Virtual Resource Allocation for Heterogeneous Services in Full Duplex-enabled Small Cell Networks with Cache and MEC

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INFOCOM Workshops 2017

May 1, Atlanta, GA, USA

Outline

- Background and Motivation
- System Model
- Problem Formulation
- Problem Reformulation and Solution
- Simulation and Performance Analysis
- Conclusion

Background

- The development of smart phones promotes more and more heterogeneous services and related applications emerging, such as high-speed multi-media, interactive gaming, AR/VR applications.
- High-data-rate service and computation-sensitive service, as two typical heterogeneous services, make the shortage of spectrum resource become especially prominent.
- With recent advances in self-interference (SI) cancellation technologies, full duplex (FD) technology becomes an effective solution to improve the utilization of spectrum.
- How to guarantee different QoE requirements of heterogeneous services in FD communication is very challenging. In the area of FD-enabled small cell networks, it is very meaningful to consider caching and mobile edge computing (MEC).

Motivation

- Related work

Caching:
With the rapid development of caching technology, popular contents can be proactively predicted and cached in the storage facilities, which shortens the distance between users and contents and offers high-QoE services.

Mobile edge computing (MEC):
Cloud-computing capabilities in radio access networks (RANs) in proximity to mobile subscribers, which becomes a promising technology to computation-sensitive services.

A challenge: how to efficiently manage different system resources?
Network function virtualization (NFV): an effective approach to manage physical network infrastructures and wireless resources.

Motivation

- Contribution

Design a novel virtualized FD-enabled small cell networks framework with caching and MEC, aiming at high data-rate and computation-sensitive services. NFV is enabled to guarantees the feasibility and flexibility of the framework. FD and caching can complement to offer high-data-rate service saving backhaul resource.

Formulate a joint virtual resource allocation problem, where user association, power control, caching and computing offloading policies and joint resource allocation are taken into account, which satisfies users' QoE requirements.

Transfer the original problem to a convex problem by variables relaxation and reformulation. A distributed algorithm is adopted to obtain the optimal solution with low complexity. Simulation results show the superiority of our scheme.

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System Model

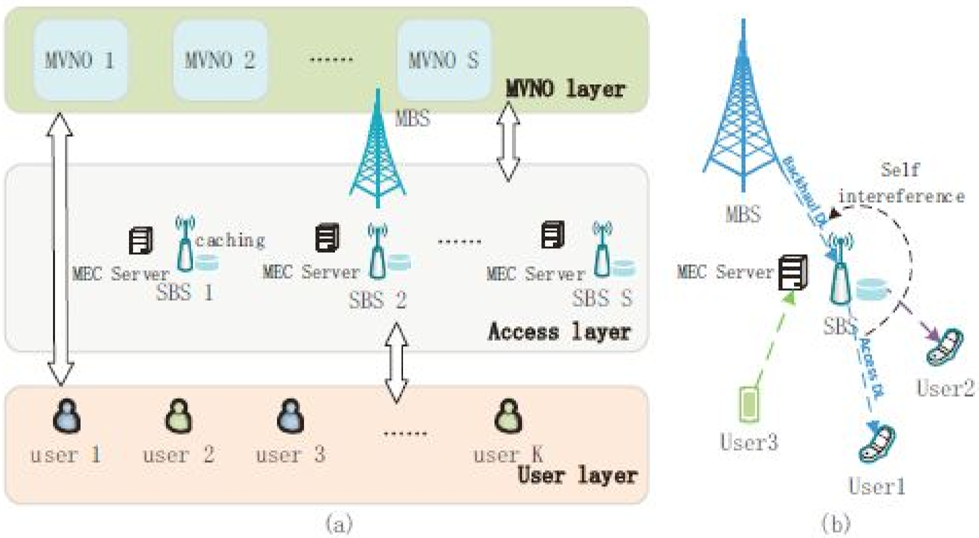

Fig. 1(a): a three-layer framework

MVNO layer: lease physical infrastructures and resources.
Access layer: one MBS and some SBSs with caching and MEC.
User layer: two kinds of users with different service requirements.

Assumption: Users do not have the authorization to access the SBSs directly. Instead, they receive the virtualized services from the MVNOs.

Fig. 1 (b) : Communication scenario

- Two content delivery ways for high-data-rate service (Service I): The SBSs directly communicate with users when required contents are cached, like User 2. Otherwise, request the content to the MBS by FD communication, like User 1.
- Computation-sensitive service (Service II): Computing tasks can be offloaded to the MEC server to execute with low delay, like User 3.

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Constraints

$$C1: \sum_{k \in S} x_{ik} \le 1, \forall i \in \Omega_A.$$

$$C2: \sum_{k \in S} x_{jk} \le 1, \forall j \in \Omega_B.$$

$$C3: \sum_{k \in S} \sum_{i \in \Omega_A} x_{ik} y_{ik} \le 1.$$

$$C4: \sum_{k \in S} \sum_{j \in \Omega_B} x_{jk} y_{jk} \le 1.$$

$$C5: \sum_{k \in S} x_{ik} y_{ik} B_d r_{ik} \ge R_i^d, \forall i \in \Omega_A.$$

$$C6: r_{ik}^b \ge r_{ik}, \forall k, i.$$

$$C7: \sum_{k \in S} \sum_{i \in \Omega_A} a_{ik} \le 1.$$

$$C8: t_{jk}^u \le T_u, \forall j \in \Omega_B.$$

$$C9: t_{jk}^e \le t_0 - T_{u,} \forall j \in \Omega_B.$$

$$C10: \sum_{i \in \Omega_A} x_{ik} c_{ik} d_{ik} \le D_k, \forall k \in S.$$

$$C11: \sum_{j \in \Omega_B} x_{jk} z_{jk} \le 1, \forall k \in S.$$

- C1: User association constraint for Service I;
- C2: User association constraint for Service II;
- C3: Downlink bandwidth constraint for Service I;
- C4: Uplink bandwidth constraint for Service II;
- C5: Minimal transmission data rate constraint for Service I;
- C6: Backhaul link rate in FD communication is not less than access link rate for Service I;
- C7: MBS power constraint in FD communication for Service I;
- C8: Transmission delay constraint for Service II;
- C9: Execution delay constraint for Service II;
- C10: Caching storage constraint for Service I;
- C11: Computing capability constraint of MEC server.

Utility Function

- *In the Service I (downlink)*

  Revenue : Transmission data rata R'_{ik} , saved backhaul band C'_{ik}

  Cost : consumed frequency band G_{ik}, cache $Cache_{ik}$ and MBS power Q_{ik}

- The utility function for user i with Service I is

$$
\begin{aligned}
u_{ik} &= \alpha_i R'_{ik} + \beta_i C'_{ik} - \gamma_i G_{ik} - \eta_i Cache_{ik} - \varepsilon_i Q_{ik} \\
&= \alpha_i x_{ik} \log y_{ik} B_d r_{ik} + \beta_i (x_{ik} y_{ik} B_d r_{ik} + x_{ik} c_{ik} (1 - hit_{ik}) \mathrm{v}_{ik}) \\
&\quad - \gamma_i x_{ik} y_{ik} B_d - \eta_i x_{ik} c_{ik} (1 - hit_{ik}) s_{ik} - \varepsilon_i x_{ik} (1 - hit_{ik}) a_{ik} P_m
\end{aligned}
$$

- *In the Service II (uplink)*

  Revenue : transmission rate of input data, saved energy consumption of users

  Cost : consumed frequency band and computing resource

- The utility function for user j with Service II is

$$
u_{jk} = \psi_j x_{jk} \log y_{jk} B_{jk} r_{jk} + \theta_j x_{jk} \frac{D_j}{w_j^l} p_j^l - \phi_j x_{jk} y_{jk} B_u - \vartheta_j x_{jk} z_{jk} w_k^c
$$

- Optimization Problem:

$$
\max_{(\mathbf{x_i}, \mathbf{x_j}, \mathbf{y_i}, \mathbf{y_j}, \mathbf{c}, \mathbf{z}, \mathbf{a})} \sum_{k \in S} \left(\sum_{i \in \Omega_A} u_{ik} + \sum_{j \in \Omega_B} u_{jk} \right)
$$

$$
s.t. \quad \text{C1-C11}
$$

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Problem Reformulation

- Variable relaxation:

$x_{ik} \in [0,1]$, $x_{jk} \in [0,1]$, $c_{ik} \in [0,1]$: the sharing in the time scale

- Variable substitution:

$\tilde{y}_{ik} = x_{ik} y_{ik}$, $\tilde{c}_{ik} = x_{ik} c_{ik}$, $\tilde{a}_{ik} = x_{ik} a_{ik}$; $\tilde{y}_{jk} = x_{jk} y_{jk}$, $\tilde{z}_{jk} = x_{jk} z_{jk}$.

- For $\tilde{y}_{ik} = x_{ik} y_{ik}$, we can get $y_{ik} = \dfrac{\tilde{y}_{ik}}{x_{ik}}$ except $x_{ik} = 0$.

To guarantee one-to-one mapping of variables, we define $y_{ik} = \begin{cases} \dfrac{\tilde{y}_{ik}}{x_{ik}}, & \text{if } x_{ik} > 0 \\ 0, & otherwise \end{cases}$

$x_{ik} \log \dfrac{\tilde{y}_{ik}}{x_{ik}}$ is well-known perspective function of logarithmic function.

The convexity of the perspective function keeps consistent with the original function. So the perspective function is concave.

$\tilde{c}_{ik} = x_{ik} c_{ik}$, $\tilde{a}_{ik} = x_{ik} a_{ik}$, $\tilde{y}_{jk} = x_{jk} y_{jk}$, $\tilde{z}_{jk} = x_{jk} z_{jk}$ are similar with $\tilde{y}_{ik} = x_{ik} y_{ik}$

- So, we conclude that the objective function is the sum of concave functions.

Problem Reformulation

Optimization problem:

$$\max_{(\mathbf{x_i},\mathbf{x_j},\tilde{\mathbf{y}}_\mathbf{i},\tilde{\mathbf{y}}_\mathbf{j},\tilde{\mathbf{c}},\tilde{\mathbf{z}},\tilde{\mathbf{a}})} \sum_{k\in\mathcal{S}}\Big(\sum_{i\in\Omega_A} u_{ik} + \sum_{j\in\Omega_B} u_{jk}\Big).$$

s.t. $C1, C2.$

$$C3': \sum_{k\in\mathcal{S}}\sum_{i\in\Omega_A} \tilde{y}_{ik} \le 1.$$

$$C4': \sum_{k\in\mathcal{S}}\sum_{j\in\Omega_B} \tilde{y}_{jk} \le 1.$$

$$C5': \sum_{k\in\mathcal{S}} \tilde{y}_{ik} B_k^d r_{ik} \ge R_i^d, \forall i \in \Omega_A.$$

$$C6': \tilde{a}_{ik} \ge \frac{x_{ik}(1-hit_{ik})p_{ki}h_{ki}(\varpi p_{ki}+\sigma^2)}{P_m h_{ik}^m \sigma^2}, \forall i, k.$$

$$C7': \sum_{k\in\mathcal{S}}\sum_{i\in\Omega_A} (1-hit_{ik})\tilde{a}_{ik} \le 1.$$

$$C8': r_{jk}^u = \tilde{y}_{jk} B_k^u r_{jk} \ge \frac{R_j}{T_u}, \forall j \in \Omega_B.$$

$$C9': \frac{D_j}{x_{jk} w_{jk}} = \frac{D_j}{\tilde{z}_{jk} w_k} \le t_0 - T_u, \forall j \in \Omega_B.$$

$$C10': \sum_{i\in\Omega_A} \tilde{c}_{ik} d_{ik} \le D_k, \forall k \in \mathcal{S}.$$

$$C11': \sum_{j\in\Omega_B} \tilde{z}_{jk} \le 1, \forall k \in \mathcal{S}.$$

- With the theory that a negative concave problem is a convex problem, we can conclude that the form of the objective function is a linear sum of convex problems.
- The optimization problem is a convex problem.

Problem Solution

- Due to the constraints, optimization variables are not separable with respect to each SBS. In order to achieve a distributed optimization algorithm, necessary decoupling measures are conducted.
- Introduce $\hat{\mathbf{x}}_{\mathbf{i}}^{k}, \hat{\mathbf{y}}_{\mathbf{i}}^{k}, \hat{\mathbf{x}}_{\mathbf{j}}^{k}, \hat{\mathbf{y}}_{\mathbf{j}}^{k}, \hat{\mathbf{a}}_{\mathbf{i}}^{k}$, as the local copies of global association indicator for SBS k . The consistence between all local variables and the associated global variables should be held.
- Then we can get the local utility function for SBS k as

$$g_k = \begin{cases} -\left(\sum_{i \in \Omega_A} u'_{ik} + \sum_{j \in \Omega_B} u'_{jk} \right), & \hat{\mathbf{x}}_{\mathbf{i}}^{k}, \hat{\mathbf{y}}_{\mathbf{i}}^{k}, \hat{\mathbf{x}}_{\mathbf{j}}^{k}, \hat{\mathbf{y}}_{\mathbf{j}}^{k}, \hat{\mathbf{a}}_{\mathbf{i}}^{k} \in \Phi_k \\ 0, & \text{otherwise} \end{cases}$$

- Optimization problem (Convex Problem):

$$\min G\left(\hat{\mathbf{x}}_{\mathbf{i}}^{k}, \hat{\mathbf{y}}_{\mathbf{i}}^{k}, \tilde{\mathbf{c}}, \hat{\mathbf{x}}_{\mathbf{j}}^{k}, \hat{\mathbf{y}}_{\mathbf{j}}^{k}, \tilde{\mathbf{z}}, \hat{\mathbf{a}}_{\mathbf{i}}^{k}\right) = \sum_{k \in S} g_k\left(\hat{\mathbf{x}}_{\mathbf{i}}^{k}, \hat{\mathbf{y}}_{\mathbf{i}}^{k}, \tilde{\mathbf{c}}, \hat{\mathbf{x}}_{\mathbf{j}}^{k}, \hat{\mathbf{y}}_{\mathbf{j}}^{k}, \tilde{\mathbf{z}}, \hat{\mathbf{a}}_{\mathbf{i}}^{k}\right)$$

$$\text{s.t. } \hat{x}_{in}^{k} = x_{in}, \hat{y}_{in}^{k} = \tilde{y}_{in}, \hat{a}_{in}^{k} = a_{in}, \forall i, k, n.$$

$$\hat{x}_{jn}^{k} = x_{jn}, \hat{y}_{jn}^{k} = \tilde{y}_{jn}, \forall j, k, n.$$

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Simulation and Performance Analysis

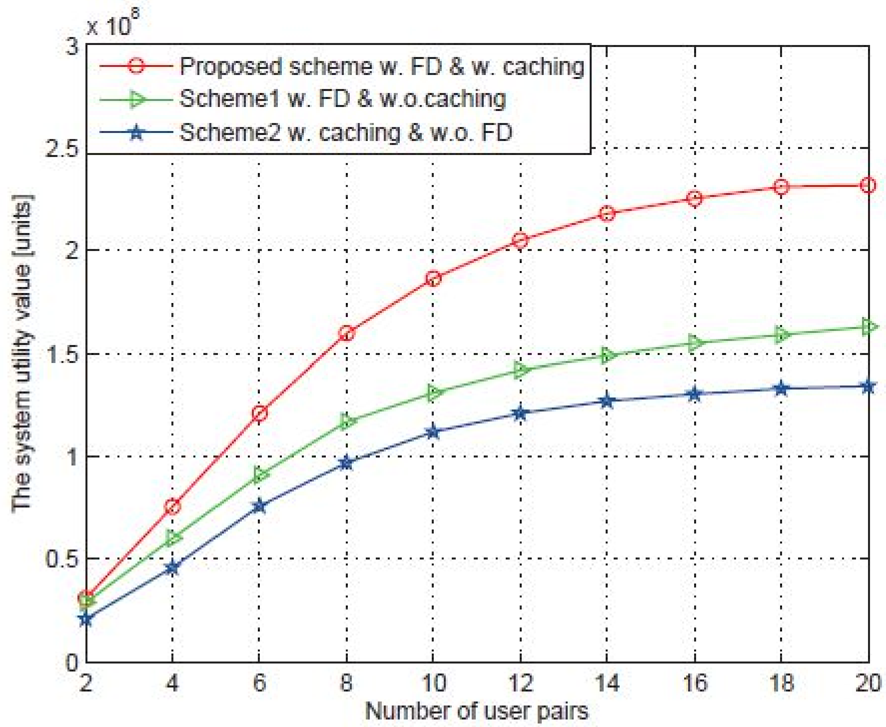

Fig.2 System utility versus the number of user pairs (the number of SBSs=4, hit ratio=0.3)

- In Fig. 2, system utility increases with the number of user pairs increasing. But the trend becomes slow. At first, the system resources are enough to allocate to users, with the increasing of users, resources become the constraint to system utility.
- We can see our proposed scheme is superior to the other two schemes. The performance of Scheme 1 is superior to Scheme 2.

Simulation and Performance Analysis

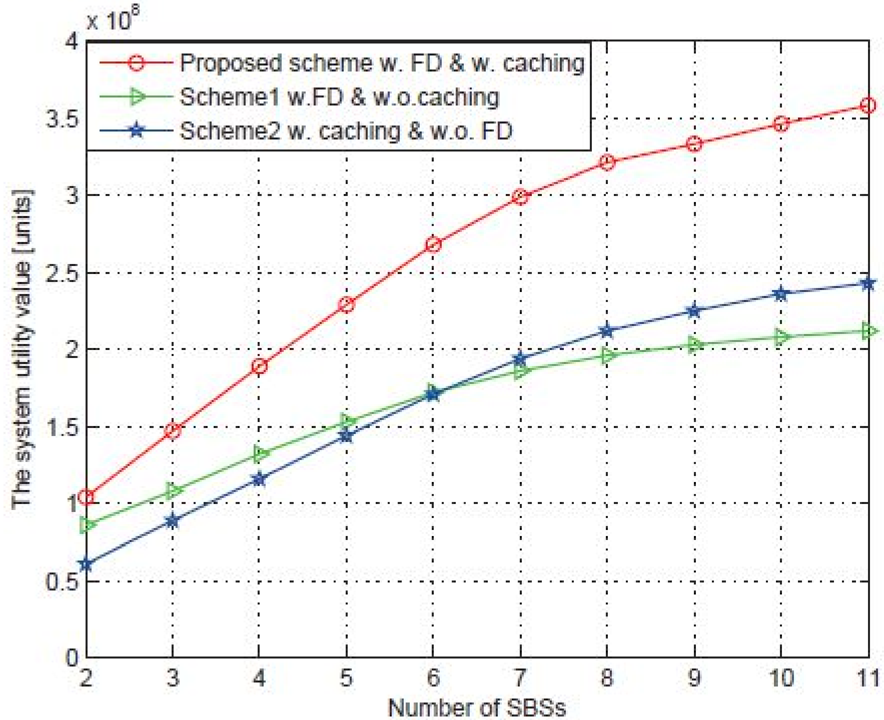

Fig.3 System utility versus the number of SBSs (the number of user pairs=10, hit ratio=0.3).

- In Fig. 3, the value of system utility increases as the number of SBSs increases and our scheme is superior to the other two schemes. The trend of growth becomes slow since the number of users is limited.
- We can find that Scheme 1 is superior to Scheme 2 at first. With the number of SBSs increasing, Scheme 2 is better than Scheme 1. It is because that more contents can be cached to serve users locally with the number of SBSs increasing.

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Conclusion

We presented a novel virtual FD-enabled small cell network framework. Then we proposed a joint scheme with respect to two main heterogeneous services. FD communication and cache were integrated to effectively save the backhaul resource.

We formulated the user association, power control, caching and computing policies and joint resource allocation problem. Variables relaxation and reformulation were conducted to guarantee the convexity of optimize problem.

A distributed algorithm was applied to obtain the optimal solution with low complexity. Simulations results showed that our proposed scheme is superior to the other two schemes from the aspects of system utility and system cost.

Thanks for your Attention !

Q&A