Interference Management in NOMA-based Fog-Radio Access Networks via Joint Scheduling and Power Adaptation

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Motivation

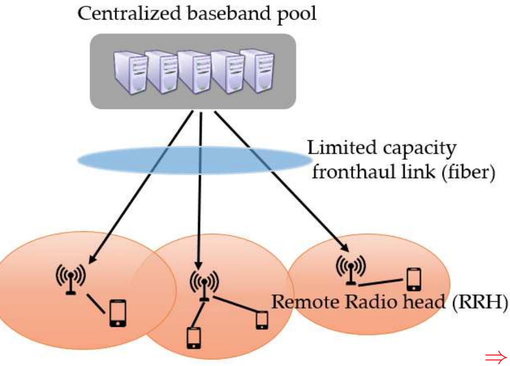
Challenges

- Increasing number of mobile subscribers (humans and machines)
- Richer multimedia contents
- More stringent and more diverse requirements
- Severe spectrum deficit

Promising architectures and techologies for 5G

- Cloud Radio Access Networks (C-RAN)
- Fog Radio Access Networks (Fog-RAN)
- Non-Orthogonal Multiple Access (NOMA)

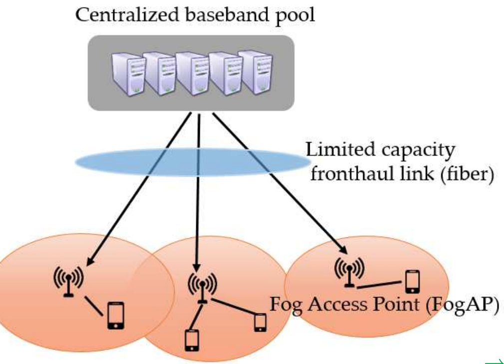
C-RAN (Cloud Radio Access Network)



- Remote Radio Heads (RRHs):
  - simple forwarding, RF
  - low cost
- Fronthaul links (optical/wireless): transport signals between RRHs and Cloud
- Cloud Baseband Units (BBUs):
  - Joint processing of huge amounts of data
  - Centralized SP and RRM
- Global network optimization

⇒ **Large burden on fronthaul links**
⇒ **Unsuited for delay-stringent real-time applications**

Fog-RAN (Fog Radio Access Network)

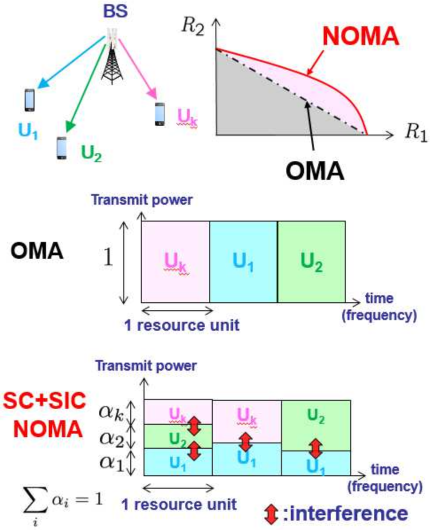


- Intelligence closer to edge
- Real-time processing
- Cloud:
  - centralized processing
  - centralized storage
- Fog Access Points (FogAPs):
  - local processing
  - distributed storage
- Distributed RRA, IM
- Reduced global network performance

⇒ **Relieve the fronthaul link burden**

⇒ **Provide a low latency**

NOMA (Non-Orthogonal Multiple Access)



Orthogonal Multiple Access

- Users served with maximum power at different resource units

Superposition Coding with Successive Interference Cancellation

- Distinct users messages are superposed in one basic resource unit
- Multiplexed in the power domain
- Strong user: decodes and subtracts signal of the weak user
- Weak user: directly decodes its signal, strong user's= interference
- Capacity-achieving scheme for Gaussian broadcast channel

Related Research Works

- Several research works about integration of NOMA with C-RAN [1] resource allocation, outage probability, energy efficiency
- Very few research works addressing resource allocation for NOMA-based Fog-RAN

$\Rightarrow$ Recent magazine[2]: resource allocation maximizing the network sum-rate

- Fairness between users is not considered (selfish users)
- Effect of the fronthaul capacity is not analysed

[1] I. Randrianantenaina et al., Joint Scheduling and Power Adaptation in NOMA-based Fog-Radio Access Networks, 2018 IEEE Globecom, Dec. 2018

[2] H. Zhang et al., Resource Allocation in NOMA-Based Fog Radio Access Networks, IEEE Wireless Communications, June 2018

Objective this Work

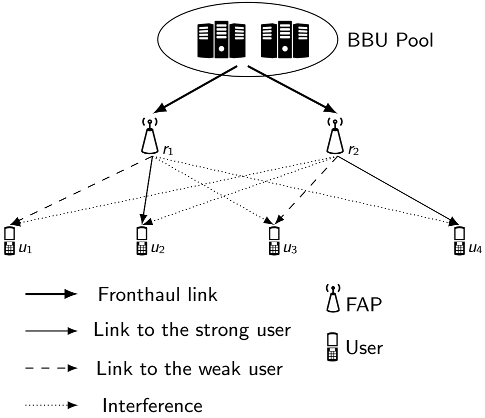
- To analyze the integration of NOMA in the downlink of a FogRAN
- To manage the interference through optimized resource allocation
- To consider **FogRAN specific constraints** FogRAN specific constraints:
  - **Fronthaul capacity limitation** for each FogAP
  - **Distributed** FogRAN control
- To improve the performance of conventional FogRAN solely based on OMA

Contributions

Considering a NOMA-based FogRAN with multiple Resource Blocks (RB):

- Maximize a network-wide utility function (weighted sum-rate)
- Optimize the **user-pair-to-FogAP assignment** under NOMA
- Assign a resource block to every user-pair
- **Optimize the power** allocated to every NOMA user pair
- **Optimize the NOMA power split** between the weak and the strong users served by each FogAP, on each RB

System Model



- FogRAN network architecture
- Every FogAP has R available resource blocks (RBs)
- Every RB serves 2 users multiplexed in power-domain NOMA
- strong user: higher channel quality (SIC)
- weak user: lower channel quality (no SIC)
- fronthaul capacity constraint $\bar{C}_f$
- Fog-RAN specific constraint: each user only served by a FogAP (local edge processing)

Optimization problem

$$\max_{\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}} \Theta(\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}) = \sum_{u\in\mathcal{U}} \alpha_u C_u(\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}) \tag{1a}$$

$$\text{s.t.} \quad 0 \leq a_{fr} \leq 1, \ \forall (f,r) \in (\mathcal{F}\times\mathcal{R}), \tag{1b}$$

$$\sum_{r\in\mathcal{R}} p_{fr} \leq \bar{P}_f, \ \forall f \in \mathcal{F}, \tag{1c}$$

$$s_{fru}, w_{fru} \in \{0,1\}, \ \forall (f,r,u) \in (\mathcal{F}\times\mathcal{R}\times\mathcal{U}), \tag{1d}$$

$$\sum_{u\in\mathcal{U}} s_{fru} = 1, \quad \forall (f,r) \in (\mathcal{F}\times\mathcal{R}), \tag{1e}$$

$$\sum_{u\in\mathcal{U}} w_{fru} = 1, \quad \forall (f,r) \in (\mathcal{F}\times\mathcal{R}), \tag{1f}$$

$$\sum_{f\in\mathcal{F}} s_{fru} + w_{fru} \leq 1, \quad \forall (u,r) \in (\mathcal{U}\times\mathcal{R}), \tag{1g}$$

$$\psi_f(\boldsymbol{P}, \boldsymbol{a}_f, \boldsymbol{S}, \boldsymbol{W}) \leq \bar{C}_f, \ \forall f \in \mathcal{F}, \tag{1h}$$

- Objective function: weighted sum-rate (user fairness provision)

Optimization problem formulation

$$\max_{\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}} \Theta(\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}) = \sum_{u\in\mathcal{U}} \alpha_u C_u(\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}) \tag{1a}$$

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$$\psi_f(\boldsymbol{P},\boldsymbol{a}_f,\boldsymbol{S},\boldsymbol{W}) \leq \bar{C}_f, \ \forall f \in \mathcal{F}. \tag{1h}$$

- Optimization variables:
  - $\boldsymbol{P}$: RBs' power allocation matrix, dimension $F \times R$
  - $\boldsymbol{A}$: NOMA power split factor matrix, dimension $F \times R$
  - $\boldsymbol{S}, \boldsymbol{W}$: assignment matrices $(F \times R \times U)$, binary.
    $\boldsymbol{S}(f,r,u) = 1$ if u is the strong user of FogAP f on RB r

Optimization problem formulation

$$\max_{\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}} \Theta(\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}) = \sum_{u\in\mathcal{U}} \alpha_u C_u(\boldsymbol{P},\boldsymbol{A},\boldsymbol{S},\boldsymbol{W}) \tag{1a}$$

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$$\psi_f(\boldsymbol{P},\boldsymbol{a}_f,\boldsymbol{S},\boldsymbol{W}) \leq \bar{C}_f,\ \forall f \in \mathcal{F}. \tag{1h}$$

- Constraints:
  - NOMA power split
  - FogAPs' power budget
  - Binary constraint
  - NOMA user pair per RB and FogAP
  - Every user is served by at most one FAP ⇒ FogRAN local operation
  - Fronthaul capacity constraint per FogAP r

Problem analysis

- **Mixed integer** optimization problem (hard to solve in general)
- The binary and the continuous parts **can not be separately solved optimally** (the mutual interference between the FogAPs)
- Assignment problem alone is a **many-to-many assignment** problem
- The considered utility function is not separable per assignment
- The continuous part is **non-convex**

Proposed Solution

⇒ Alternate between 3 steps until convergence or a maximum number of iterations is reached:

1- Solve the **assignment problem given a fixed power allocation** (initial or solution of Step 2).

2- Solve the **power allocation under the assignment solution** of Step 1.

3- Optimize the **NOMA power split** for every RB at every FogAP.

Two Assignment Algorithms

1. **Hungarian-based** assignment algorithm
   - Considering one RB, the assignment problem is a **one-to-one assignment** problem
   - The **fronthaul capacity is not taken into consideration**

2. **Multiple Choice Knapsack Problem (MCKP)-based** assignment algorithm
   - For every FogAP, the assignment finds the best pair of users for each RB
   - **Fronthaul capacity taken into consideration**
   - FogRAN-specific constraint: every user must be served by one FogAP for a given RB $\Rightarrow$ Solved by **auction**

Power allocation to every RB of every FogAP

$$\max_{\boldsymbol{P}} \Theta(\boldsymbol{P}, \boldsymbol{A}, \boldsymbol{S}, \boldsymbol{W}) = \sum_{r \in \mathcal{R}} \left(\sum_{\substack{f \in \mathcal{F} \\ u \in \mathcal{U}}} s_{fru} \alpha_u C^{(s)}_{fru}(\boldsymbol{p}_r, a_{fr}) + w_{fru} \alpha_u C^{(w)}_{fru}(\boldsymbol{p}_r, a_{fr}) \right) \tag{4a}$$

$$\text{s.t.} \quad \sum_{r \in \mathcal{R}} p_{fr} \leq \bar{P}_f, \ \forall f \in \mathcal{F}, \tag{4b}$$

$$\psi_f(\boldsymbol{P}, \boldsymbol{a}_f, \boldsymbol{S}, \boldsymbol{W}) \leq \bar{C}_f, \ \forall f \in \mathcal{F}. \tag{4c}$$

- Alternating Direction Method of Multipliers (**ADMM**):
  - For separable utility (our utility function is **separable per RB**)
  - Two iterative steps:
    - Optimizes for each direction considering that the variables corresponding to other directions are constant, using dual variables
    - Updates the dual variables
  - **Decreases the complexity**, in our case from to $\mathcal{O}\left((RF)\right)^3$ to $R\mathcal{O}\left(F\right)^3$

NOMA Power Split Optimization

$$\max_{\boldsymbol{A}} \Theta(\boldsymbol{P}, \boldsymbol{A}, \boldsymbol{S}, \boldsymbol{W}) \tag{5a}$$

$$\text{s.t.} \quad 0 \leq a_{fr} \leq 1, \ \forall (f, r) \in (\mathcal{F} \times \mathcal{R}), \tag{5b}$$

$$\psi_f(\boldsymbol{P}, \boldsymbol{a}_f, \boldsymbol{S}, \boldsymbol{W}) \leq \bar{C}_f, \ \forall f \in \mathcal{F} \tag{5c}$$

- The power split for a FogAP does not affect the other FogAPs
- NOMA power split is **optimized at every FogAP**
- For every FogAP, the objective function is separable in the RBs ⇒ **ADMM** is applied

Results

Simulation settings

FogAPs	7 (with wrap-around architecture)
Users	28 (uniformly distributed in the coverage of the FogAPs)
$\boldsymbol{a_o}$	**0.01**
Bandwidth	10Mhz
Carrier frequency	2.5Ghz
Channel fading	Rayleigh
Channel shadowing effect	$l(d) = 36.7 \log 10(d) + 22.8 + 20 \log 10(f_c)$

Table: Simulation parameters taken from the 3GPP standard.

Utility functions

- Sum-rate(SR):

  $\alpha_u = 1$ for all users

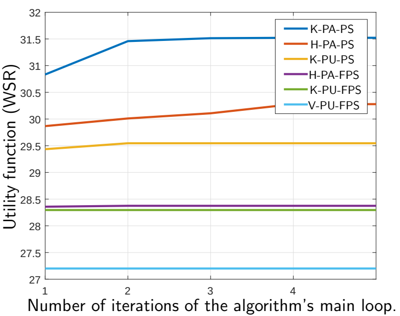
- Weighted sum rate (WSR):

  $\alpha_u = \frac{1}{\bar{C}_u^{(\tau)}}$, the inverse of the average user rate $\bar{C}_u^{(\tau)}$ over a time window τ

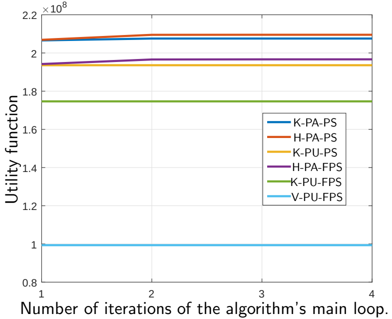
Simulation results

Algorithms Performance: convergence of different algorithms, $\bar{C}_f = 10^8$

V	Voronoi-based assignment	PU	Uniform power allocation	FPS	Fixed NOMA power split
H	Hungarian-based assignment	PA	Optimized power allocation	PS	Optimized power split
K	MCPK-based assignment	WSR	Weighted sum-rate	SR	Sum-rate



(a) WSR maximization, $\tau = 50$

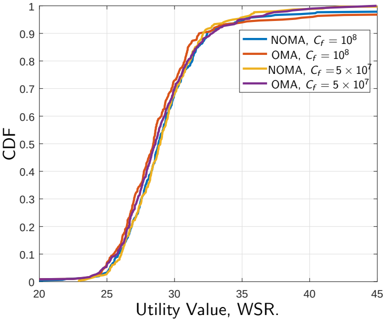


(b) SR maximization

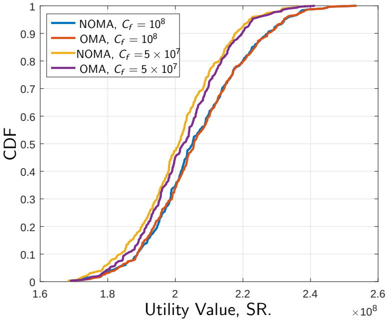
- Comparisons with conventional assignment, uniform power allocation, fixed NOMA power split
- Proposed algorithms achieve the best SR and WSR

Simulation results

NOMA vs. OMA - Utility for different fronthaul capacities



(a) WSR maximization.



(b) SR maximization.

- for the same fronthaul capacity, NOMA provides higher WSR compared to OMA
- for larger fronthaul capacity, NOMA achieves similar SR as OMA

Simulation results

NOMA vs. OMA - Jain's fairness index

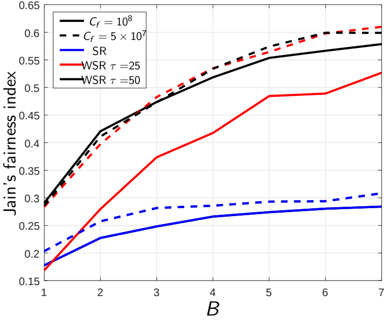
- Measure of the fairness between users: $1/U$ (worst case) to 1 (best case)
- Maximum when all users are served with the same rate

Utility	WSR		SR	
$\bar{C}_f$	5×10^7	10^8	5×10^7	10^8
NOMA	0.42	0.42	0.25	0.22
OMA	0.31	0.32	0.24	0.23

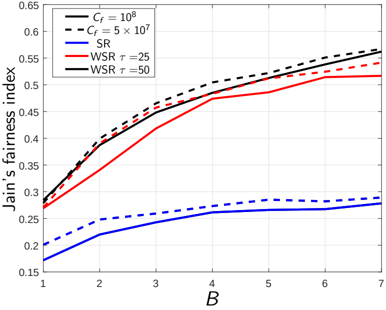
- NOMA outperforms OMA, for all fronthaul capacities
- Large fairness enhancement under WSR maximization

Simulation results

Number of RBs - Jain's fairness index



(a) Hungarian-based assignment.



(b) MCKP-based assignment.

- fairness increases with number of RBs
- higher fairness with larger window τ
- higher fairness for lower fronthaul capacity: weak users have higher chance to be allocated

Conclusion

- Investigated the **joint scheduling and power allocation problem** for the DL of a NOMA-based FogRAN cellular network for WSR maximization
- Resource allocation solved iteratively in **3 optimization steps**:
  - **User-to-FAP-and-RB assignment** (discrete optimization)
  - **Power allocation** to RBs (continuous optimization)
  - **NOMA power split** between weak and strong users within every RB
- Compared to OMA, the proposed NOMA strategy under FogRAN constraints increases user fairness without harming network SR under the different fronthaul capacity levels
- Future works:
  - joint optimization of caching and resource allocation in NOMA-based FogRAN
  - enable diverse QoS/QoE satisfaction: eMBB, mMTC, URLLC, etc.

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Utility reformulation

- Every term in the utility is a function of both the assignment variables (binary) and power allocation (continuous).

  $\Rightarrow$ Complication of the assignment problem.

- For a given RB, every user is served by at most one FogAP (as strong or as weak user)

  $\Rightarrow$ Possible reformulation of the utility function.