Cloud Radio-Access Networks: Capacity, Coding Strategies, and Optimization

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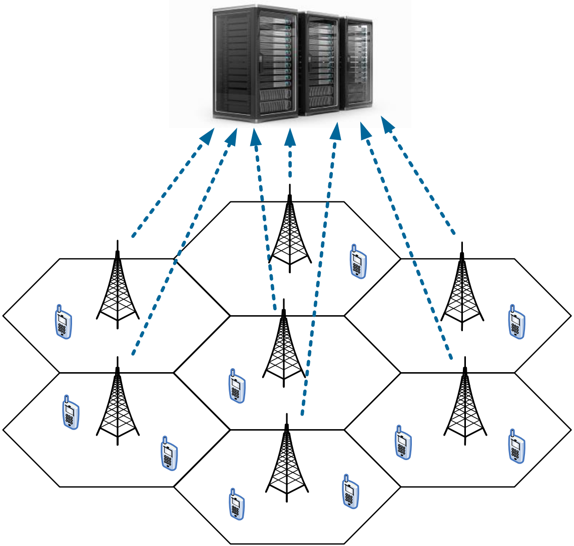
Virtualization of Wireless Access for 5G

- Future 5G wireless cellular network:
  - Requirements: Gbps capacity, 1ms latency, 10^5 connectivity
  - Bottleneck: Path-loss, fading, and interference
- Emerging trends:
  - Dense
    - Heterogeneous network; Small cell
  - Massive
    - Massive MIMO at each BS
  - Cooperative
    - Signal processing for interference cancellation
- This talk: Capacity and optimization of cooperative networks.

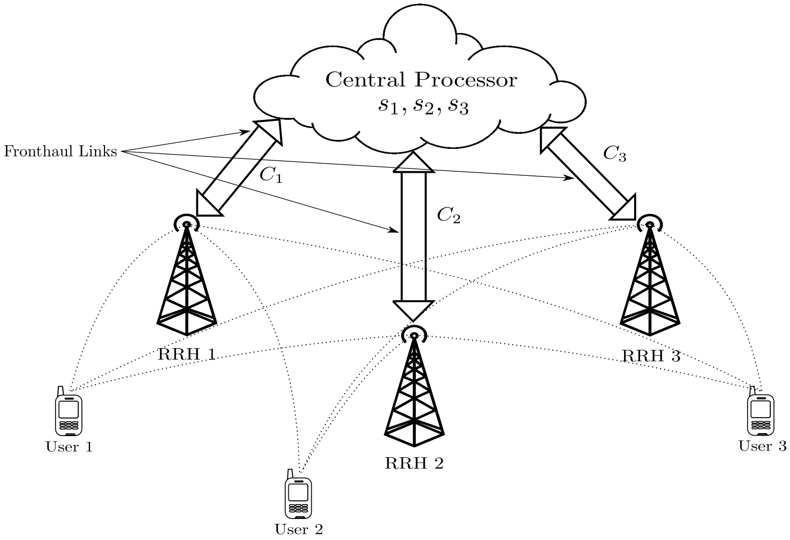
Cooperating BSs in the Cloud



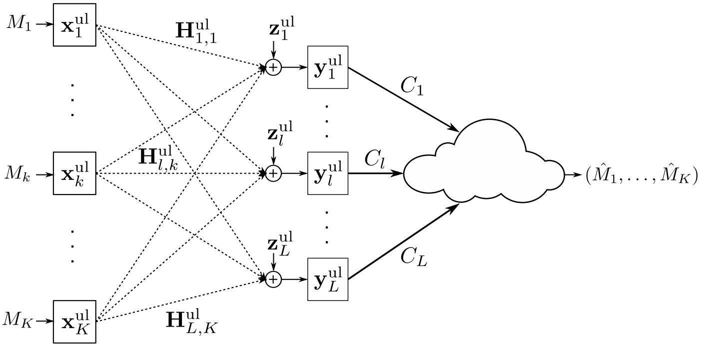
Cloud Radio-Access Network (C-RAN)

- Benefits of C-RAN:
  - ◇ Allows a cost-effective way to deploy and upgrade wireless platform;
  - ◇ Opens up new possibilities for the optimization of air-interface;
  - ◇ Enables cooperative communication for interference mitigation;
  - ◇ Provides an implementation of coordinated multi-point (CoMP).
- This talk: Information theoretical analysis of C-RAN
  - ◇ Multicell Joint Processing for Uplink C-RAN
  - ◇ Multicell Beamforming for Downlink C-RAN

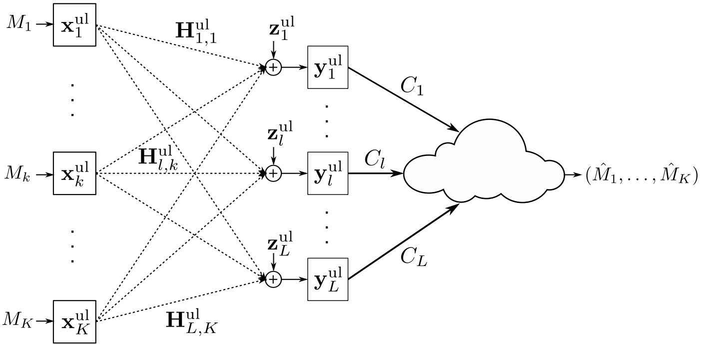
Wireless Access via the Cloud



Uplink Multicell Joint Processing



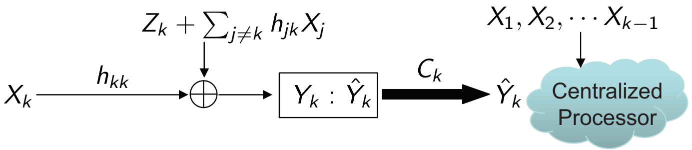
- $X_1, X_2, \ldots, X_K$ are user terminals; $Y_1, Y_2, \ldots, Y_L$ are RRHs.
- Practical constraint: Fronthaul capacity limited to C_l.
- Goal: To maximize the overall capacities for all users.



- What should each RRH do? Local detection vs. compression...
- What should the cloud do? Successive vs. joint decoding...
- How should we design transmit signaling?

Successive Interference Cancellation in the Cloud

Equivalent channel of user k in the k^{th} decoding stage:



- The quantized observation at RRH k is sent to the centralized processor via the fronthaul link of rate C_k.
- Previously decoded X_1 to X_{k-1} serve as side information for Wyner-Ziv compression and for decoding of X_k, achieving:

$$R_k = \frac{1}{2} \log \frac{1 + \overline{\mathsf{SINR}}_k}{1 + 2^{-2C_k} \overline{\mathsf{SINR}}_k}$$

where $\overline{\mathsf{SINR}}_k = (h_{kk}^2 P_k)/(N_0 + \sum_{j>k} h_{jk}^2 P_j)$

- Per-RRH decoding with SIC:

$$R_k = I(X_k; \hat{Y}_k | X_1, \cdots, X_{k-1})$$

subject to $I(Y_k; \hat{Y}_k | X_1, \cdots, X_{k-1}) \leq C_k$.

- Joint-RRH decoding can do better:

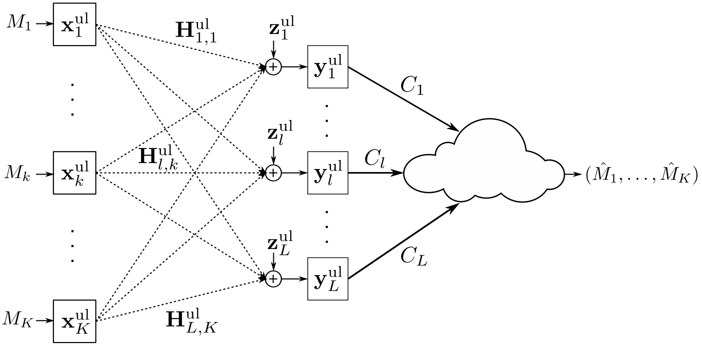
$$R_k = I(X_k; \hat{Y}_1, \cdots, \hat{Y}_L | X_1, \cdots, X_{k-1}),$$

subject to $I(Y_k; \hat{Y}_k | \hat{Y}_1, \cdots, \hat{Y}_{k-1}) \leq C_k$.

Uplink C-RAN as a Multiple-Access Relay Channel

- Each RRH compresses Y_i into $\hat{Y}_i$
  - Compression can be done with Wyner-Ziv or single-user coding.
- The cloud decodes the quantized received signals $\{\hat{Y}_1, \cdots, \hat{Y}_L\}$, then the transmit messages $X_1, X_2, \ldots, X_K$, successively or jointly.
- Information theoretical justification:
  - Joint decoding proposed by Sanderovich-Somekh-Poor-Shamai ('09) and Sanderovich-Shamai-Steinberg-Kramer ('08)
  - Avestimehr-Diggavi-Tse ('09): "Wireless Network Info Flow"
  - Lim-Kim-El Gamal-Chung ('11): "Noisy Network Coding"

Optimality of Gaussian Signaling and Quantization



- Fact: Assuming Gaussian quantization, optimal input is Gaussian.
- Theorem: Assuming Gaussian input, optimal quantizer is Gaussian.
- However, joint Gaussian signal/quantization may not be optimal
  - Binary counterexample: Sanderovich-Shamai-Steinberg-Kramer'08

Uplink C-RAN as Virtual Multiple-Access Channel

Theorem (Achievable rate region)

Achievable rate under sum fronthaul constraint C:

$$\sum_{i \in S} R_i \leq \log \frac{\left|\mathrm{H}_S K_{X(S)} \mathrm{H}_S^H + \Lambda_q + \sigma^2 I\right|}{|\Lambda_q + \sigma^2 I|}$$

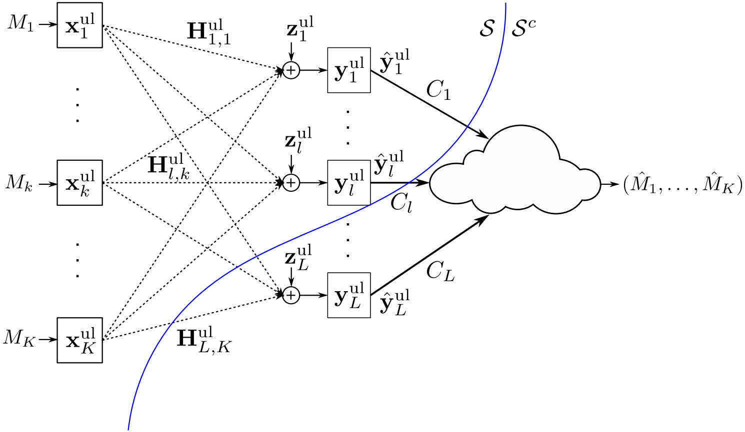
either subject to (for Wyner-Ziv coding, V-MAC-WZ):

$$\log \frac{\left|\mathrm{H} K_X \mathrm{H}^H + \Lambda_q + \sigma^2 I\right|}{|\Lambda_q|} \leq C$$

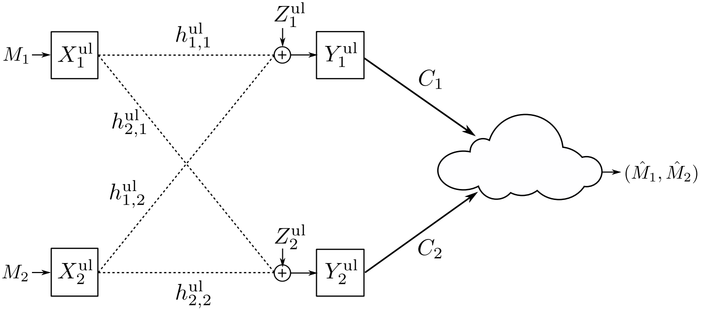
or subject to (for single-user compression, V-MAC-SU):

$$\log \frac{\left|diag(\mathrm{H} K_X \mathrm{H}^H) + \Lambda_q + \sigma^2 I\right|}{|\Lambda_q|} \leq C$$

where $\Lambda_q = \mathrm{diag}(q_1, q_2, \ldots, q_L)$ is the quantization noise level.



- Cut-set Bound: $R(\mathcal{S}) = \sum_{k \in \mathcal{S}} R_k \leq I(\mathrm{x}^{\mathrm{ul}}(\mathcal{S}); \mathrm{y}^{\mathrm{ul}}(\mathcal{S}^c) | \mathrm{x}^{\mathrm{ul}}(\mathcal{S}^c))$
- Achievable rate using noisy network coding: $R(\mathcal{S}) \leq$ $I(\mathrm{x}^{\mathrm{ul}}(\mathcal{S}); \hat{\mathrm{y}}^{\mathrm{ul}}(\mathcal{S}^c), \mathrm{y}_d^{\mathrm{ul}} | \mathrm{x}^{\mathrm{ul}}(\mathcal{S}^c)) - I(\mathrm{y}^{\mathrm{ul}}(\mathcal{S}); \hat{\mathrm{y}}^{\mathrm{ul}}(\mathcal{S}) | \mathrm{x}_{\mathrm{ul}}^N, \hat{\mathrm{y}}^{\mathrm{ul}}(\mathcal{S}^c), \mathrm{y}_d^{\mathrm{ul}})$
- Set quantization noise at background noise level: $\hat{\mathrm{y}}_k^{\mathrm{ul}} \approx \mathrm{y}_k^{\mathrm{ul}}$.



Successive-decoding region for MAC

$$R_1 < I(X_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_2^{\mathrm{ul}});$$
$$R_2 < I(X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_1^{\mathrm{ul}});$$
$$R_1 + R_2 < I(X_1^{\mathrm{ul}}, X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}})$$

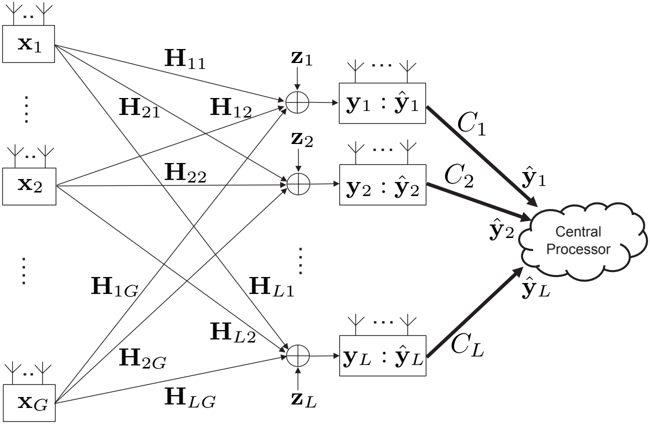
Wyner-Ziv Compression

$$C_1 > I(Y_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}} | \hat{Y}_2^{\mathrm{ul}});$$
$$C_2 > I(Y_2^{\mathrm{ul}}; \hat{Y}_2^{\mathrm{ul}} | \hat{Y}_1^{\mathrm{ul}});$$
$$C_1 + C_2 > I(Y_1^{\mathrm{ul}}, Y_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}})$$

Comparing with Noisy Network Coding

$$
\begin{aligned}
R_1 &< I(X_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_2^{\mathrm{ul}}); \\
R_1 &< I(X_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_2^{\mathrm{ul}}) + C_1 - I(Y_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}} | \hat{Y}_2^{\mathrm{ul}}, X_2^{\mathrm{ul}}); \\
R_1 &< I(X_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_2^{\mathrm{ul}}) + C_2 - I(Y_2^{\mathrm{ul}}; \hat{Y}_2^{\mathrm{ul}} | \hat{Y}_1^{\mathrm{ul}}, X_2^{\mathrm{ul}}); \\
R_1 &< I(X_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_2^{\mathrm{ul}}) + C_1 + C_2 - I(Y_1^{\mathrm{ul}}, Y_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_2^{\mathrm{ul}}); \\
R_2 &< I(X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_1^{\mathrm{ul}}); \\
R_2 &< I(X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_1^{\mathrm{ul}}) + C_1 - I(Y_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}} | \hat{Y}_2^{\mathrm{ul}}, X_1^{\mathrm{ul}}); \\
R_2 &< I(X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_1^{\mathrm{ul}}) + C_2 - I(Y_2^{\mathrm{ul}}; \hat{Y}_2^{\mathrm{ul}} | \hat{Y}_1^{\mathrm{ul}}, X_1^{\mathrm{ul}}); \\
R_2 &< I(X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_1^{\mathrm{ul}}) + C_1 + C_2 - I(Y_1^{\mathrm{ul}}, Y_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}} | X_1^{\mathrm{ul}}); \\
R_1 + R_2 &< I(X_1^{\mathrm{ul}}, X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}}); \\
R_1 + R_2 &< I(X_1^{\mathrm{ul}}, X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}}) + C_1 - I(Y_1^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}} | \hat{Y}_2^{\mathrm{ul}}); \\
R_1 + R_2 &< I(X_1^{\mathrm{ul}}, X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}}) + C_2 - I(Y_2^{\mathrm{ul}}; \hat{Y}_2^{\mathrm{ul}} | \hat{Y}_1^{\mathrm{ul}}); \\
R_1 + R_2 &< I(X_1^{\mathrm{ul}}, X_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}}) + C_1 + C_2 - I(Y_1^{\mathrm{ul}}, Y_2^{\mathrm{ul}}; \hat{Y}_1^{\mathrm{ul}}, \hat{Y}_2^{\mathrm{ul}})
\end{aligned}
$$

Uplink C-RAN with Multiple Antennas



- Uniform quantization noise level is optimal only at high SQNR.
- In general: Jointly optimize transmit and quantization covariances.
- Solution: Successive convex approximation with WMMSE.
- WMMSE-SCA: Optimal Tx/Rx beamforming then compression.

Simulation Result: V-MAC-WZ

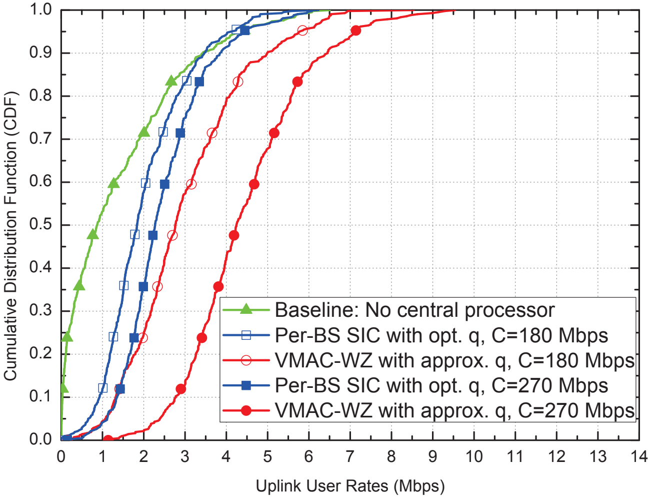


Figure: CDF of user rates in a 7-cell cluster: VMAC-WZ vs. Per-BS SIC.

Simulation Result: Sum-Rate vs Backhaul

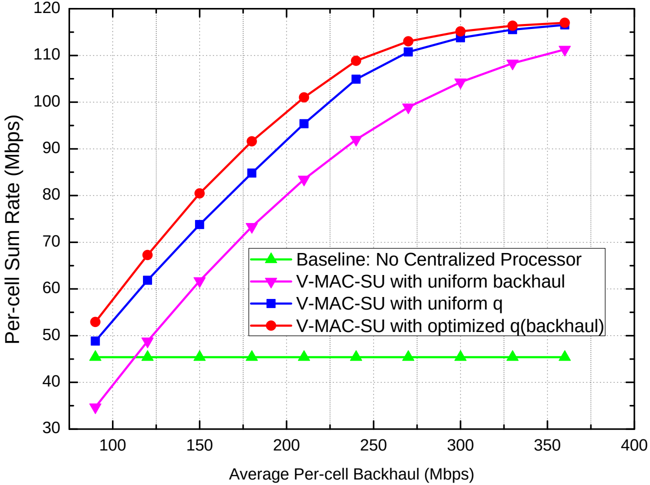


Figure: Per-cell sum rate vs. average per-cell fronthaul capacity.

Benefit of Beamform-Compress-Forward

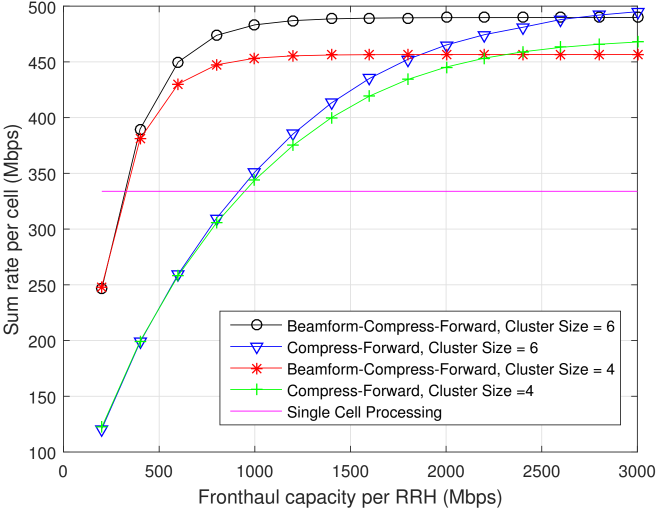
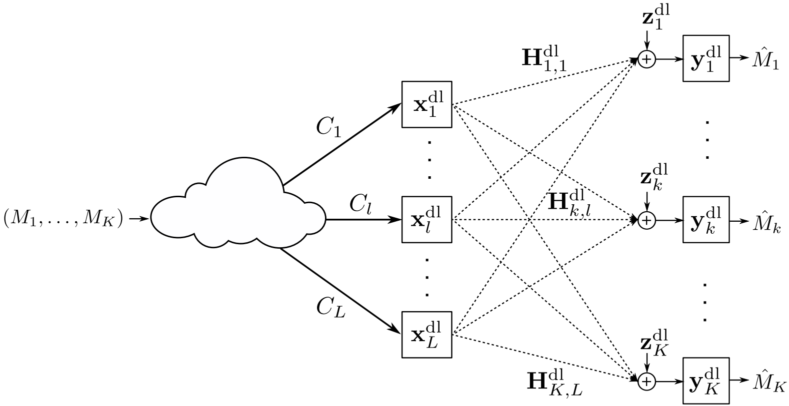


Figure: 12-antenna RRH serving 2 users: Compress vs. Beamform-Compress.

Downlink C-RAN as a Broadcast Relay Channel

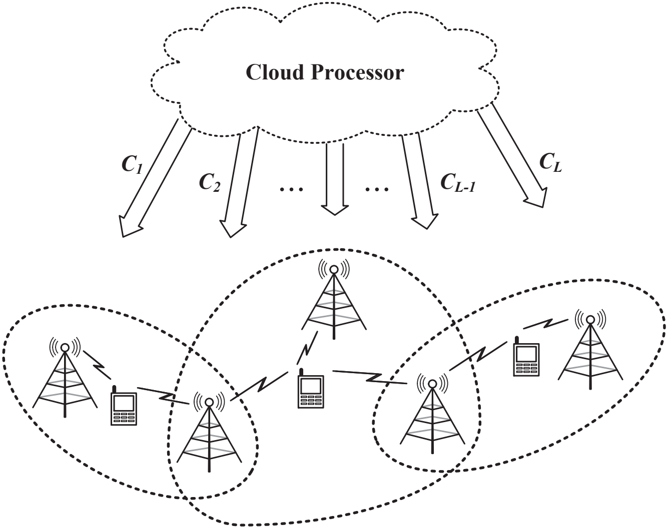


- How to enable cooperation across clusters of RRHs?
  - Message-sharing with a cluster of RRHs for joint beamforming.
  - Precode at the cloud. Compress-forward precoded signals to RRHs.
    - Multivariate compression [Park-Simeone-Sahin-Shamai '13].

Data-Sharing vs. Compression

- Two fundamental coding strategies for downlink C-RAN:
  - *Data-Sharing*: CP distributes each user's data to a cluster of RRHs. Each RRH has access to multiple data streams then precode.
  - *Compression*: CP computes the beamformer, then compresses and distributes the precoded signal to the RRHs.
- How to best utilize the limited fronthaul?
  - In Data-Sharing, limit the cluster size;
  - In Compression, control quantization level.

Optimizing Clustering in Message-Sharing



"Personalized" cloud

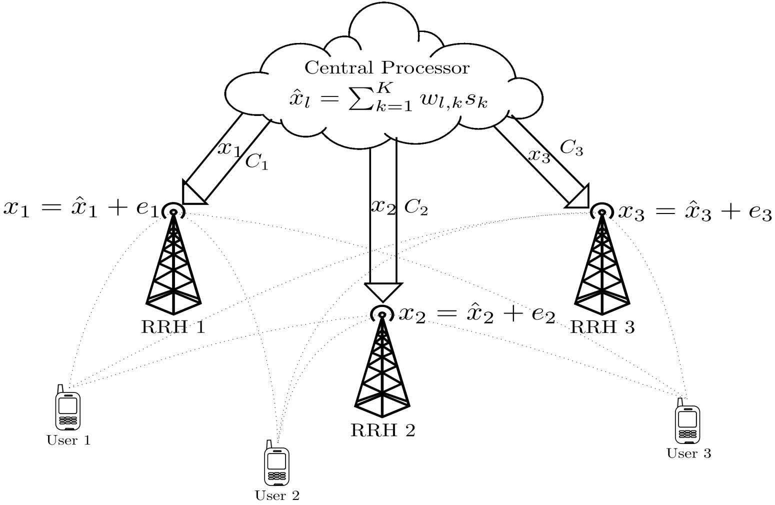
Sparse Beamforming for the Downlink C-RAN

- Weighted sum-rate maximization under per-RRH power constraints and per-RRH fronthaul constraints assuming single-stream per user:

$$
\begin{aligned}
\text{maximize} \quad & \sum_k \alpha_k R_k \\
\text{subject to} \quad & \sum_k \|\mathbf{w}_k^l\|_2^2 \le P_l, \ \forall l \\
& \sum_k \left\| \|\mathbf{w}_k^l\|_2^2 \right\|_0 R_k \le C_l, \ \forall l
\end{aligned}
$$

- Use ℓ_1 re-weighting and compressed sensing [Candès-Wakin-Boyd'08]
- The WMMSE approach can be used to find a local optimum. [Christensen-Agarwal-Carvalho-Cioffi '08], [Shi-Razaviyayn-Luo-He '11], [Kaviani-Simeone-Krzymien-Shamai '12]
- Related work: Zhao-Quek-Lei ('13), Luo-Zhang-Lim ('14), Zhuang-Lau ('14),

Better Strategy: Compression for Multicell Beamforming



- Full cooperation possible, but compression introduces quantization noises.
- Optimizing by majorization-minimization: [Park-Simeone-Sahin-Shamai '13]

Compression Strategy

- Precoded signals intended for RRHs formed at central processor:

$$\hat{\mathrm{x}} = [\hat{x}_1, \cdots, \hat{x}_L]^T = \sum_{k=1}^{K} \mathrm{w}_k s_k$$

- Quantization for $\hat{\mathrm{x}}$ modeled as $\mathrm{x} = \hat{\mathrm{x}} + \mathrm{e}$, where e is the quantization noise with covariance Q, independent of $\hat{\mathrm{x}}$.
- Achievable rate for user k is

$$R_k = \log \left(1 + \frac{|\mathrm{h}_k^H \mathrm{w}_k|^2}{\sum_{j \neq k} |\mathrm{h}_k^H \mathrm{w}_j|^2 + \sigma^2 + |\mathrm{h}_k^H \mathrm{Q} \mathrm{h}_k|} \right)$$

- The fronthaul capacity constraint must satisfy

$$\log \left(1 + \frac{\sum_{k=1}^{K} |w_{l,k}|^2}{q_l} \right) \leq C_l$$

Here, Q is assumed diagonal; multivariate Q also possible.

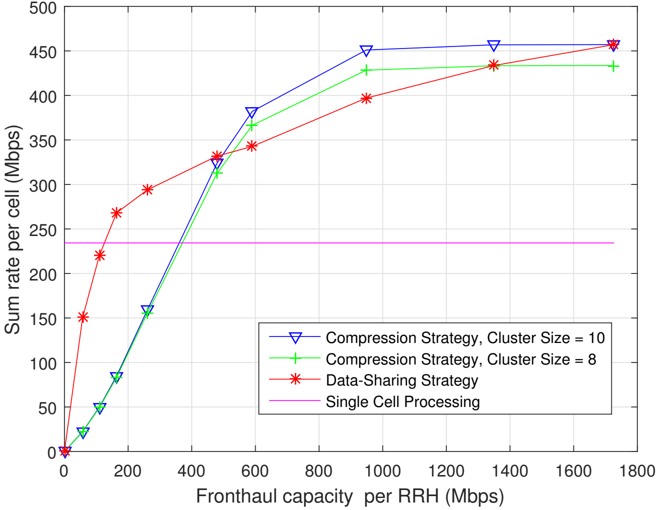
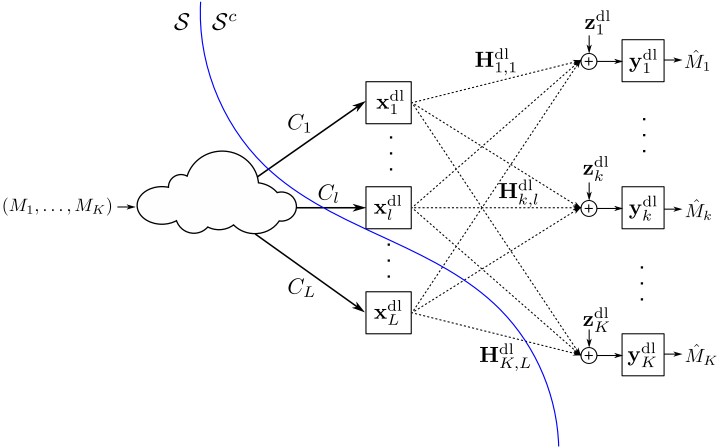
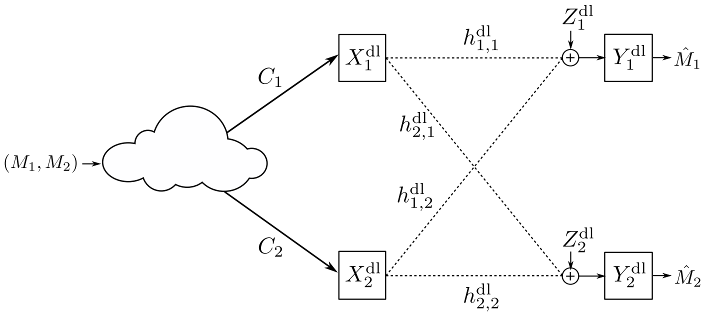


Figure: 4-antenna RRH with Independent Compression.



- Cut-Set: $R(\mathcal{S}) \leq I(\mathsf{x}^{\mathrm{dl}}(\mathcal{S}); \mathsf{y}^{\mathrm{dl}}(\mathcal{S}^c) | \mathsf{x}^{\mathrm{dl}}(\mathcal{S}^c))$
- Distributed Decode-Forward: $R(\mathcal{S}) \leq I(\mathsf{x}^{\mathrm{dl}}(\mathcal{S}); \mathsf{u}(\mathcal{S}^c) | \mathsf{x}^{\mathrm{ul}}(\mathcal{S}^c))$
  $-\sum_{k\in\mathcal{S}^c}[I(\mathsf{u}_k^{\mathrm{dl}}; \mathsf{u}(\mathcal{S}_k^c), \mathsf{x}_{\mathrm{dl}}^N | \mathsf{x}_k^{\mathrm{dl}}, \mathsf{y}_k^{\mathrm{dl}}) + I(\mathsf{x}_k^{\mathrm{dl}}; \mathsf{x}^{\mathrm{dl}}(\mathcal{S}_k^c))]$
- To achieve constant gap: Choose u_k close to $\mathsf{y}_k^{\mathrm{dl}}$.

Approximate Optimality of Compression-like Strategy



Marton's Region for Broadcast

$$
\begin{aligned}
R_1 &< I(U_1; Y_1^{\mathrm{dl}}) \\
R_2 &< I(U_2; Y_2^{\mathrm{dl}}) \\
R_1 + R_2 &< I(U_1; Y_1^{\mathrm{dl}}) + I(U_2; Y_2^{\mathrm{dl}}) \\
&\quad - I(U_1; U_2);
\end{aligned}
$$

Correlated Compression

$$
\begin{aligned}
C_1 &> I(X_1^{\mathrm{dl}}; U_1, U_2); \\
C_2 &> I(X_2^{\mathrm{dl}}; U_1, U_2); \\
C_1 + C_2 &> I(X_1^{\mathrm{dl}}, X_2^{\mathrm{dl}}; U_1, U_2) \\
&\quad + I(X_1^{\mathrm{dl}}; X_2^{\mathrm{dl}})
\end{aligned}
$$

$$
\begin{aligned}
R_1 &< I(U_1, Y_1^{\mathrm{dl}}); \\
R_1 &< I(U_1, Y_1^{\mathrm{dl}}) + C_1 - I(U_1; X_1^{\mathrm{dl}}); \\
R_1 &< I(U_1, Y_1^{\mathrm{dl}}) + C_2 - I(U_1; X_2^{\mathrm{dl}}); \\
R_1 &< I(U_1, Y_1^{\mathrm{dl}}) + C_1 + C_2 - I(U_1; X_1^{\mathrm{dl}}, X_2^{\mathrm{dl}}); \\
R_2 &< I(U_2, Y_2^{\mathrm{dl}}); \\
R_2 &< I(U_2, Y_2^{\mathrm{dl}}) + C_1 - I(U_2; X_1^{\mathrm{dl}}); \\
R_2 &< I(U_2, Y_2^{\mathrm{dl}}) + C_2 - I(U_2; X_2^{\mathrm{dl}}); \\
R_2 &< I(U_2, Y_2^{\mathrm{dl}}) + C_1 + C_2 - I(U_2; X_1^{\mathrm{dl}}, X_2^{\mathrm{dl}}); \\
R_1 + R_2 &< I(U_1, Y_1^{\mathrm{dl}}) + I(U_2, Y_2^{\mathrm{dl}}) - I(U_1; U_2); \\
R_1 + R_2 &< I(U_1, Y_1^{\mathrm{dl}}) + I(U_2, Y_2^{\mathrm{dl}}) - I(U_1; U_2) + C_1 - I(U_1, U_2; X_1^{\mathrm{dl}}); \\
R_1 + R_2 &< I(U_1, Y_1^{\mathrm{dl}}) + I(U_2, Y_2^{\mathrm{dl}}) - I(U_1; U_2) + C_2 - I(U_1, U_2; X_2^{\mathrm{dl}}); \\
R_1 + R_2 &< I(U_1, Y_1^{\mathrm{dl}}) + I(U_2, Y_2^{\mathrm{dl}}) - I(U_1; U_2) + C_1 + C_2 - I(U_1, U_2; X_1^{\mathrm{dl}}, X_2^{\mathrm{dl}}) \\
&\qquad - I(X_1^{\mathrm{dl}}; X_2^{\mathrm{dl}})
\end{aligned}
$$

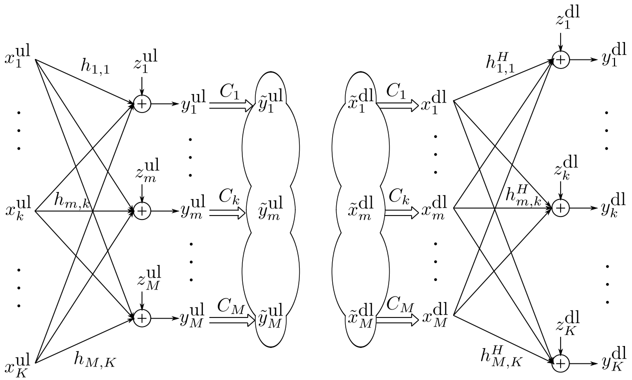
Uplink versus Downlink C-RAN

Uplink

- Multiple-access-relay channel
- Simple encoders, complex cloud decoder
- Compress-forward with independent or Wyner-Ziv compression
- Noisy network coding within constant gap

Downlink

- Broadcast-relay channel
- Simple decoders, complex cloud encoder
- Compression strategy with independent or multivariate compression covering
- Distributed decode-forward within constant gap



(a) Uplink (b) Downlink

- Uplink-downlink duality for compression-based beamforming
  - Under same sum-power and individual fronthaul constraints.
  - Achievable rates of the uplink and downlink are the same.
- Generalization of uplink-downlink duality to MAC-BC with relays.

Sum-Power Minimization Using Duality

- Uplink: Fixed-point method

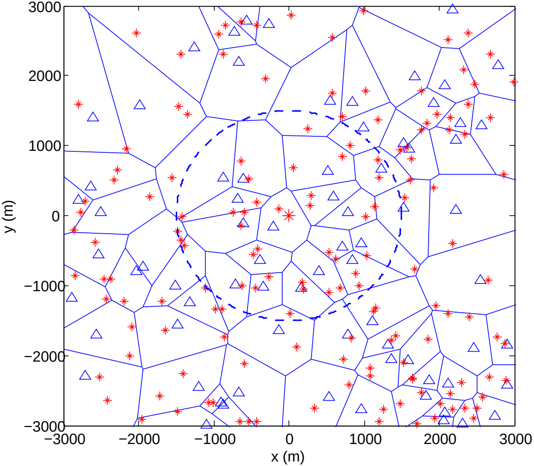
$$\begin{aligned} \underset{\{p_i^{\mathrm{ul}},\mathbf{w}_i\},\{q_l^{\mathrm{ul}}\}}{\text{minimize}} \quad & P^{\mathrm{ul}}(\{p_i^{\mathrm{ul}}\}) \\ \text{subject to} \quad & R_k^{\mathrm{ul}}(\{p_i^{\mathrm{ul}},\mathbf{w}_i\},\{q_l^{\mathrm{ul}}\}) \geq R_k, \quad \forall k, \\ & C_l^{\mathrm{ul}}(\{p_i^{\mathrm{ul}}\},q_l^{\mathrm{ul}}) \leq C_l, \quad \forall l. \end{aligned}$$

- Downlink: Based on uplink solution

$$\begin{aligned} \underset{\{p_i^{\mathrm{dl}},\mathbf{v}_i\},\{q_l^{\mathrm{dl}}\}}{\text{minimize}} \quad & P^{\mathrm{dl}}(\{p_i^{\mathrm{dl}}\},\{q_l^{\mathrm{dl}}\}) \\ \text{subject to} \quad & R_k^{\mathrm{dl}}(\{p_i^{\mathrm{dl}},\mathbf{v}_i\},\{q_l^{\mathrm{dl}}\}) \geq R_k, \quad \forall k, \\ & C_l^{\mathrm{dl}}(\{p_i^{\mathrm{dl}},\mathbf{v}_i\},q_l^{\mathrm{dl}}) \leq C_l, \quad \forall l. \end{aligned}$$

Performance Analysis of C-RAN

- Achievable rates in C-RAN are significantly influenced by:
  - Distances between transmitters and receivers.
  - Random channel fading realizations.
- Stochastic geometry provides analytic tool [Andrews-Baccelli-Ganti'11]



Obtaining signal and interference distributions is the main challenge!

- Model distance-dependent channel characterization:
  $\mathrm{g}_{ilmj} = \sqrt{\beta_{ilmj}}\mathrm{h}_{ilmj}$ with $\mathrm{h}_{ilmj} \sim \mathcal{CN}(0, \mathrm{I}_M)$, $\beta_{ilmj} = \left(1 + \frac{r_{ilmj}}{d_0}\right)^{-\alpha}$
- Approximate signal and interference distributions as Gamma distributions with modified parameters [Heath-Wu-Kwon-Soong'11]

$$\mathrm{g}_{il}^{\mathrm{H}}\mathrm{g}_{il} = \sum_{b=1}^{B_l} \beta_{ilbl}\mathrm{h}_{ilbl}^{\mathrm{H}}\mathrm{h}_{ilbl} \sim \Gamma(k_{il}, \theta_{il})$$

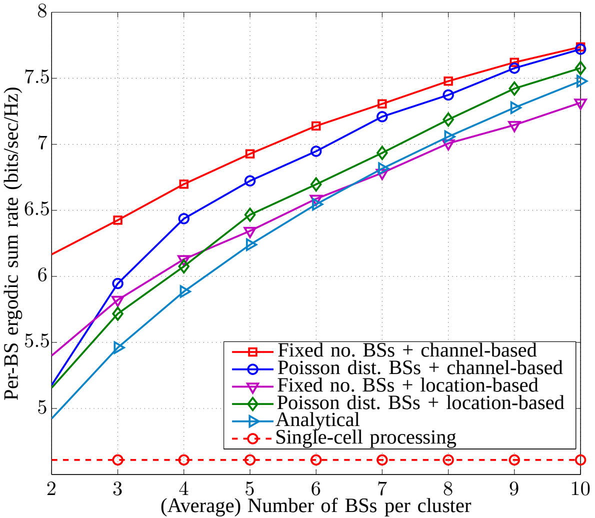
where $k_{il} = M\frac{\left(\sum_{b=1}^{B_l}\beta_{ilbl}\right)^2}{\sum_{b=1}^{B_l}\beta_{ilbl}^2}$, $\theta_{il} = \frac{\sum_{b=1}^{B_l}\beta_{ilbl}^2}{\sum_{b=1}^{B_l}\beta_{ilbl}}$

- Key fact:

$$\ln(1+x) = \int_0^\infty \frac{e^{-z}}{z}(1 - e^{-xz})dz$$

Ergodic rate can be characterized in terms of Laplace transforms!

How Large Should the Cluster Size Be?



Cluster sizes are limited by the fronthaul and by CSI acquisition.

Conclusions

- Cloud radio-access network is an enabling architecture that allows
  - Joint signal processing across the RRHs;
  - Advanced network optimization.
- Network-wide optimization is likely to be done in the cloud.
- Summary of results in this talk:
  - Uplink: Compression with optimized quantization levels.
  - Downlink: Message-sharing and compression are viable strategies.
  - Design: Duality, WMMSE, ℓ_1 reweighting, Succ. Convex Approx.
  - Analysis: Information theory, Optimization, Stochastic geometry.
- Future wireless cellular architecture:
  - Dense, massive, *and* cooperative.

Further Information

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