Energy-efficient resource allocation in C-RANs with temporal and QoS constraints

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Outline

The considered network

- **C-RAN** system with a set $\mathcal{H}$ of **radio remote heads (RRHs)**
- A virtually centralized **baseband unit (BBU)** pool
- Multiple users served through **downlink** communications
- time-slotted communications

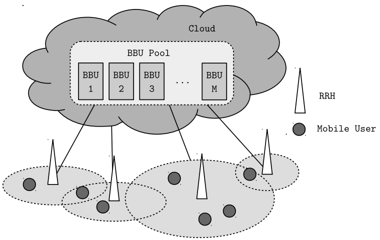

Figure: The considered scenario.

Modeling the RRHs

RRHs:

- equipped with multiple antennas
- transmit on a set $\mathcal{S}$ of available channels
- power constrained
- connected to the BBU pool through high-performance optical fibers
- exploit both Joint Transmission (JT) and Coordinated Multi-Point (CoMP) communications

Modeling the Users

Users:

- equipped with single-antenna transceivers
- receive data on a single channel
- submit service requests with temporal and a minimum QoS requirements
- multiple users can share the same downlink channel

Modeling the BBU pool

BBU pool:

- where signal processing, user scheduling and power control/allocation is performed
- (theoretically) limited computational capabilities

The considered problem

Our goal

To find an optimal **joint user scheduling and power control policy** that meets all users' **requirements** and satisfies system's **constraints** within a given **finite horizon** T

Problem Formulation

- Let $\mathcal{R}$ be the set of the requests
- For each request $r \in \mathcal{R}$ we have:

$$r = \left(n, t_r^0, \delta_r, \gamma_r, m_r, \mathbf{G}_r\right)$$

where

- n: the requesting user
- $t_r^0 \in \mathcal{T} = \{1, 2, \ldots, T\}$: the starting time of the request
- δ_r: the duration of the temporal window
- γ_r: the minimum SINR level requirement
- m_r: the amount of computational resources needed for signal processing
- $\mathbf{G}_r$: the channel gain matrix

Problem Formulation (cont'd)

- Let P_j be the maximum transmission power for RRH $j \in \mathcal{H}$
- Let $p_{rjs}(t) \in [0, P_j]$ be the **transmission power** of j on subcarrier s at time slot t w.r.t. request r
- Let $y_j(t) \in \{0, 1\}$ be the **RRH activation indicator**

- The SINR is defined as follows:

$$\mathrm{SINR}_{rs}(t) = \frac{\sum_{j \in \mathcal{H}} p_{rjs}(t) g_{rjs}}{\sigma^2 + \sum_{j \in \mathcal{H}} \sum_{r' \in \mathcal{R}, r' \neq r} p_{r'js}(t) g_{r'js}} \quad (1)$$

Power Consumption Model at the RRH side

- Each RRH $j \in \mathcal{H}$ produces **transmission** and **activation** power costs

Transmission power consumption

$$\mathcal{C}_j^{\mathcal{T}\mathcal{X}}(\mathbf{p}(t)) = \sum_{r \in \mathcal{R}} \sum_{s \in \mathcal{S}} p_{rjs}(t) \tag{2}$$

Activation power consumption

$$\mathcal{C}_j^{\mathcal{A}}(\mathbf{y}(t)) = y_j(t) \left(P_j^{(\mathrm{ON})} + P_j^{(\mathrm{F})} \right) \tag{3}$$

where

- $\mathbf{p}(t) = (p_{rjs}(t))_{r \in \mathcal{R}, j \in \mathcal{H}, s \in \mathcal{S}}$
- $\mathbf{y}(t) = (y_j(t))_{j \in \mathcal{H}}$,

Power Consumption Model at the BBU side

- Let $a_{rs}(t) \in \{0, 1\}$ be the **request allocation variable** of request r on channel s
- Each scheduled request $r \in \mathcal{R}$ produces a **processing** power cost

Processing power consumption

$$\mathcal{C}_r^{\mathcal{B}}(\mathbf{a}(t)) = P^{(\mathrm{BBU})}(m_r) \sum_{s \in \mathcal{S}} a_{rs}(t) \qquad (4)$$

where

- $P^{(\mathrm{BBU})}(m_r)$: the power consumption due to the utilization of m_r resources in the BBU pool
- $\mathbf{a}(t) = (a_{rs}(t))_{r \in \mathcal{R}, s \in \mathcal{S}}$

A weighted power consumption model

The **weighted power consumption** at time-slot t is

$$\mathcal{C}(\mathbf{a}(t), \mathbf{p}(t), \mathbf{y}(t)) = \underbrace{\mathcal{C}^{\mathcal{TX}}(\mathbf{p}(t))}_{\text{Transmission}} + \underbrace{\omega_R \mathcal{C}^{\mathcal{A}}(\mathbf{y}(t))}_{\text{Activation}} + \underbrace{\omega_B \mathcal{C}^{\mathcal{B}}(\mathbf{a}(t))}_{\text{Processing}}$$

where

- $\mathcal{C}^{\mathcal{TX}}(\mathbf{p}(t)) = \sum_{j \in \mathcal{H}} \mathcal{C}_j^{\mathcal{TX}}(\mathbf{p}(t))$
- $\mathcal{C}^{\mathcal{B}}(\mathbf{a}(t)) = \sum_{r \in \mathcal{R}} \mathcal{C}_r^{\mathcal{B}}(\mathbf{a}(t))$
- $\mathcal{C}^{\mathcal{A}}(\mathbf{y}(t)) = \sum_{j \in \mathcal{H}} \mathcal{C}_j^{\mathcal{A}}(\mathbf{y}(t))$

A weighted power consumption model (cont'd)

The **weighted overall power consumption** of the system is

$$\mathcal{C}(\mathbf{a}, \mathbf{p}, \mathbf{y}) = \sum_{t \in \mathcal{T}} \mathcal{C}(\mathbf{a}(t), \mathbf{p}(t), \mathbf{y}(t)) \tag{5}$$

where

- $\mathbf{p} = (\mathbf{p}(t))_{t \in \mathcal{T}}$
- $\mathbf{a} = (\mathbf{a}(t))_{t \in \mathcal{T}}$
- $\mathbf{y} = (\mathbf{y}(t))_{t \in \mathcal{T}}$

Problem Statement

$$(\mathbf{A}): \min_{\mathbf{a},\mathbf{p},\mathbf{y}} \quad \mathcal{C}(\mathbf{a},\mathbf{p},\mathbf{y})$$

s.t.

$$\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}} a_{rs}(t) = 1, \qquad \forall r\in\mathcal{R} \tag{6}$$

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}} p_{rjs}(t) \leq y_j(t)P_j, \qquad \forall j\in\mathcal{H}, \forall t\in\mathcal{T} \tag{7}$$

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}} m_r a_{rs}(t) \leq M, \qquad \forall t\in\mathcal{T} \tag{8}$$

$$\text{SINR}_{rs}(t) \geq \gamma_r a_{rs}(t), \qquad \forall s\in\mathcal{S}, \forall r\in\mathcal{R}, \forall t\in\mathcal{T} \tag{9}$$

$$\sum_{t\notin[t_r^0, t_r^0+\delta_r]}\sum_{s\in\mathcal{S}} a_{rs}(t) = 0, \qquad \forall r\in\mathcal{R} \tag{10}$$

$$\sum_{t\notin[t_r^0, t_r^0+\delta_r]}\sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{H}} p_{rjs}(t) = 0, \qquad \forall r\in\mathcal{R} \tag{11}$$

$$a_{rs}(t) \in \{0,1\}, \qquad \forall r\in\mathcal{R}, \forall s\in\mathcal{S}, t\in[t_r^0, t_r^0+\delta_r] \tag{12}$$

$$y_j(t) \in \{0,1\}, \qquad \forall j\in\mathcal{H}, \forall t\in\mathcal{T} \tag{13}$$

A discussion on Problem (**A**)

- Problem (**A**) is a Mixed-Integer Non-Linear Problem (MINLP)
- It is easy to prove that it is **NP-hard**
- It is **dynamic**

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Dynamic Programming (DP)

The proposed DP-based solution

- Let us consider time-slot t and a given $(\mathbf{a}(t), \mathbf{y}(t))$

$$\mathcal{C}(\mathbf{a}(t), \mathbf{p}(t), \mathbf{y}(t)) = \underbrace{\mathcal{C}^{\mathcal{TX}}(\mathbf{p}(t))}_{\text{Need to be calculated}} + \underbrace{\omega_R \mathcal{C}^{\mathcal{A}}(\mathbf{y}(t))}_{\text{Fixed}} + \underbrace{\omega_B \mathcal{C}^{\mathcal{B}}(\mathbf{a}(t))}_{\text{Fixed}}$$

The proposed DP-based solution

- The problem reduces to find a power allocation policy that minimizes the **transmission power consumption**

$$\begin{aligned}\Psi(\mathbf{a}(t),\mathbf{y}(t)) = \min_{\mathbf{p}(t)} \quad & \sum_{r\in\mathcal{R}^*(\mathbf{a}(t))} \sum_{s\in\mathcal{S}_r^*(\mathbf{a}(t))} \sum_{j\in\mathcal{H}^*(\mathbf{y}(t))} p_{rjs}(t) \\ \text{s.t.} \quad & \sum_{r\in\mathcal{R}^*(\mathbf{a}(t))} \sum_{s\in\mathcal{S}_r^*(\mathbf{a}(t))} p_{rjs}(t) \le P_j, \qquad \forall j \in \mathcal{H}^*(\mathbf{y}(t)) \\ & \mathrm{SINR}_{rs}(t) \ge \gamma_r, \qquad \forall s \in \mathcal{S}_r^*(\mathbf{a}(t)), \forall r \in \mathcal{R}^*(\mathbf{a}(t))\end{aligned}$$

where

- $\mathcal{R}^*(\mathbf{a}(t)) = \{r \in \mathcal{R}(t) : \sum_{s\in\mathcal{S}} a_{rs} = 1\}$
- $\mathcal{S}_r^*(\mathbf{a}(t)) = \{s \in \mathcal{S} : a_{rs} = 1, r \in \mathcal{R}^*(\mathbf{a}(t))\}$
- $\mathcal{H}^*(\mathbf{y}(t)) = \{j \in \mathcal{H} : y_j(t) = 1\}$

An LP formulation

- $\Psi(\mathbf{a}(t), \mathbf{y}(t))$ is obtianed by solving a Linear Programming (LP) problem
- It can be solved efficiently (e.g., **polynomial time**) through simplex or interior point methods

Writing the Bellman's Equation

- Let us consider time-slot t and a given $(\mathbf{a}(t), \mathbf{y}(t))$

$$
\begin{aligned}
J(\mathcal{R}(t), t) = \min_{\mathbf{a}(t), \mathbf{y}(t)} \quad & \Psi(\mathbf{a}(t), \mathbf{y}(t)) + \omega_R \mathcal{C}^{\mathcal{A}}(\mathbf{y}(t)) \\
& + \omega_B \mathcal{C}^{\mathcal{B}}(\mathbf{a}(t)) + J(\mathcal{R}(t+1), t+1) \\
\text{s.t.} \quad & \sum_{\tau=t}^{T} \sum_{s \in \mathcal{S}} a_{rs}(\tau) = 1, && \forall r \in \mathcal{R}(t) \\
& \sum_{r \in \mathcal{R}(t)} \sum_{s \in \mathcal{S}} m_r a_{rs}(t) \leq M \\
& a_{rs}(t) \in \{0, 1\}, && \forall r \in \mathcal{R}(t), \forall s \in \mathcal{S} \\
& y_j(t) \in \{0, 1\}, && \forall j \in \mathcal{H} \\
& \sum_{s \in \mathcal{S}} a_{rs}(t) = 0, && \forall r \notin \mathcal{R}(t)
\end{aligned}
$$

Simulation Results

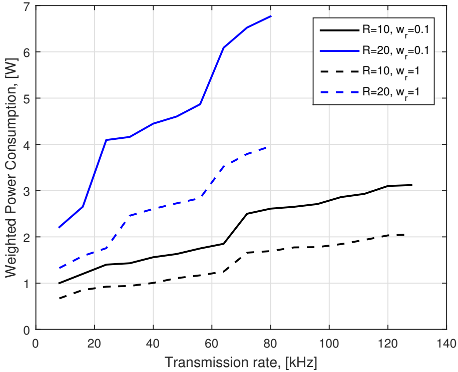

Figure: Weighted power consumption as a function of the target rate.

Complexity of the proposed solution

- The original problem is **combinatorial** and has **exponential** complexity
- The proposed solution has complexity $\mathcal{O}(TO_P(S+1)^R 2^{R+H})$

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Still exponential
Perfect knowledge

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Online Greedy Heuristic

Some considerations

- If $(\mathbf{a}(t), \mathbf{y}(t))$ is given, the problem is LP
- We aim at finding a good heuristic for $(\mathbf{a}(t), \mathbf{y}(t))$
- Intuition:
  1. **Interference** increases the power consumption
  2. **JT** and **CoMP** increase the power consumption
  3. Using the same RRH to serve many users **simultaneously** is power-efficient
  4. Users with better **channel conditions** and **loose QoS requirements** need less power

Proposed Online Greedy Approach

1. We activate those RRHs that serves the **highest number of requests** while consuming the **minimum amount of power**
2. We build an ϵ-**orthogonal scheduling policy** $(\mathbf{a}_{\epsilon}^{\perp}(t), \mathbf{y}_{\epsilon}^{\perp}(t))$ such that interference is zero (or bounded by a small ϵ)
3. We use the **residual power** on each RRH to schedule requests through JT and CoMP
4. We obtain the final **greedy scheduling policy** $(\mathbf{a}^{G}(t), \mathbf{y}^{G}(t))$
5. We solve $\Psi(\mathbf{a}^{G}(t), \mathbf{y}^{G}(t))$ to obtain the **power control policy** $\mathbf{p}^{G}(t)$

Conclusions

- Optimal solutions for the joint power control and scheduling problem with QoS and temporal constraints can be designed
- However, it is **NP-hard**
- Sub-optimal and low complexity algorithms should be designed

Future Work

- Complete the design of the heuristic
- Simulation campaigns based on real datasets and settings
- Derive a theoretical bound w.r.t. the heuristic algorithm (if possible)

Thank you!

Thank you for your attention!!

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