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Mean-field Games for Distributed Caching in Ultra-Dense Small Cell Networks

Kenza Hamidouche, Walid Saad and Mérouane Debbah

Motivation

- Exponential growth of mobile video traffic.
- Limited capacity of wireless networks.
- Dense deployment of small base stations (SBSs).
- Capacity-limited and heterogeneous backhaul links.

Solution: Distributed caching

- Predict the popularity of the files.
- Cache the content at the SBSs ahead of time.

Challenges and Contribution

- Consider the high density of small cell networks.
- Consider the time-varying dynamics of the storage spaces and channel.

Mean-field games

- Define the download rate $\mathbf{n}_{k,t} = (n_{k,t}^{(1)}, \dots, n_{k,t}^{(N)})$ of all the SBSs for each file k .
- Proof the existence of a mean-field Nash equilibrium.

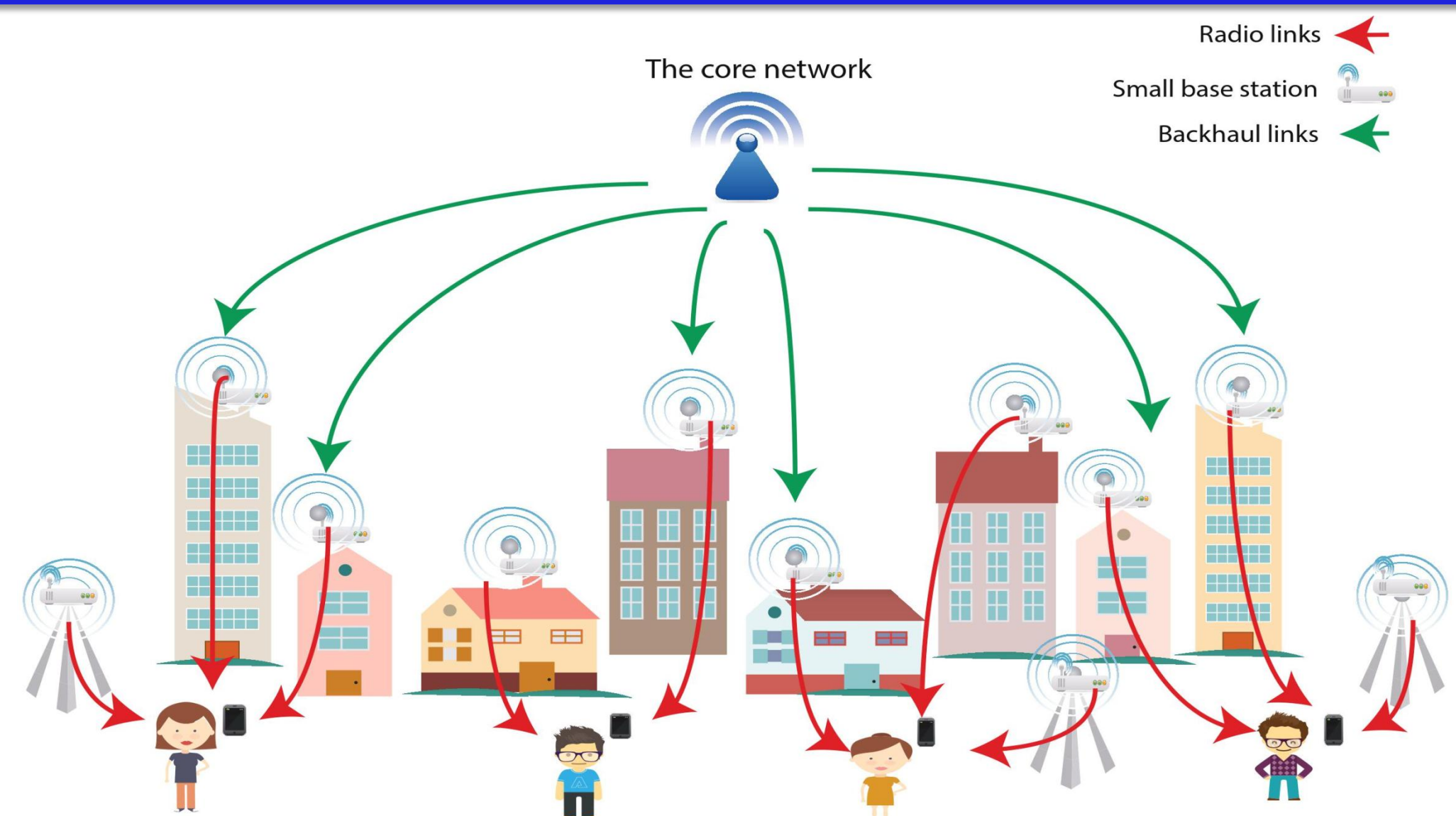
System Model

- Consider a small cell network (SCN):
 - N SBSs serving users from a set \mathcal{V} of V files.
 - Limited allocated backhaul capacity: $B_{k,t}^{(i)}$.
 - Limited storage capacity: o_i .
 - The cost function:

$$J_{k,t}^{(i)}(n_{k,t}^{(i)}, \mathbf{n}_{k,t}^{(-i)}) = c_{k,t}^{(i)}(n_{k,t}^{(i)}) + g_t^{(i)}(n_{k,t}^{(i)}) + \nu_i [s_{k,t}^{(i)} - q_k] + \omega_i [\sum_{k=1}^V s_{k,t}^{(i)} - o_i]$$

Accounting for:

- The inter-SBSs redundancy.
- The in-SBS redundancy.
- The backhaul cost.
- The storage cost.



Stochastic Game Formulation

- The stochastic differential caching game (SDG) is defined by $(\mathcal{N}, (\mathcal{Y}_i)_{i \in \mathcal{N}}, \mathcal{A}_i)_{i \in \mathcal{N}}, (\mathcal{J}_i)_{i \in \mathcal{N}}$ where:

- \mathcal{N} is the set of players.
- \mathcal{Y}_i is the set space of SBS i 's state $\mathbf{y}_{k,t}^{(i)} = (h_t^{(i)}, s_{k,t}^{(i)})$:

$$\begin{cases} dh_t^{(i)} = \frac{\alpha}{2}(\mu - h_t^{(i)})dt + \sigma_h dB_t, \\ ds_{k,t}^{(i)} = [n_{k,t}^{(i)}q_k - \beta(1 - p_{k,t}^{(i)})\bar{\zeta}_t] dt + \sigma_s dB_t. \end{cases}$$

- \mathcal{A}_i is the set of admissible caching control.
- $\mathcal{J}_k^{(i)}$ is the cost function:

$$\mathcal{J}_k^{(i)} = \mathbb{E} \left[\int_0^T J_{k,t}^{(i)}(n_{k,t}^{(i)}, \mathbf{n}_{k,t}^{(-i)}) dt + \psi^{(i)}(\lambda_T) \right]$$

- Solving the SDG amounts to solving the Hamiltonian Jacobi-Bellman (HJB) equation for all the SBSs

$$\begin{aligned} & \partial_t v_{k,t}^{(i)}(\mathbf{y}_k) + [n_{k,t}^{(i)}q_k - \beta(1 - p_{k,t}^{(i)})\bar{\zeta}_t] \partial_s v_{k,t}^{(i)}(\mathbf{y}_k) \\ & + \frac{\alpha}{2}(\mu - h_t^{(i)}) \partial_h v_{k,t}^{(i)}(\mathbf{y}_k) + \frac{\sigma_s^2}{2} \partial_{ss}^2 v_{k,t}^{(i)}(\mathbf{y}_k) + \frac{\sigma_h^2}{2} \partial_{hh}^2 v_{k,t}^{(i)}(\mathbf{y}_k) \\ & + J_{k,t}^{(i)}(n_{k,t}^{(i)}, \mathbf{n}_{k,t}^{(-i)}) = 0, \end{aligned}$$

Mean-Field Game Formulation

- Substitute all the individual interactions by the mean-field:

$$m_{k,t} = \frac{1}{N} \sum_{i=1}^N \delta_{\mathbf{y}_{k,t}^{(i)}}$$

- The state $\mathbf{y}_{k,t} = (h_t, s_{k,t})$ of a generic SBS can then be given by:

$$\begin{cases} dh_t = \frac{\alpha}{2}(\mu - h_t)dt + \sigma_h dB_t, \\ ds_{k,t} = [n_{k,t}q_k - \beta(1 - p_{k,t})\bar{\zeta}_t] dt + \sigma_s dB_t. \end{cases}$$

- Finding the optimal control amounts to solving the coupled system of HJB and Fokker-Planck-Kolmogorov (FPK) equations:

$$\begin{aligned} & \partial_t v_{k,t}(\mathbf{y}_k) + [n_{k,t}q_k - \beta(1 - p_{k,t})\bar{\zeta}_t] \partial_s v_{k,t}(\mathbf{y}_k) \\ & + \frac{\alpha}{2}(\mu - h_t) \partial_h v_{k,t}(\mathbf{y}_k) + \frac{\sigma_s^2}{2} \partial_{ss}^2 v_{k,t}(\mathbf{y}_k) + \frac{\sigma_h^2}{2} \partial_{hh}^2 v_{k,t}(\mathbf{y}_k) \\ & + J_{k,t}(n_{k,t}, m_{k,t}) = 0, \\ & m_{k,0}(\mathbf{y}_k) = \rho_0(\mathbf{y}_k), \forall \mathbf{y}_k, \\ & \partial_t m_{k,t}(\mathbf{y}_k) + [n_{k,t}q_k - \beta(1 - p_{k,t})\bar{\zeta}_t] \partial_s m_{k,t}(\mathbf{y}_k) \\ & + \frac{\alpha}{2}(\mu - h_t) \partial_h m_{k,t}(\mathbf{y}_k) - \frac{\sigma_s^2}{2} \partial_{ss}^2 m_{k,t}(\mathbf{y}_k) - \frac{\sigma_h^2}{2} \partial_{hh}^2 m_{k,t}(\mathbf{y}_k) = 0. \end{aligned}$$

Results

Proposition:

Solving the system of HJB and FPK equations results in a unique mean-field equilibrium.

Simulation parameters:

- An increasing popularity of one file over time
- The storage capacity of the SBS is $o = 2/5$
- The initial distribution of the considered file follows a normal distribution $\mathcal{N}(0.2, 0.1)$.

