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Resource allocation for network profit maximization in NOMA-based F-RANs: a game-theoretic approach

Key words: Fog radio access network; Non-orthogonal multiple access; Game theory; Cache placement; Resource allocation

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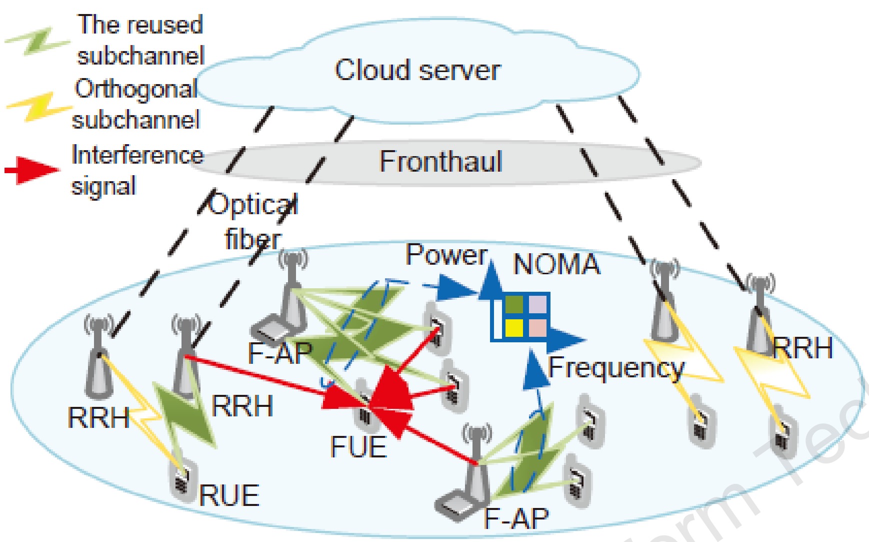
Motivation

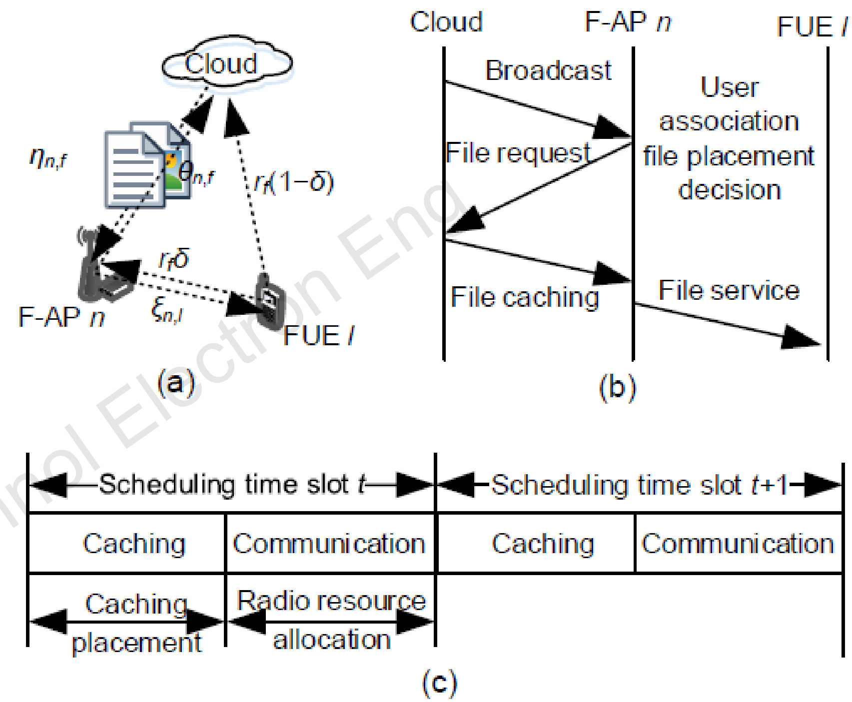
- There exists a gap between the large demands of UEs and the limited capabilities of network infrastructures
  - Centralized global signal processing, management, allocation for communication, caching, and computing resources
  - Heavy burden between ever-increasing demands and traffic
  - Large energy consumption from the cloud to the UEs
- NOMA-based F-RANs improve the network throughput and spectrum efficiency by resource sharing
  - Abilities of resource management, distributed signal processing, edge computing, and caching in F-RANs
  - SE improvement by the NOMA protocol which allows the UEs to access the F-Aps simultaneously with the same subchannel and various power
- Multi-domain resource allocation is needed in 5G and 6G networks with energy-efficient networking technique

Ideas

- Integrate the NOMA-based transmission and file caching in F-RANs and jointly allocate the caching and communication resources
  - In the caching phase, F-Aps are responsible for caching files according to the file price and user requests to further reduce the transmission energy and burden of backhaul links.
  - In the transmission phase, F-APs serve multiple FUEs via the NOMA protocol in the F-AP mode, underlaid with the RRHs in the cellular mode.
  - Formulate a resource allocation problem to maximize network profit, which takes both cost of caching and energy efficiency into consideration.
- Decompose the problem into the CP sub-problem and RRA sub-problem, and propose two algorithms.
  - For the CP sub-problem, propose a simulated annealing iterative method
  - For the RRA sub-problem, propose a hierarchical Stackelberg game: a non-cooperative power allocation algorithm, and a one-to-many subchannel matching algorithm
- Examine the impact of the proposed method and verify the efficiency

System model





- NOMA-based F-RANs comprising the cloud server, F-APs, RRHs, and UEs.

- F-AP mode: F-AP---FUE; RRH mode: RRH---RUE;
  Cloud mode: cloud---F-AP---UE

System model

Caching model:

The profit of the cloud: $$U = \sum_{n=1}^{N}\sum_{f=1}^{F}\theta_{n,f}\eta_{n,f} + \sum_{n=1}^{N}\sum_{l=1}^{L}\sum_{f=1}^{F}\xi_{n,l}Z_{l,f}\eta_{n,f}r_f\left(1-\delta\right).$$

The profit of the F-APs: $$V = v_1V_1 + v_2V_2 + \ldots + v_NV_N, \quad V_n = V_n^{\rm re} - V_n^{\rm ex},$$

$$V_n^{\rm ex} = \sum_{f=1}^{F}\theta_{n,f}\eta_{n,f}. \quad V_n^{\rm re} = \sum_{f=1}^{F}\eta_{n,f}\left(\kappa d_{nc} + c_{nc}\right) + \sum_{f=1}^{F}\sum_{l=1}^{L}\xi_{n,l}Z_{l,f}\eta_{n,f}r_f\delta$$

expenditure revenue

Transmission model:

The data transmission rate of FUE *q* accessing F-AP *n*:

$$g_{n,q} = B\log_2\left(1 + \frac{x_{n,r}y_{r,n}p_{n,q}\left|h_{n,q}\right|^2}{\sigma^2 + I_1 + I_2 + I_3}\right),$$

$$I_1 = \sum_{j=1}^{q-1}p_{n,j}\left|h_{n,q}\right|^2, \; I_2 = x_{n,r}y_{r,n}p_r\left|h_{r,n,q}\right|^2, \quad I_3 = \sum_{i=1, i\neq n}^{m_r}x_{i,r}y_{r,i}p_{i,q}\left|h_{i,n,q}\right|^2$$

System model

Transmission model

The data transmission rate of RUE *r*: $g_r = B\log_2\left(1+\frac{p_r|h_r|^2}{\sigma^2+\sum_{i=1}^{m_r} x_{i,r}y_{r,i}p_{i,r}|h_{i,r}|^2}\right)$

The network energy efficiency:

$$\mathrm{EE}=\frac{\sum_{n=1}^{N}\sum_{q=1}^{Q_n} g_{n,q}+\sum_{r=1}^{R} g_r}{\sum_{n=1}^{N}\sum_{q=1}^{Q_n} p_{n,q}+\sum_{r=1}^{R} p_r+P_{\mathrm{cir}}^{\mathrm{F}}+P_{\mathrm{cir}}^{\mathrm{R}}}$$

The network profit: $\mathcal{P}=\rho_1(V+U)+\rho_2\mathrm{EE}$

The optimization problem:

$$\max_{\theta,\xi,\eta,\boldsymbol{p},\{\boldsymbol{x},\boldsymbol{y}\}} \mathcal{P}$$

$$\begin{aligned}
\text{s.t. } & \xi_{n,l}\in\{0,1\},\ \eta_{n,f}\in\{0,1\},\\
& \forall n\in\mathcal{N},\ \forall f\in\mathcal{F},\ \forall l\in\mathcal{L},\\
& x_{n,r}\in\{0,1\},\ y_{r,n}\in\{0,1\},\ \forall n\in\mathcal{N},\ \forall r\in\mathcal{R},\\
& 0\le\theta_{n,f}\le\theta_{\max},\\
& \sum_{n=1}^{N}\xi_{n,l}=1,\ \sum_{l=1}^{L}\xi_{n,l}\le Q,\ \forall l\in\mathcal{L},\ \forall n\in\mathcal{N},
\end{aligned}$$

$$\begin{aligned}
& \sum_{f=1}^{F}\eta_{n,f}s_{\mathrm{f}}\le S_n^{\mathrm{C}},\ \forall n\in\mathcal{N},\\
& \sum_{q=1}^{Q_n}p_{n,q}=p_n^{\max},\ p_{n,q}>0,\ \forall n\in\mathcal{N},\\
& \phi_n(x_n,p_n)\ge\phi_n^{\min},\ \phi_r(y_r)\ge\phi_r^{\min}\\
& \forall r\in\mathcal{R},\ \forall n\in\mathcal{N},\\
& \sum_{r=1}^{R}x_{n,r}=1,\ \sum_{n=1}^{N}y_{r,n}\le M.
\end{aligned}$$

Problem solution

Decomposition:

- Caching placement sub-problem

The optimization problem for cloud

$$\max_{\theta_{n,f}} U$$
$$\text{s.t. } 0 \le \theta_{n,f} \le \theta_{\max}, \forall n \in \mathcal{N}, \ \forall f \in \mathcal{F}$$

The optimization problem for F-APs

$$\max_{\eta_{n,f}, \xi_{n,l}} \quad V$$
$$\text{s.t. } \xi_{n,l} \in \{0,1\}, \forall n \in \mathcal{N}, \ \forall l \in \mathcal{L},$$
$$\sum_{n=1}^{N} \xi_{n,l} = 1, \ \forall l \in \mathcal{L},$$
$$\sum_{l=1}^{L} \xi_{n,l} \le Q, \ \forall n \in \mathcal{N},$$
$$\eta_{n,f} \in \{0,1\}, \ \forall n \in \mathcal{N}, \ \forall f \in \mathcal{F}$$

Algorithm 1 Cache placement (CP) algorithm

1: **Initialize:** the CP, user association, and the price randomly as η_0, ξ_0, θ_0, which satisfy constraints (12a), (13a)–(13d), the initial profit of the cloud as $U(0)$, and that of F-APs as $V(0)$, $t = 1, k, T$

2: **while** $|V(t) - V(t-1)| > \zeta$ **do**

3: Compute the difference of the evaluation function between two solutions, $\mathrm{d}E = V(\eta_{t+1}, \xi_{t+1}) - V(\eta_t, \xi_t)$

4: **if** $\mathrm{d}E \ge 0$ **then**

5: Update $\eta_{t+1} = \eta_t, \ \xi_{t+1} = \xi_t$

6: **else**

7: $\exp\left(\frac{\mathrm{d}E}{kT}\right) > \mathrm{rand}(1)$

8: Update $\eta_{t+1} = \eta_t, \ \xi_{t+1} = \xi_t$

9: Change the temperature, $T = \tau T$

10: $t = t + 1$

11: Return $\eta_{n,f}$ to the cloud and compute the profit function U by expression (12)

12: Update $\theta = \theta + \Delta_\theta$

13: Return θ^* and output U

14: **end if**

15: **end while**

Problem solution

Decomposition:

- Radio resource allocation sub-problem

The optimization problem

$$\max_{\{\boldsymbol{x},\boldsymbol{y}\},\boldsymbol{p}} \ \mathrm{EE}$$

$$\text{s.t.} \ \sum_{q=1}^{Q_n} p_{n,q} = p_n^{\max}, \ p_{n,q} > 0, \ \forall n \in \mathcal{N},$$

$$\phi_n(x_n, p_n) \geq \phi_n^{\min}, \ \forall n \in \mathcal{N},$$

$$\phi_r(y_r) \geq \phi_r^{\min}, \ \forall r \in \mathcal{R},$$

$$x_{n,r} \in \{0,1\}, \ \forall r \in \mathcal{R},$$

$$y_{r,n} \in \{0,1\}, \ \forall n \in \mathcal{N},$$

$$\sum_{r=1}^{R} x_{n,r} = 1, \ \sum_{n=1}^{N} y_{r,n} \leq M$$

↓

Stackelberg game

Leader: F-AP power allocation

$$\max_{\boldsymbol{p}} \left. \frac{\sum_{n=1}^{N}\sum_{q=1}^{Q_n} g_{n,q}}{\sum_{n=1}^{N}\sum_{q=1}^{Q_n} p_{n,q} + P_{\mathrm{cir}}^{\mathrm{F}}} \right|_{\Omega(n)=r}$$

$$\text{s.t.} \quad \sum_{q=1}^{Q_n} p_{n,q} = p_n^{\max}, \ p_{n,q} > 0, \ \forall n \in \mathcal{N},$$

$$\phi_n(x_n, p_n) > \phi_n^{\min},$$

$$t_n \leq t_n^{\max}, \ \forall n \in \mathcal{N}$$

Follower: RRH subchannel matching

1. Players: F-APs in $\mathcal{N}$ and RRHs in $\mathcal{R}$.

2. Strategies: The strategy set of the F-APs is constituted by all members in the set of RRH $\mathcal{R}$, and vice versa.

3. Utility: The utility of the F-APs is EE and the utility of the RRHs is the suffered interference

Problem solution

Leader: F-AP power allocation

Algorithm 2 Non-cooperative game based power allocation algorithm

```
Initialize: p*_{n,q}(0) according to the average power distribution scheme, i = 1
while p*_{n,q}(i) ≠ 0 do
    for n ∈ N do
        Calculate the optimal power value according to Eq. (21)
        if p*_{n,q}(i) ≠ p*_{n,q}(i − 1) then
            Repeat
        end if
    end for
end while
```

Follower: RRH subchannel matching

Algorithm 3 One-to-many matching based subchannel allocation algorithm

```
Initialize: the preference lists of all players. Denote S_u = {1, 2, ..., N} as the set of F-APs which do not match any RRH yet and S_m = ∅ as the initial set of F-APs which match certain RRHs
while S_u ≠ ∅ do
    for n ∈ N do
        Each F-AP sends the request to the RRH with the highest ranking from set R
    end for
    for r ∈ R which receives a request from n do
        if m_r = 0 then
            RRH r accepts the request directly. m_r ← m_r + 1. Mark x_{n,r} = y_{r,n} = 1 and remove n from S_u to S_m; prefer n to its current candidate n′, if there exists any feasible FAP n
            if 0 < m_r < M then
                r holds n as a partner. Mark x_{n,r} = y_{r,n} = 1 and remove n from S_u to S_m. m_r ← m_r + 1
                if m_r = M then
                    RRH r accepts F-AP n if it ranks higher than any current candidate and removes the F-AP item n′ which ranks the lowest at that time. Mark x_{n,r} = y_{r,n} = 1, x_{n′,r} = y_{r,n′} = 0, remove n from S_u to S_m, and remove n′ from S_m to S_u
                else
                    RRH r rejects the request directly and removes RRH r from PL_{F−APn}
                end if
            end if
        end if
    end for
end while
```

Simulation results

CP sub-problem

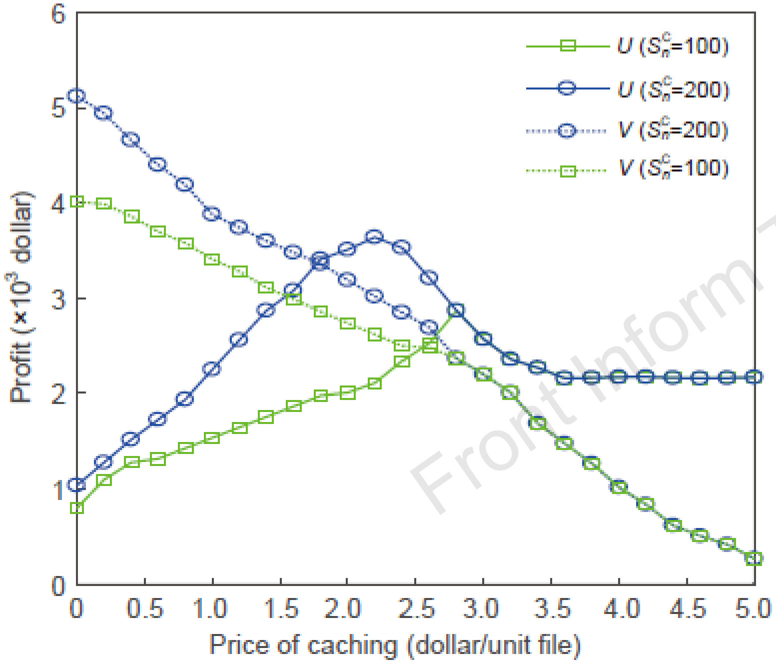


Fig. 3 Impact of the price on the profit of the cloud and F-APs

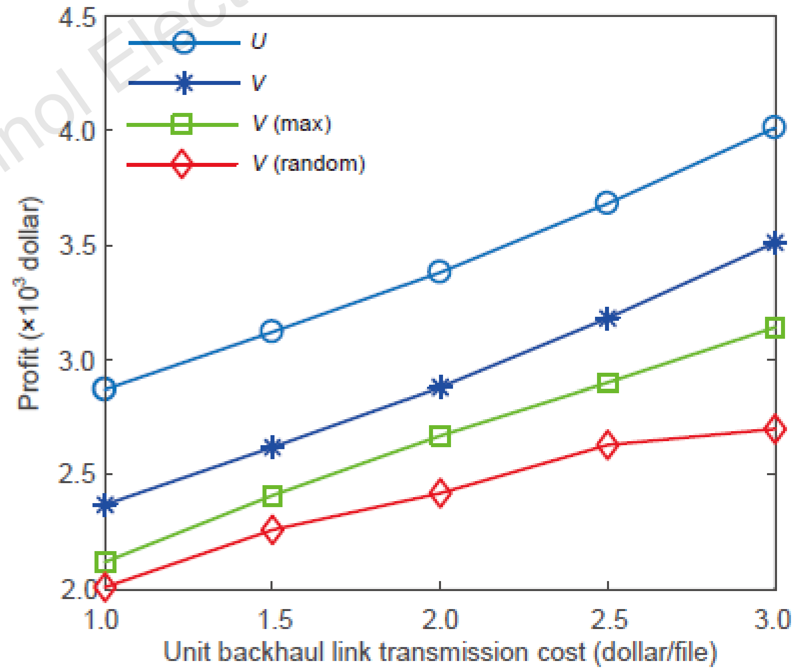


Fig. 4 Maximum profit vs. unit backhaul transmission cost

Simulation results

RRA sub-problem

Matching algorithm

Power allocation algorithm

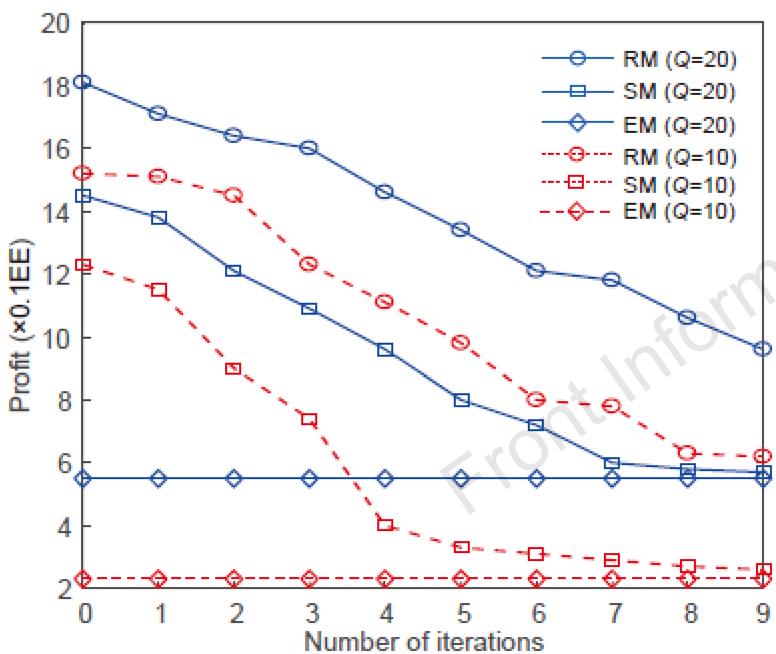


Fig. 5 Comparison among SM, RM, and EM

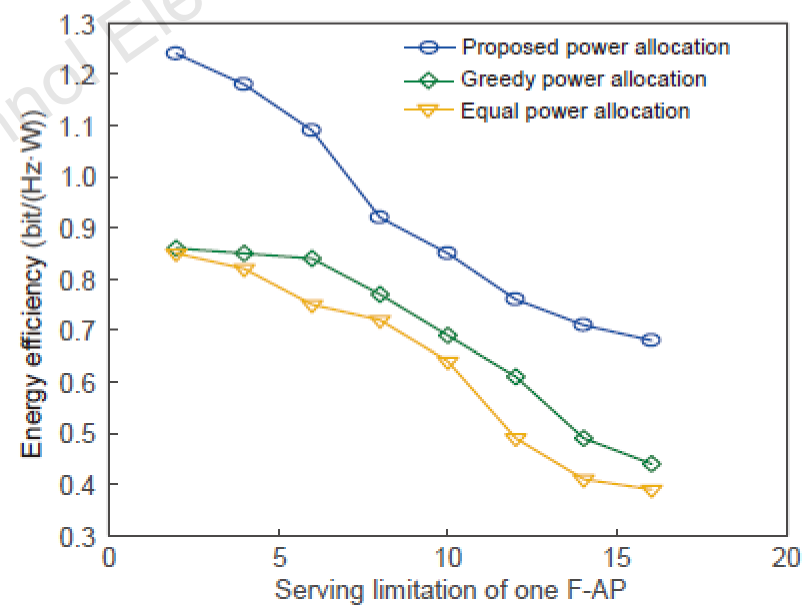


Fig. 6 Energy efficiency vs. serving limitation of one F-AP using NOMA

Simulation results

RRA sub-problem

Power allocation algorithm

Network profit performance

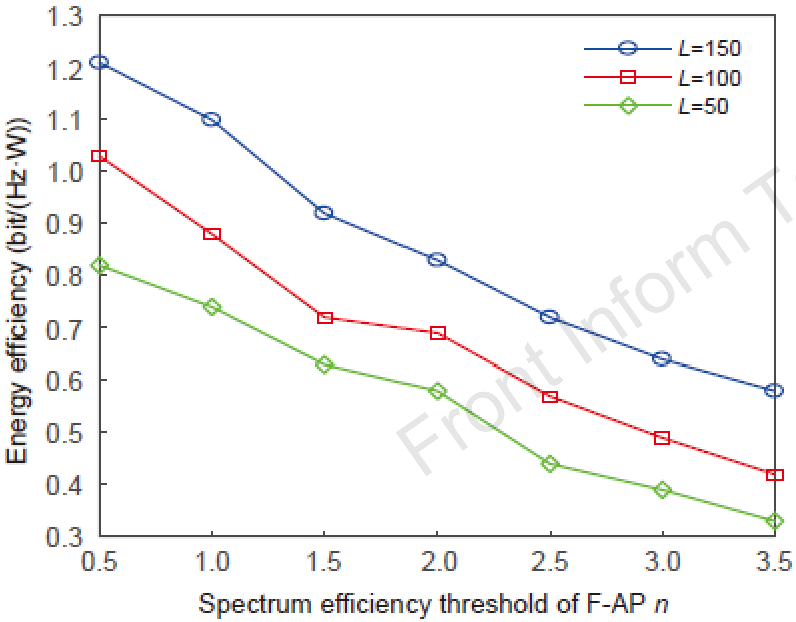


Fig. 7 Performance of energy-efficient power allocation vs. the spectrum efficiency threshold of F-AP n

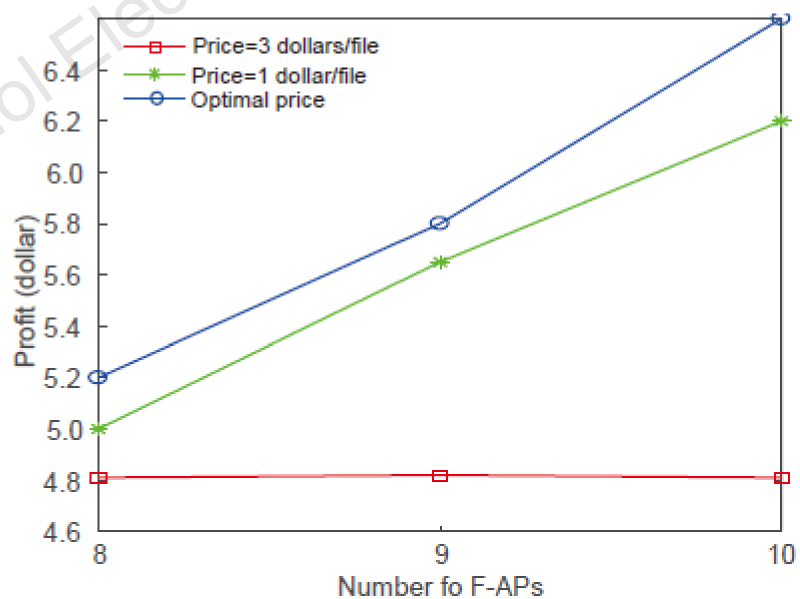


Fig. 8 Performance of network profit

Conclusions

- We focus on the resource allocation in NOMA-based F-RAN with the F-APs of edge caching, computing, and communication capabilities.
- We formulate an optimization problem for network profit maximization by jointly optimizing CP, pricing of files, and power and subchannel allocation.
- Two sub-problems are formulated to solve the NP-hard problem easily.

Shi YAN (Member, IEEE) received the Ph.D. degree in communication and information engineering from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2017. He is currently an Associate Professor with the State Key Laboratory of Networking and Switching Technology, BUPT. In 2015, he was an Academic Visiting Scholar with Arizona State University, Tempe, AZ, USA. His research interests include game theory, resource management, deep reinforcement learning, stochastic geometry, and fog radio access networks.