (Shitz), “Cooperative wireless cellular systems: An information-theoretic view,” *Foundations and Trends in Communications and Information Theory*, vol. 8, nos. 1-2, pp. 1-177, 2012.

[Ng et al ‘12] C. T. K. Ng, C. Tian, A. J. Goldsmith, and S. Shamai (Shitz), “Minimum expected distortion in Gaussian source coding with fading side information,” *IEEE Trans. Inf. Theory*, vol. 58, no. 9, pp. 5725–5739, Sep. 2012

[Wainwright ‘12] M. Wainwright, “Graphical models and message-passing: Some introductory lectures,” tutorial available at www.eecs.berkeley.edu/wainwrig/kyoto12.

References

[Park et al TVT'13] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), "Robust and efficient distributed compression for cloud radio access networks," *IEEE Trans. Veh. Tech.*, vol. 62, no. 2, pp. 692-703, Feb. 2013.

[Park et al SPL'13] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), "Joint decompression and decoding for cloud radio access networks," *IEEE Sig. Processing Letters*, vol. 20, no. 5, pp. 503-506, May 2013.

[Hong-Caire '13] S.-N. Hong and G. Caire, "Compute-and-forward strategy for cooperative distributed antenna systems," *IEEE Trans. Inf. Theory*, vol. 59, no. 9, pp. 5227-5243, Sep. 2013.

[Hong-Caire '13] S.-N. Hong and G. Caire, "Compute-and-forward strategy for cooperative distributed antenna systems," *IEEE Trans. Inf. Theory*, vol. 59, no. 9, pp. 5227-5243, Sep. 2013.

[Karasik et al '13] R. Karasik, O. Simeone and S. S. Shitz, "Robust Uplink Communications over Fading Channels with Variable Backhaul Connectivity," *IEEE Trans. Wireless Commun.*, vol. 12, no. 11, pp. 5788-5799, November 2013.

[Ni et al '13] W. Ni, R. P. Liu, I. B. Collings and X. Wang, "Indoor cooperative small cells over Ethernet," *IEEE Comm. Mag.*, vol. 51, no. 9, pp. 100-107, Sep. 2013.

References

[Zhou-Yu ’13] 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.

[Park et al TSP’13] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Joint precoding and multivariate backhaul compression for the downlink of cloud radio access networks,” *IEEE Trans. Sig. Processing*, vol. 61, no. 22, pp. 5646-5658, Nov. 2013.

[Karasik et al ’13] R. Karasik, O. Simeone and S. Shamai (Shitz), “Robust uplink communications over fading channels with variable backhaul connectivity,” *IEEE Trans. Wireless Comm.*, vol. 12, no. 11, pp. 5788-5799, Nov. 2013.

[Pedarsani et al ’13] R. Pedarsani, M. A. Maddah-Ali and U. Niesen, “Online coded caching,” arXiv:1311.3646, Nov. 2013.

[Liao et al ‘13] W.-C. Liao, M. Hong, H. Farmanbar, X. Li, Z.-Q. Luo and H. Zhang, “Min flow rate maximization for software defined radio access networks,” arXiv:1312.5345, Dec. 2013.

[Golrezaei et al ’13] N. Golrezaei, K. Shanmugam, A. G. Dimakis, A. F. Molisch and G. Caire, “Femtocaching: Wireless video content delivery through distributed caching helpers,” *IEEE Trans. Inf. Theory*, vol. 59, no. 12, pp. 8402-8413, Dec. 2013.

References

[Park et al ’14] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Robust layered transmission and compression for distributed uplink reception in cloud radio access networks,” *IEEE Trans. Veh. Technol.*, vol. 63, no. 1, pp. 204-216, Jan. 2014.

[Patil-Yu ‘14] P. Patil and W. Yu, “Hybrid compression and message-sharing strategy for the downlink cloud radio-access network,” in *Proc. Inf. Theory and Application Workshop (ITA) 2014*, San Diego, CA, Feb. 2014.

[Kang et al TWC‘14] J. Kang, O. Simeone, J. Kang and S. Shamai (Shitz), “Joint signal and channel state information compression for the backhaul of uplink network MIMO systems,” *IEEE Trans. Wireless Comm.*, vol. 13, no. 3, pp. 1555-1567, Mar. 2014.

[Park et al CISS‘14] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Performance evaluation of multiterminal backhaul compression for cloud radio access networks,” in *Proc. IEEE CISS ‘14*, Princeton, NJ, Mar. 2014.

[Rost et al ‘14] P. Rost, C. J. Bernardos, A. D. Domenico, M. D. Girolamo, M. Lalam, A. Maeder, D. Sabella and D. Wubben, “Cloud technologies for flexible 5G radio access networks,” *IEEE Comm. Mag.*, vol. 52, no. 5, pp. 68-76, May 2014.

[MAli-Niesen ‘14] M. A. Maddah-Ali and U. Niesen, “Fundamental limits of caching,” *IEEE Trans. Inf. Theory*, vol. 60, no. 5, pp. 2856-2867, May 2014.

References

[Dhillon-Caire ‘14] H. S. Dhillon and G. Caire, “Wireless backhaul networks: capacity bound, scalability analysis and design guidelines,” arXiv:1406.2738, Jun. 2014

[Liu-Kang ‘14] N. Liu and W. Kang, “A new achievability scheme for downlink multicell processing with finite backhaul capacity,” in *Proc. IEEE ISIT ‘14*, Honolulu, Hawaii, Jul. 2014.

[He-Nazer-Shamai ‘14] W. He, B. Nazer and S. Shamai (Shitz), “Uplink-downlink duality for integer-forcing,” in *Proc. IEEE ISIT ‘14*, Honolulu, Hawaii, Jul. 2014.

[Park et al TVT‘15] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Multihop backhaul compression for the uplink of cloud radio access networks,” to appear in *IEEE Trans. Veh. Technol.*, 2015.

[Park et al WCL‘14] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Inter-cluster design of precoding and fronthaul compression for cloud radio access networks,” *IEEE Wireless Comm. Ltters*, vol. 3, no. 4, pp. 369-372, Aug. 2014.

[Andrews et al JSAC‘14] 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.

References

[Park et al SPM‘14] S.-H. Park, O. Simeone, O. Sahin and S. Shamai (Shitz), “Fronthaul compression for cloud radio access networks,” *IEEE Sig. Processing Mag.*, vol. 31, no. 6, pp. 69-79, Nov. 2014.

[Katz-Zaidel-Shamai ‘14] G. Katz, B. M. Zaidel and S. Shamai (Shitz), “On layered strategies for cooperative processing in clustered cellular architectures,” submitted to *IEEE Trans. Veh. Tech.*

[Jain-Kim-Giannakis ‘14] S. Jain, S.-J. Kim and G. B. Giannakis, “Backhaul-constrained multi-cell cooperation leveraging sparsity and spectral clustering,” arXiv:1409.8359, Sep. 2014.

[Kang et al TVT‘16] J. Kang, O. Simeone, J. Kang and S. Shamai (Shitz), “Fronthaul compression and precoding design for C-RANs over Ergodic fading channels,” IEEE Trans. Veh. Technol., vol. 65, no. 7, pp. 5022-5032, Jul. 2016.

[MPeng et al WC‘15] M. Peng, C. Wang, V. Lau and H. V. Poor, “Fronthaul-constrained cloud radio access networks: insight and challenges,” *IEEE Wireless Comm.*, vol. 22, no. 2, pp. 152-160, Apr. 2015.

[MPeng et al arXiv‘15] M. Peng, S. Yan, K. Zhang and C. Wang, “Fog computing based radio access networks: Issues and challenges,” arXiv:1506.04233, Jun. 2015.

References

[MAli-Niesen ‘15] M. A. Maddah-Ali and U. Niesen, “Decentralized coded caching attains order-optimal memory-rate tradeoff,” *IEEE/ACM Trans. Networking*, vol. 23, no. 4, pp. 1029-1040, Aug. 2015.

[Lundqvist, CTN-Sep. 2015] H. Lundqvist, Senior Research, Huawei Sweden, “Death by starvation?: backhaul and 5G,” *IEEE ComSoc Technology News*, CTN Issue: Sep. 2015.

[XPeng et al ‘15] X. Peng, J.-C. Shen, J. Zhang and K. B. Letaief, “Backhaul-aware caching placement for wireless networks,” arXiv:1509.00558, Sep. 2015.

[Hong-Caire ‘15] S.-N. Hong and G. Caire, “Beyond scaling laws: On the rate performance of dense device-to-device wireless networks,” *IEEE Trans. Inf. Theory*, vol. 61, no. 9, pp. 4735-4750, Sep. 2015.

[Bi et al ‘15] S. Bi, R. Zhang, Z. Ding and S. Cui, “Wireless communications in the era of big data,” arXiv:1508.06369, Aug. 2016.

[China ‘15] China Mobile, “Next generation fronthaul interface,” White Paper, Oct. 2015.

[Ugur et al ‘15] Y. Ugur, Z. H. Awan and A. Sezgin, “Cloud radio access networks with coded caching,” arXiv:1512.02385, Dec. 2015.

References

[Tao et al ‘15] M. Tao, E. Chen, H. Zhou and W. Yu, “Content-centric sparse multicast beamforming for cache-enabled cloud RAN,” arXiv:1512.06938, Dec. 2015.

[Tandon-Simeone ‘16] R. Tandon and O. Simeone, “Fog radio access networks: Fundamental latency trade-offs,” in *Proc. IEEE Inf. Theory and Applications Workshop (ITA) 2016*, La Jolla, CA, Jan. 2016.

[Dai-Yu ‘16] B. Dai and W. Yu, “Energy efficiency of downlink transmission strategies for cloud radio access networks,” arXiv:1601.01070, Jan. 2016.

[Chen et al ‘16] Z. Chen, J. Lee, T. Q. S. Kountouris, “Cooperative caching and transmission design in cluster-centric small cell networks,” arXiv:1601.00321, Jan. 2016.

[Naderializadeh et al ‘16] N. Naderializadeh, M. A. Maddah-Ali and A. S. Avestimehr, “Fundamental limits of cache-aided interference management,” arXiv:1602.04207, Feb. 2016.

[Cisco ‘16] Cisco, “Cisco visual networking index: Global mobile data traffic forecast update, 2015-2020,” White paper, Feb. 2016.

[Wang et al ‘16] R. Wang, J. Zhang and K. B. Letaief, “Mobility-aware caching for content-centric wireless networks: Modeling and methodology,” arXiv:1605.03709, May 2016.

References

[Dhifallah et al ‘16] O. Dhifallah, H. Dahrouj, T. Y. Al-Naffouri and M.-S. Alouini, “Robust beamforming in cache-enabled cloud radio access networks,” arXiv:1605.09321, May 2016.

[Liu-Patil-Yu ‘16] L. Liu, P. Patil and W. Yu, “An uplink-downlink duality for cloud radio access network,” in *Proc. IEEE Intern. Symp. Inf. Theory (ISIT) 2016*, Barcelona, Spain, Jul. 2016.

[Park-Simeone-Shamai SPAWC‘16] S.-H. Park, O. Simeone and S. Shamai (Shitz), “Joint cloud and edge processing for latency minimization in fog radio access networks,” in *Proc. IEEE SPAWC 2016*, Edingburgh, UK, Jul. 2016.

[Agiwal et al ‘16] M. Agiwal, A. Roy and N. Saxena, “Next generation 5G wireless networks: A comprehensive survey," *IEEE Comm. Surveys & Tutorials*, vol. 18, no. 3, 3rd quart., pp. 1617-1655, 2016.

[Yang et al ‘16] T. Yang, N. Liu, W. Kang and S. Shamai, “An upper bound on the sum capacity of the downlink multicell processing with finite backhaul capacity,” arXiv:1609.00833, Sep. 2016.

[Park-Simeone-Shamai TWC‘16] S.-H. Park, O. Simeone and S. Shamai (Shitz), “Joint optimization of cloud and edge processing for fog radio access networks,” IEEE Trans. Wireless Comm., vol. 15, no. 11, pp. 7621-7632, Nov. 2016.

References

[Boccardi et al ‘16] F. Boccardi et al., “Spectrum pooling in mmWave networks: Opportunities, challenges, and enablers,” *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 33–39, Nov. 2016.

[Aguerri et al ‘17] 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 ‘17] X. Wu, L. P. Barnes and A. Ozgur, “The capacity of the relay channel,” arXiv:1701.02043, Jan. 2017.

[Shamai et al ITA ‘17] S.-H. Park, O. Simeone and S. Shamai (Shitz), “Sum-rates for Wyner-type C-RAN uplink with inter-connected oblivious radio units,” in *Proc. Inf. Theory and Application Workshop (ITA) 2017*, San Diego, CA, Feb. 2017.

[Bidokhti et al ‘17] S. S. Bidokheti, G. Kramer and S. Shamai (Shitz), “Capacity bounds on the downlink of symmetric, multi-relay, single receiver C-RAN networks,” arXiv:1702.01828, Feb. 2017.

[Hamidouche et al ‘17] K. Hamidouche, W. Saad, M. Debbah, J. B. Song and C. S. Hong, “The 5G cellular backhaul management dilemma: To cache or to serve,” arXiv:1705.01207, May 2017.

References

[Park et al TVT‘18] S.-H. Park, O. Simeone and S. Shamai (Shitz), "Multi-tenant C-RAN with spectrum pooling: Downlink optimization under privacy constraints," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 10492-10503, Nov. 2018

[Zeide et al ICSEE‘18] M. Zeide, O. Simeone and S. Shamai (Shitz), “Confidential communication in C-RAN systems with infrastructure sharing,” in *Proc. IEEE ICSEE 2018*, Eliat, Israel, Dec. 2018.

[Park et al Entropy‘19] S.-H. Park, O. Simeone and S. Shamai (Shitz), “Robust baseband compression against congestion in packet-based fronthaul networks using multiple description coding,” *Entropy*, vol. 21, no. , pp. 1-15, Apr. 2019.

Abstract

Wireless Networks via the Cloud: An Information Theoretic View

Cloud based wireless networks referred also as Cloud Radio Access Networks (C-RANs) emerge as appealing architectures for next-generation wireless/cellular systems whereby the processing/decoding is migrated from the local base-stations/radio units (RUs) to a control/central units (CU) in the "cloud". The network operates via fronthaul digital links connecting the CU and the RUs (operating as relays). In this talk, we will address basic information theoretic aspects of such networks, with emphasis of simple oblivious processing at the RUs, which is attractive from the practical point of view. The uplink and downlink are examined from a network information theoretic perspective. The analytic approach, as applied to simple wireless/cellular models illustrates the considerable performance gains to be expected by advanced network information theoretically inspired techniques, carrying also practical implications. An outlook, pointing out interesting theoretical directions, referring also to Fog radio access networks (F-RAN), concludes the presentation.

The overview is based on joint studies with I.E. Augerri, G. Caire, S.-H. Park, O. Sahin, O. Simeone and , A. Zaidi.

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