Game Theoretic Approach for Resource Allocation in Small Cell Networks

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02 December 2016,
Amphi F3.06, CentraleSupélec, Gif-sur-Yvette, France.
Introduction

Motivation

- Exponential growth of mobile video traffic [Cis].
- Emergence of heterogeneous small cell networks with new challenges.
- Classical optimization techniques and solutions (i.e., cell densification, acquiring more spectrum, etc.) are cost-ineffective.

This calls for the development of novel approaches that leverage underused spectrum and recent advances in storage/memory [Zha+15a; BBD14]. In this thesis, we focus on:

Distributed caching & spectrum management

as a way of

- Offloading the backhaul,
- Satisfying users’ quality-of-service (QoS) requirements.


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**Distributed caching & spectrum management**

- Offloading the backhaul,
- Satisfying users’ quality-of-service (QoS) requirements.


Introduction

Distributed Caching

- **Idea:** Duplicate popular content and store it in the small base stations (SBSs) [Gol+13].
- Which files to cache at each SBS and when?
- Requires the cooperation of multiple stackholders (content providers, users, network operators).
- The impact of predicted requests on the performance of current requests?

**Literature Overview:**

- Minimize the expected user’s delay [Gol+13].
- Consider user’s mobility [PT13].
- Consider the geographical position of SBSs [BG15].
- Create MIMO cooperation opportunities between SBSs [LL15].

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Introduction
LTE over Unlicensed Channels

- **Idea:** Exploit the underused unlicensed channels [Zha+15b].
- Integration of unlicensed channels into the LTE system.
- Minimum change of the LTE air-interface.
- Ensure the coexistence of multiple systems.

**Literature Overview:**
- Unlicensed spectrum allocation using matching theory [Gu+15].
- The economic aspect of LTE-U based on auction theory [Yu+16].
- Performance analysis of integrated LTE-U when sharing the unlicensed bands [Gal+15].

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Introduction

1. Introduction

2. The Economics of Distributed Caching in Small Cell Networks

3. Backhaul Management in Cache-enabled Small Cell Networks

4. The Optimization of LTE-U and WiFi Coexistence over Unlicensed Channels

5. Conclusions and Additional Remarks
Part I: The Economics of Distributed Caching in Small Cell Networks

Contributions:
- Incite content providers to cache their data,
- account for the interdependence between multiple agents, and
- model information asymmetry.

Related Publications:
System Model

Network model

- A set $\mathcal{M}$ of $M$ macro base stations (MBSs) deployed by a mobile network operator (MNO).
- A set $\mathcal{S}$ of $S$ small base stations.
- 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.

Content providers’ type

- Each CP is defined by the traffic it generates in the network.
- The CPs’ types are sorted in an ascending order and classified into $K$ types $\theta_1, \ldots, \theta_K$ with $K \leq C$:
  \[
  \theta_1 < \ldots < \theta_k < \ldots < \theta_K, \quad k \in \{1, \ldots, K\}. \tag{1}
  \]
- Specify a suitable performance-reward bundle contract $(\pi, \rho) = (\text{price, storage allocation})$. 
The Economics of Distributed Caching in Small Cell Networks

System Model

- 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 $\rho$,
  - $\alpha_{ij}(\rho(\theta), \theta)$ is the data rate of user $j$ served by SBS $i$ and,
  - $\alpha_{mi}'$ is the achievable rate by an SBS $i$ from MBS $m$.

- The total rate of the users of CP $k$ can be given by:
  \[
  r_k(\rho(\theta), \theta_k) = \sum_{i \in S} \sum_{j \in U_{ki}} r_{ij}(\theta),
  \]  
  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 $k$. 
Utilities of the MNO and the CPs

- The utility function of a CP $k$ of type $\theta_k$:
  \[ u_k(\theta) = r_k(\rho_k(\theta), \theta_k) - \pi_k(\theta). \]  
  (4)

- A proper utility function for the MNO is given by:
  \[ v_k(\theta) = \pi_k(\theta) - c_k(\theta, \theta_k), \]  
  (5)
  where $\pi_k$ is the price that the operator charges CPs of type $k$.

- The goal of the MNO is to maximize the global benefit of the CPs:
  \[
  \max_{(\pi_k, \rho_k)} \sum_{k \in C} u_k(\rho_k(\theta), \theta_k) \\
  \text{subject to } \sum_{k \in C} v_k(\theta) \geq 0.
  \]  
  (6)

Contract theory and mechanism design [BD05].

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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,*

$$r_k(\rho_k(\theta_k, \theta_{-k}), \theta_k) - \pi_k \geq 0, \forall k \in \{1, \ldots, K\}. \tag{7}$$

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.,

$$r_k(\rho_k(\hat{\theta}_k, \theta_{-k}), \theta_k) - \pi_k \geq r_k(\rho_k(\hat{\theta}_k, \theta_{-k}), \theta_k) - \pi_k. \tag{8}$$
Incentive Mechanism Analysis

Optimization problem

$$\begin{align*}
\text{max} & \quad \sum_{k \in C} u_k(\rho_k(\theta), \theta_k) \\
\text{subject to} & \quad r_k(\rho_k(\theta_k, \theta_{-k}), \theta_k) - \pi_k \geq 0, \quad \forall k \in \{1, \ldots, K\}, \\
& \quad r_k(\rho_k(\theta_k, \theta_{-k}), \theta_k) - \pi_k \geq r_k(\rho_k(\hat{\theta}_k, \theta_{-k}), \theta_k) - \pi_k, \\
& \quad \sum_{k \in C} v_k(\theta) \geq 0. \\
\end{align*}$$

Theorem

The unique efficient solution of the optimization problem (9) can be given by:

$$\begin{align*}
\rho_k^* \in \arg \max_{\rho_k} \sum_{i} \left[ r_i(\rho_i(\hat{\theta}), \hat{\theta}_i) - c_i(\hat{\theta}) \right], \forall k, \\
\pi_k(\hat{\theta}) = \left[ \max_{\rho_i} \sum_{i \neq k} r_i(\rho_i(\hat{\theta}_{-k}), \hat{\theta}_i) - c_i(\hat{\theta}_{-k}) \right] - \left[ \sum_{i \neq k} r_i(\rho_i^*(\hat{\theta}), \hat{\theta}_i) - c_i(\hat{\theta}) \right], \\
\text{(a)} & \quad \text{maximized social welfare when CP} \ k \text{ is not considered while in (b), CP} \ k \text{ is considered. Moreover, } \hat{\theta} \text{ represents the revealed type by the CPs while } \theta \text{ is the real type of the CPs.}
\end{align*}$$
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’ type.

- It is better off for a content provider to select a contract designed for its own type.
The achievable sum-rate by the CPs’ users of higher type is higher under the proposed mechanism.

The equal allocation of the storage might be globally inefficient for the MNO.
Part II: Backhaul Management in Cache-enabled Small Cell Networks

Contributions:
• Model the impact of caching on the backhaul, and
• propose a distributed backhaul management algorithm.

Related Publications:
System Model

System model

- A set $\mathcal{M}$ of $M$ micro base stations (MBSs).
- A set $\mathcal{N}$ of $N$ small base stations (SBSs).
- Each SBS $n$ has $F_n$ predicted files and other current requests to serve.
- The total set of predicted files is $f_c = \sum_{n \in \mathcal{N}} s_n$.

Three different backhaul types:

1. Wired backhaul of capacity $C_{\text{max}}$.
2. A set of millimeter wave (mmW) backhaul resource blocks (BRBs) $\mathcal{K}_1$.
3. A set of sub-6 GHz band BRBs $\mathcal{K}_2$.

Goal: Define the number of predicted files to download without affecting the QoS of current requests.

Minority Games [Mor04].

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The players are the SBSs.

- The max number of files that can be served over the backhaul is $\phi \in [0, F]$.
- Each SBS $n$ has to select a strategy $s_n \in S_n = \{0, 1, \ldots, F_n\}$.

It is challenging to derive any result on the performance of the outcome of the game.
Introduce a set of virtual SBSs $\mathcal{V} = \bigcup_{n \in \mathcal{N}} \mathcal{V}_n$.

For each SBS $n$ create $F_n - 1$ virtual SBSs.

Each SBS has one predicted file and a strategy set $S = \{c, d\}$.

The required rate to serve the current requests is $R_n$.

The required rate to serve the predicted requests is $D_n(c)$.

The utility of choosing each strategy is given by:

$$
\begin{cases}
  u_n(c, f_c) = -R_n - D_n(c) + \sum_{m \in \mathcal{M}} \left( c_{mn}(f_c) + \sum_{k \in \mathcal{K}} \omega_k \log(1 + \gamma_{mkn}) \eta_{mkn}(f_c) \right), \\
  u_n(d, f_d) = -u_n(c, f_c + 1).
\end{cases}
$$

where,

- $c_{mn}(f_c)$ is the allocated wired backhaul to SBS $n$,
- $w_k$ is the bandwidth of BRB $k \in \mathcal{K}_1 \cup \mathcal{K}_2$,
- $\gamma_{mkn}$ is the SINR/SNR between MBS $m$ and SBS $n$ over BRB $k$,
- $f_d = \sum_{n \in \mathcal{N}} F_n - f_c$ is the number of predicted files that the SBSs decide not to download.
- $\eta_{mkn}(f_c)$ is the wireless BRBs allocation outcome [Sem+15].

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The evolution of the utility functions:

Desirable outcome:

Definition: Proper Mixed Nash Equilibrium

A proper mixed Nash equilibrium (PMNE) specifies an optimal mixed strategy $p^*_n$ for each SBS $n \in \mathcal{N}$ such that:

$$\bar{u}_n(p^*_1, \ldots, p^*_{n-1}, p^*_n, p^*_{n+1}, \ldots, p^*_N) \geq \bar{u}_n(p^*_1, \ldots, p^*_{n-1}, p_n, p^*_{n+1}, \ldots, p^*_N).$$

(13)
Proposition: Existence of a fair PMNE for the BMMG

There exists a unique fair PMNE for the BMMG, where each SBS $n \in \mathcal{N}$, chooses a strategy profile $p_n = [B(1, F_n, p), B(2, F_n, p), ... , B(i, F_n, p), ... , B(F_n, F_n, p)]$. Here, $B(i, F_n, p)$ is the binomial distribution and the probability $p$ is the same for all the SBSs in $\mathcal{N}$.

How to reach this equilibrium?

- Propose a reinforcement learning algorithm.
- Each time slot is denoted $t$.
- Algorithm parameters:
  - Estimated instantaneous utility,
    $$\tilde{u}_n(a_n(t)) = u_n(a_n(t), a_{-n}(t)) + \epsilon_{n, a_n(t)},$$ (14)
  where $a_n(t) \in \{c, d\}$.
  - Estimated expected utility,
    $$\hat{u}_n(t) = \left[ \hat{u}_n(c, t), \hat{u}_n(d, t) \right].$$ (15)
Proposed Reinforcement Learning Algorithm

Any reinforcement learning algorithm can be defined as follows ($\forall n \in G$, $\forall a \in \{c, d\}$):

$$
\begin{align*}
\hat{u}_n(x, t) &= \hat{u}_n(x, t - 1) + \alpha_n(t) \mathbb{I}_{\{a_n(t) = c\}} \left( \hat{u}_n(a_n(t)) - \hat{u}_n(x, t - 1) \right), \\
p_n(t) &= p_n(t - 1) + \lambda_n(t) \left( \tilde{\beta}_n^{(\kappa_n)}(\hat{u}_n(t)) - p_n(t - 1) \right),
\end{align*}
$$

(16)

where $x = a_n(t)$, $\tilde{\beta}_n^{(\kappa_n)}(x, \hat{u}_n(t)) = \frac{\exp(\kappa_n \hat{u}_n(x, t))}{\exp(\kappa_n \hat{u}_n(c, t)) + \exp(\kappa_n \hat{u}_n(d, t))}$ and, $\kappa_n$ is a learning parameter.

**Theorem**

The proposed algorithm converges to a unique Boltzmann-Gibbs equilibrium (BGE) with parameter $\kappa_n$, $\forall n \in G$, in the SBMMG and we have:

$$
\begin{align*}
\lim_{t \to \infty} p_n(t) &= p^*_n, \\
\lim_{t \to \infty} \hat{u}_n(x, t) &= \bar{u}_n(x, p^*_n).
\end{align*}
$$

(17)
Proposed Reinforcement Learning Algorithm

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\[
\begin{align*}
\lim_{t \to \infty} p_n(t) &= p_n^*, \\
\lim_{t \to \infty} \hat{u}_n(x, t) &= \bar{u}_n(x, p_{-n}^*).
\end{align*}
\]
Simulation Parameters

- We consider 2 MBSs and 5 SBSs.
- The total bandwidth capacity of 1Gbps.
- The total number of predicted files is 150 files distributed over the SBSs.
- $\alpha_n(t) = 1/t$ and $\lambda_n(t) = 1/t^2$.
- Three algorithms are compared:
  - The proposed decentralized reinforcement algorithm (BMRL).
  - A centralized greedy algorithm (CGA).
  - An ideal and optimal centralized algorithm (OCA).
Expected utility vs number of predicted files

**Figure**: Remaining backhaul capacity per SBS with respect to the number of files.

- The backhaul is exploited efficiently in a fully distributed manner.
Figure: Amount of requested predicted data with respect to the backhaul capacity.

- The amount of predicted files can be up to 50% higher in the BMRL compared to CGA.
Part III: The Optimization of LTE-U and WiFi Coexistence over Unlicensed Channels

Contributions:

• Propose a new game-theoretic framework for LTE-U and WiFi coexistence, and
• design a distributed algorithm for a harmonious coexistence over unlicensed channels.

Related Publications:


System Model

System model

- A set $S$ of $S$ LTE-U SBSs.
- A set $W$ of $W$ WiFi users (WUs).
- A set $C$ of $C$ of unlicensed channels.
- The goal of the SBSs is to serve their traffic in a limited period $T_{\text{max}}$.
- The WUs use listen-before-talk (LBT) scheduling scheme.
- The set of WUs over channel $c$ is $W_c$.
- The set of SBSs over channel $c$ is $S_c$.

A multi-game coexistence mechanism for LTE-U systems:

- Formulate the power control problem of the SBSs as a noncooperative problem.
- Formulate the unlicensed channels selection as a matching game.
Low-level Game: Power Control Problem Formulation

A noncooperative game $G(t_w) = \{S, \{P_i\}_{i \in S}, \{v_i(p_i)\}_{i \in S}\}$:

- The set of SBSs $S$ corresponds to the set of players.
- $v_i(p_i)$ is the cost function per SBS and given by:
  \begin{equation}
  v_i(p_i) = \sum_{c \in C} p_{ic}.
  \end{equation}

- $P_i$ is the strategy set of SBS $i$ given by:
  \begin{align}
  P_i(p_{-i}) &= \left\{ p_{ic} \in \mathbb{R}_+ : \sum_{c \in C} p_{ic} \leq p_{i}^{\text{max}}, p_{ic} \leq p_{c}^{\text{max}}, \right. \\
  \left. l_{ic} / w_c \log(1 + \gamma(p_{ic}, p_{-i}, W_c)) \leq \left[ T_{\text{max}} - t_{wc}(W_c) \right]^+, \forall c \in C \right\},
  \end{align}

where $W_c$ is the set of WUs that transmit over unlicensed channel $c$ and $t_{wc}(W_c)$ is the required time for the WUs to serve all their traffic.

- Dependence of the strategy set on other SBS’s selected strategies.
Low-level game: Power Control Problem Formulation

- The solution concept is the Debreu equilibrium (DE) defined as follows.

**Definition**

A strategy profile $p^{DE}$ is a Debreu equilibrium (DE) of the game $G(t_w)$ if, for all the SBSs $i \in S$, we have $p_i^{DE} \in \mathcal{P}_i(p_{-i})$ with

$$v_i(p_i^{DE}, p_{-i}^{DE}) \leq v_i(p_i, p_{-i}^{DE}),$$

for all $p_i \in \mathcal{P}(p_{-i}^{DE})$.

**Theorem**

The unique DE power allocation strategy for SBS $i$ over channel $c$ to its served LTE users is given by:

$$p_{ic}^{DE} = \frac{\beta}{|h_{ic}|^2} \cdot \frac{1 - 2^{-\alpha_{ic}}}{\sum_{j=1}^{S} 2^{-\alpha_{jc}} - S + 1}.$$  

(21)

with $\alpha_{ic} = \frac{l_{ic}}{\omega_c(T_{max} - t_{wc})}$ and $\beta = \sigma^2 + \sum_{j \in \mathcal{W}_c} p_{jc} |h_{jc}|^2$. 
The unlicensed allocation game can be defined as a one-sided matching game 
\( \mathcal{P} = (\mathcal{W}, \mathcal{A}, \{v_{wc}\}_{w\in\mathcal{W}, c\in\mathcal{C}}, \{\prec_w\}_{w\in\mathcal{W}}, \mu) \) where,

- The set \( \mathcal{W} \) of WUs represents the set of players.
- The set of actions \( \mathcal{A} = \mathcal{C} \cup \{c_0\} \) that correspond to the unlicensed channels.
- \( \prec_w \) is the preference relation of the WUs. \( c \prec_w c' \) when WU \( w \) prefers channel \( c \) to channel \( c' \).
- \( v_{wc} \) is the utility of WU \( w \) when serving its traffic over the unlicensed channel \( c \),

\[
\nu_{wc}(c, p_c, \mathcal{W}_c) = T_{\text{max}} - \hat{t}_c(p_c) - t_{wc}(\mathcal{W}_c, S_c),
\]

where \( p_c = [p_{1c}, \ldots, p_{Sc}] \) is the transmit power of all the SBSs over channel \( c \), and \( t_{wc}(\mathcal{W}_c, S_c) \). \( \hat{t}_c \) is the maximal duration during which the SBSs transmit.
High-level Game: Channel Allocation for the WUs

Definition

A *matching* between the WUs and unlicensed bands $\mu$ is a mapping from the set $\mathcal{W} \cup \mathcal{C}$ into the set $\mathcal{W} \cup \mathcal{C}$ such that for every $w \in \mathcal{W}$ and $c \in \mathcal{C}$:

- $\mu(c)$ is contained in $\mathcal{W}$ and $\mu^{-1}(w)$ is contained in $\mathcal{C}$,
- $|\mu^{-1}(w)| \leq 1$ for all $w \in \mathcal{W}$,
- $|\mu(c)| \leq q_c$ for all $c \in \mathcal{C}$,
- $c \in \mu^{-1}(w)$ if and only if $w \in \mu(c)$,

where $q_c$ is the maximum number of WUs that can be served over channel $c$.

Desirable outcome:

Definition

A matching $\mu$ lies in *the core* of the one-sided matching $(\mathcal{W}, \mathcal{C}, <, \{u_{wc}\}_{w \in \mathcal{W}, c \in \mathcal{C} \cup \mathcal{c}_0})$, if there is no coalition of WUs, $\mathcal{W}' \subseteq \mathcal{W}$, and a matching $\mu'$ such that:

- $\mu'^{-1}(\mathcal{W}) \in \{\mathcal{c}_0\}_{\forall i \in \mathcal{W}'}$ for all $s \in \mathcal{W}'$,
- $(\mu, \mu^{-1}(w), p) \leq_w (\mu', \mu'^{-1}(w), p)$ for all $w \in \mathcal{W}'$,
- $(\mu, \mu^{-1}(w), p) <_w (\mu', \mu'^{-1}(w), p)$ for some $w \in \mathcal{W}'$. 
Proposed One-sided Matching Algorithm

- Each WU selects one of the channels randomly.
- The WUs define their lists of preferences over the unlicensed channels.
- The WUs are ranked randomly.
- The WU $w_0$ sends a request to one of the WUs that is assigned to its most preferred channel called $w_1$.
- WU $w_1$ sends a request to $w_2$ including $w_0$ in the list of WUs that lead to its request.
- All the requesting WUs includes a list that contains all the requesting WUs that have lead to its request.
- At the end of the requests process, each WU checks the existence of a cycle in the received list from its requesting WUs.
- All the WUs that belong to a cycle exchange their partners and the WUs update their preferences list based on the remaining WUs.
Algorithm Properties

**Theorem**

The WUs-channels assignment that results from the proposed algorithm is the unique matching in the core of the formulated one-sided matching.

**Multi-game result:**

**Definition**

A strategy profile \((p^{DE}, \mu)\) is a multi-game stable outcome of the game \(M\) that is composed of the noncooperative game \(G\) and the one-sided matching game \(\mu\) if for all SBS \(i \in S\) and for all WU \(w \in W\), the two following conditions hold:

- \(v_i(p^{DE}_i, \mu) \leq v_i(p_i, p^{DE}_{-i}, \mu)\), and
- \(\exists \mu', \text{ and } W' \subseteq W\) such that, \(\forall w \in W', v_{wc}(p^{DE}, \mu, \mu^{-1}(w)) \geq_w v_{wc'}(p^{DE}, \mu', \mu'^{-1}(w)).\)

**Corollary**

The formulated multi-game admits a stable outcome if and only if the feasibility conditions are satisfied.
Simulation Parameters

- Number of SBSs: 40
- Number of WUs: 30
- Mean time of a successful transmission: 5 $\mu s$
- Mean time of a collision: 1 $\mu s$
- Mean time of idle channel: 3 $\mu s$
- Number of channels: 10
- RTS: 20 bytes
- CTS: 14 bytes
- $DIFS$: 34 $\mu s$
- $SIFS$: 16 $\mu s$
- Transmit power of the WUs: 0.5W
- Transmit power of the SBSs: 1W
The Optimization of LTE-U and WiFi Coexistence over Unlicensed Channels

SBSs sum-rate with respect to the WiFi traffic load and number of WUs/APs

The proposed mechanism enables the SBSs to adapt the amount of offloaded traffic to the unlicensed channels based on the WiFi traffic load.

Figure: BSs sum-throughput with respect to the WiFi traffic load and number of WUs/APs.
In LBT, the WiFi network saturates faster than in the multi-game case.

The sum-throughput of the WUs significantly higher in the multi-game compared to LBT.

Figure: Sum-throughput of the WUs in LBT and the multi-game.
Conclusions and Additional Remarks
Conclusions

In this work

- We have focused on both proactive caching and spectrum management in next-generation cellular networks.

In the first part

- We have proposed an economic framework to ensure the successful deployment of caching solutions.
- We have used mechanism design and contract theory to capture information asymmetry in practical systems.

In the second part

- We have modeled the impact of caching on the non-cached requested files in cellular networks as a minority game.
- We have proposed a reinforcement learning algorithm that enables the SBSs to decide whether to cache files or serve urgent requests.

In the third part

- We have proposed multi-games as a novel game-theoretic framework for LTE-U systems.
- We have modeled a joint unlicensed channel assignment and power control problem to prevent LTE-U SBSs from jeopardizing the performance of the WiFi users.
Extensions and Possible Future Directions

In the first part

- **Multiple operators case:** Account for the impact of MNOs multiplicity on designing the pricing models.
- **Hidden actions case:** Enable both MNOs and CPs to design contracts knowing that that the CPs are not aware of the caching policies used by the MNOs.
- **Joint caching and pricing model:** Analyze the impact of the caching policies on the pricing model.

In the second part

- **User-cell association policies:** Design joint backhaul management and user-cell association policies.
- **Caching policies:** Design joint backhaul management and distributed caching policies.
- **Multi-casting opportunities:** Study the impact of multi-casting on the backhaul management mechanism.

In the third part

- **LTE-U incentive:** Design an economic framework that incites user to accept being served over unlicensed channels.
- **Context-aware LTE-U:** Use transfer learning to enable the LTE-U SBSs to exploit the context information learned in one system (eg. LTE network) to develop more efficient resource allocation mechanisms on the second system (eg. WiFi network).
List of Publications I

**Journal papers:**


**Conference papers:**


Kenza Hamidouche, Walid Saad, Mérouane Debbah, and H Vincent Poor. “Mean-field games for distributed caching in ultra-dense small cell networks”. In: *American Control Conference (ACC)*. 2016.


Kenza Hamidouche, Walid Saad, and Mérouane Debbah. “Multi-Games for LTE and WiFi Coexistence over Unlicensed Channels”. In: International conference on Network Games, Control and Optimization. 2016.


Thank you for your attention
Questions?

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