Breaking the Economic Barrier of Caching in Cellular Networks: Incentives and Contracts

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Outline

1 Introduction

2 System Model

3 Proposed Incentive Mechanism for Caching

4 Simulation Results

5 Conclusions and Perspectives
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1. Introduction
2. System Model
3. Proposed Incentive Mechanism for Caching
4. Simulation Results
5. Conclusions and Perspectives
Motivation

- Exponential growth of mobile video traffic [1].
  - Proliferation of social networks.
  - Increasing number of mobile devices.
- Limited capacity of the deployed wireless networks [2]
  - Dense deployment of small base stations (SBSs).
  - Capacity-limited heterogeneous backhaul links in small cell networks (SCNs).

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Motivation

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Distributed caching

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Distributed Caching

- **Idea:** Duplicate data and store it in the small cells [3].
- Caching involves, users, mobile network operators (MNOs), and content providers (CPs).
- How can MNOs incite CPs to cache their content at the SBSs?

Introduction

Literature Overview

Distributed caching:
- Minimize the expected user’s delay [4].
- Consider user’s mobility [5].
- Consider the geographical position of SBSs [6].
- Create MIMO cooperation opportunities between SBSs [7].

Business of distributed caching:
- Stackelberg game to maximize the revenue of the MNO and users’ QoS [8].
- Stackelberg game to jointly maximize the profit of MNOs and CPs [9].
- Minimize the SBSs' cost by incitivizing users to share their cached content [10].

Presence of asymmetric information


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A set $\mathcal{M}$ of $M$ macro base stations (MBSs) deployed by an MNO.
A set $\mathcal{S}$ of $S$ small base stations (SBSs).
A set $\mathcal{U}$ of $U$ user equipments (UEs).
A set $\mathcal{C}$ of $C$ content providers (CPs) with different traffic loads and content popularity.
The CPs’ types are sorted in an ascending order and classified into $K$ types $\theta_1, \ldots, \theta_K$ with $K \leq C$:

$$\theta_1 < \ldots < \theta_k < \ldots < \theta_K, \quad k \in \{1, \ldots, K\}.$$  \hfill (1)

Specify a suitable performance-reward bundle contract $(\pi, \rho) = (\text{price, storage allocation})$. 

- System Model

- Content Providers

- Macro base station

- Small base station

- Backhaul links
The data rate from SBS $i$ to user $j$ is:

$$\alpha_{ij}(\rho(\theta), \theta) = \mathbb{E}_t \left[ w_{ij} \log \left( 1 + \frac{p_{ij}|h_{ij}|^2}{\sigma^2 + I(\rho, \theta)} \right) \right].$$  

(2)
The achievable rate by an SBS $i$ from MBS $m$:

$$\alpha'_{mi} = \mathbb{E}_t \left[ w_{mi} \log \left( 1 + \frac{p_{mi} |h_{mi}|^2}{\sigma^2 + I'} \right) \right],$$  

(3)

where $I' = \sum_{l \in \mathcal{M} \setminus m} p_{li} |h_{li}|^2$ is the interference experienced by SBS $i$ from all the other transmitting MBSs.
The achievable rate of user $i$ from SBS $j$ in a cache-enabled network:

$$r_{ij}(\theta) = (1 - \beta_{if}(\rho(\theta), \theta)) \min \{\alpha_{ij}(\rho(\theta), \theta), \alpha'_{mi}\} + \beta_{if}(\rho(\theta), \theta)\alpha_{ij}(\rho(\theta), \theta),$$

where $\beta \in \{0, 1\}^{S \times F_k}$ is the outcome of the MNO’s storage allocation $\rho$. 
The total rate of the users of CP \( k \) can be given by:

\[
r_k(\rho(\theta), \theta_k) = \sum_{i \in S} \sum_{j \in U_{ki}} r_{ij}(\theta),
\]  

(5)

where \( U_{ki} \subseteq U_k \) is the set of users that request at least one file from CP \( k \) by using SBS \( i \), and \( U_k \) is the set of users requesting files of CP \( k \).
<table>
<thead>
<tr>
<th></th>
<th>Outline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
</tr>
<tr>
<td>2</td>
<td>System Model</td>
</tr>
<tr>
<td>3</td>
<td>Proposed Incentive Mechanism for Caching</td>
</tr>
<tr>
<td>4</td>
<td>Simulation Results</td>
</tr>
<tr>
<td>5</td>
<td>Conclusions and Perspectives</td>
</tr>
</tbody>
</table>
Utilities of the MNO and the CPs

- The utility function of a CP $k$ of type $\theta_k$:
  \[ u_k(\theta) = r_k(\rho_k(\theta), \theta_k) - \pi_k(\theta). \]  
  \hspace{1cm} (6)

- A proper utility function for the MNO is given by:
  \[ v_k(\theta) = \pi_k(\theta) - c_k(\theta, \theta_k), \]  
  \hspace{1cm} (7)

where $\pi_k$ is the price that the operator charges CPs of type $k$. 
Utilities of the MNO and the CPs

- The total utility of the operator can be given by:

\[ v = \sum_{k \in C} v_k(\theta). \]  

(8)

- Maximizes the global benefit of the CPs:

\[ \max_{(\pi_k, \rho_k)} \sum_{k \in C} u_k(\rho_k(\theta), \theta_k) \]

subject to \( v \geq 0. \)

(9)
Feasibility of a Contract

Definition

Individual Rationality (IR): The contract that a CP selects should guarantee that the utility of the CP is nonnegative for any $\theta_{-k}$ declared by the other CPs,

$$r_k(\rho_k(\theta_k, \theta_{-k}), \theta_k) - \pi_k \geq 0, \quad \forall k \in \{1, ..., K\}. \quad (10)$$

Definition

Incentive Compatibility (IC): A contract satisfies incentive compatibility constraint if each CP of type $\theta_k$ prefers to reveal its real type $\theta_k$ rather than another type $\hat{\theta}_k$, i.e.,

$$r_k(\rho_k(\theta_k, \theta_{-k}), \theta_k) - \pi_k \geq r_k(\rho_k(\hat{\theta}_k, \theta_{-k}), \theta_k) - \pi_k. \quad (11)$$
Incentive Mechanism Analysis

Optimization problem

\[
\begin{align*}
\text{max}_{(\pi_k, \rho_k)} & \quad \sum_{k \in C} u_k(\rho_k(\theta), \theta_k) \\
\text{subject to} & \quad r_k(\rho_k(\theta_k, \theta_{-k}), \theta_k) - \pi_k \geq 0, \quad \forall k \in \{1, \ldots, K\}, \\
& \quad r_k(\rho_k(\theta_k, \theta_{-k}), \theta_k) - \pi_k \geq r_k(\rho_k(\hat{\theta}_k, \theta_{-k}), \theta_k) - \pi_k, \\
& \quad \nu \geq 0.
\end{align*}
\]
Proposed Incentive Mechanism for Caching

Solution of the incentive optimization problem

Theorem

The unique efficient solution of the optimization problem (12) can be given by:

$$\rho^*_k \in \arg \max_{\rho_k} \sum_i \left[ r_i(\rho_i(\hat{\theta}), \hat{\theta}_i) - c_i(\hat{\theta}) \right], \forall k,$$

$$\pi_k(\hat{\theta}) = \left[ \max_{\rho_i} \sum_{i \neq k} r_i(\rho_i(\hat{\theta}_{-k}), \hat{\theta}_i) - c_i(\hat{\theta}_{-k}) \right] - \left[ \sum_{i \neq k} r_i(\rho^*_i(\hat{\theta}), \hat{\theta}_i) - c_i(\hat{\theta}) \right],$$

where (a) represents the maximized social welfare when CP $k$ is not considered while in (b), CP $k$ is considered. Moreover, $\hat{\theta}$ represents the revealed type by the CPs while $\theta$ is the real type of the CPs.
Proof of the Theorem

Lemma

The proposed mechanism is incentive compatible.

Lemma

Truth telling is a dominant strategy under (14).

Lemma

The proposed mechanism (14) is individually rational.

Lemma

The proposed mechanism (14) is weakly budget-balanced.
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Simulation Parameters

- We consider 5 CPs with 5 different traffic loads from 1 to 5.
- For each CP, a set of 100 files with a popularity that follows a Zipf distribution.
- The MNO deploys one MBS and 10 SBSs.
- The storage capacity of each SBS is 1Gbits.
Served content via backhaul with respect to CPs’ type

**Figure:** The amount of served content via backhaul with respect to CPs types.
Figure: Utility of CPs as a function of the CPs’ type and storage allocation policy.
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Conclusions and Perspectives

- Proposed a novel cache incentive framework.
- Used contract theory to account for the presence of asymmetric information.
- Proposed a model that accounts for the interdependence between contracts.
- Showed via simulations the effectiveness of the proposed framework.

Perspectives
- Extend the model by explicitly defining the caching policy.
- Extend the framework for multiple competing MNOs.
Thank you for your attention.

Questions?

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