A Novel Strategic Caching and Availability Optimization for Wireless Unmanned Aerial Vehicle Communication Networks

Mohamed El Amrani, Hamid Garmani, Driss Ait Omar, Mohamed Ouaskou, Abdelkarim Ait Temghart, and Mohamed Baslam

***Abstract*—The growing complexity in the 5G technology has created a necessity for UAV(Unmanned Aerial Vehicle)-assisted cellular networks as base stations. This is helpful for a wider coverage with higher transmission rates as it addresses three critical issues, i.e. location, performance and bandwidth. Besides, the integration of caching into conventional UAV infrastructure has received significant attentions since it can bring contents and memory storage closer to a mobile device. In a dynamic resource caching for wireless mobile networks, drone's settings contain important options for supporting a wide variety of applications and services, including the network access fee, quality of service (QoS) , number of cached contents, cache access fee and beaconing duration. A theoretic model based on game theory is developed to study the effect of competition among UAVs that have caching and sharing revenue model. Note that an optimal usage of UAV capabilities would thus lead to a cost-effective strategy for energy consumption and QoS requirements.**

***Index Terms*—Wireless Communication, UAV, Beaconing Duration, Service fee, Quality of Service, Game Theory, Nash Equilibrium.**

I. INTRODUCTION

It is evident that drone applications are playing an increasingly prominent role in military, public, and civilian domains. Thus, this new technology needs to be further explored as they have been successfully used in various scenarios related to disaster and risk management, including earthquakes, landslides, floods, fires, tsunamis, etc ([1] [2]). Unmanned aerial vehicles (UAVs), better known as drones, are equipped with low-cost navigation sensors that enables detection, localization, and tracking of any target for more accurate predictions and the effectiveness of specific intervention options.

Not only can UAVs support effective both offensive and defensive military operations, but they can also be used as aerial base stations (BSs) to deliver reliable, cost-effective, and on-demand flying antenna systems. For the 5G network deployment in early stage, these artificial satellites relay and amplify radio telecommunication signals via a transponder so as to provide real-time communications with satellites enabling uplinks and downlinks ([3]). More precisely, UAV-assisted communications have several promising advantages compared to fixed nodes such as the flexibility of network deployment, real-time data, and high flexibility. Therefore, UAV systems are expected to be the key component of the wireless because this platform can potentially facilitate mobile devices to be an all-coverage network to guarantee fast and ubiquitous connectivity in terrestrial cellular network.

Despite the progress made and the positive results achieved, drones are not able to launch and carry out a given mission with the autonomous flight capability. This is due to mainly technical limitations, including radio frequency (RF) restrictions, battery life, trajectory planning, severe weather conditions, restricted areas and moving obstacles. Besides, a number of logistical and privacy concerns are constantly rising when using drones as flying base stations. In order to gain a new perspective on this topic, the focus was placed on how to improve the efficiency of data transmission and optimize operational costs. In this context, we suggest UAV-aided small-cell content caching network to maximize the efficiency of content delivery and communicate locally near the end users. This process temporarily stores copies of files to use in high-speed memory chips, so that mobile devices can access the Internet content from drones to increase data retrieval performance. A cache's primary purpose is to extend coverage and provide high-quality network so as the requests for data can be served faster even if the origin server could be located anywhere in the world. In this context, Information-centric network offers a content centric paradigm to manage the explosion of content demand in the Internet architecture. ICN is a potential networking architecture for the Internet of Things. In ICN (Information-centric Networking), the content is requested by using unique names instead of IP, every node in the network can cache and serve the requested content. Benefits of ICN are a robust communication for ad-hoc networks, better response time using network caching, improved bandwidth utilization, security, mobility, etc ([4]).

In this paper, we use a new economic game theory model in which the autonomous coordinated flying for groups of UAVs can be deployed in real time to maximize network coverage. In this case, a non-cooperative game between drones is formulated to meet some target quality of service (QoS) while having constraints specified by beaconing duration and service fee. The proposed model of the competitive game among drones attempt to reach a Nash equilibrium point. In this steady state, there is no incentive for all drones to deviate from their strategies for changing their outcomes. Moreover, we design a distributed algorithm that converges to a situation representing the optimal solution. This is a concern that may

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Corresponding author: M. El Amrani (e-mail: med.el.amran@gmail.com).

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be best addressed using Bertrand game model to derive the fee of fairness and then analyze the equilibrium distribution of outputs among the drones. Numerical experiments are conducted to seek and evaluate the factors that impact the drones' strategies on their expected profits.

The remainder of this paper is organized as follows. In Section 2, we first discuss briefly some related works. The theoretical models presented in Section 3 aim specifically to formulate and model UAV systems and their utility function that explain drones' behavior among risky or uncertain choices. In the same line, Section 4 and Section 5 provide theoretical analysis of the considered non-cooperative game theory that focuses on the Nash equilibrium of the mixed-strategy best-response. The results of the simulation are reported through Section 6, with concluding discussion in Section 7.

II. RELATED WORKS

There have been several recent studies where UAV-assisted cellular networks is proposed as a cost-effective solution for ubiquitous coverage. The authors in [5] [6] study cellular networks that implement cellular radio access nodes to meet the requirements of 5G New Radio (NR) performance. In this context, game theory is used to address more complicated problems of optimizing resource allocation in UAV-based communication. In [7] the authors introduced a comprehensive review of the existing game theoretic techniques that handle various applications of drone-based communication networks. The authors in [8] used a non-cooperative sub-modular game to model beaconing periods scheduling manner, to maximize the coverage probability of mobile devices. To support ground-based units, the authors in [9] rely on Genetic algorithms and non-cooperative games for ensuring the optimal flying solutions and maximizing coverage as well. In [10], the authors proposed a theoretical framework to model the interaction of UAVs that act as a flying base station. To this aim, they use a non-cooperative game model to determine the best pricing strategy while guaranteeing high levels of UAVs availability. Due to the limited on-board battery size, it is necessary to define optimal periodic beaconing by taking into account the limited battery capacity of the UAVs and their difficulties in recharging. Besides, edge-caching has received much attention as an efficient technique to reduce the latency to access popular content and overcome backhaul congestion, especially during peak traffic [11] [12]. Similarly, the authors in [13] presented a novel proposed scheme based on proactive caching to support the drone with limited flight endurance and payload capacity. More precisely, the proposed solution aims to minimize the file caching cost and recovery cost. This was achieved mainly by jointly optimizing the drone communication scheduling, drone trajectory, and file caching policy. In addition to focusing on the overall network performance, the authors in [14] have suggested a new scheme to ensure secure transmission for UAV-relayed wireless networks with caching capability. In [15] the authors implemented an online caching-based wireless UAV by jointly optimizing UAV trajectory, transmission power, and caching scheduling. For an effective architecture that improves the wireless coverage, authors in [16] employ backscattering communication (BackCom) to transmit data to guarantee the effectiveness of real-time transmission and minimize the data collection latency. This will undoubtedly contribute to the further strengthening the UAV's lifetime network and improve the ground cellular networks' coverage as well.

As outlined above, the activity scheduling of the UAV as aerial base stations has been extensively investigated during the past few years. Those studies, however, have mainly examined various strategic decisions to define the optimal fee and the appropriate beaconing duration of UAVs with limited battery capacity. Thus, this work is specifically carried out to explore fair competition between UAVs having caching and sharing revenue model associated with energy efficiency improvements. Furthermore, to the best of our knowledge, none of the previous work analyses the most significant impacts of using caching service and sharing revenue model in a UAVs network. To explore these issues, the present paper moves toward this less explored case, where each UAV chooses the network access fee, QoS, number of cached contents, cache access fee and beaconing duration. According to this specific situation, we conduct simulation experiments to demonstrate the practicality of our approach and show how caching and sharing revenue model affect the UAV's energy efficiency as well as the QoS and the pricing strategies.

III. PROBLEM FORMULATION

In this paper, we consider a telecommunication network having G UAVs, in which each UAV is in competition with the other UAVs for the users on the ground. The monetary flow between different entities is shown in Figure 1 with different fees as described in the Table I. Each UAV j picks its availability duration ξ_j represented by the periodic beaconing time chosen within the interval $[0, T]$, a service fee per data unit p_{s_j}, a content access fee p_{c_j}, QoS q_{s_j} and number of cached items $H_j = \sum_{f=1}^{F} h_{jf}$.

A. Notations

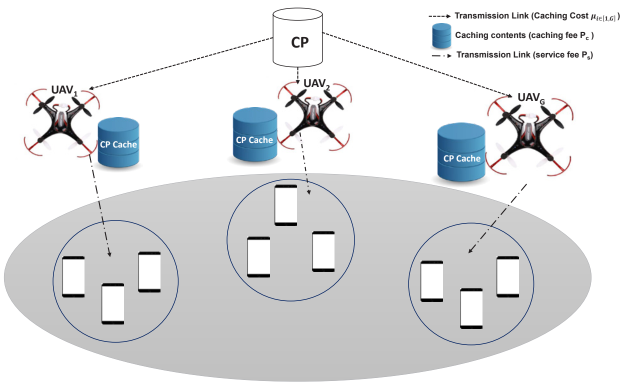

Fig. 1. Model architecture.

B. Service probability

The UAVs are connected through wireless backhuaul to the core network and move randomly according to a Random

TABLE I
SUMMARY OF NOTATION.

Notation	Description
G	Number of UAVs.
F	Number of items.
p_{s_j}	Network access fee of UAV_j.
p_{c_j}	Content access fee of UAV_j.
q_{s_j}	Quality of service of UAV_j.
ξ_j	Beaconing period durations of UAV_j.
μ_j	Caching cost of UAV_j.
ϑ_j	backhaul bandwidth cost.
T	Time slot.
m	Time window.
p_{t_j}	Transmission fee paid by UAV_j.
ρ_j^g	Sensitivity of UAV_j to fee p_{s_g} of UAV_g.
σ_j^g	Sensitivity of UAV_j to QoS q_{s_g} of UAV_g.
α_j^g	Sensitivity of UAV_j to fee p_{c_g} of UAV_g.
δ_j^g	Sensitivity of UAV_j to beaconing period ξ_g of UAV_g.
P_{srv_j}	Successful contact probability of UAV_j.
D_j^0	the potential demand of ground users of UAV_j.
d_j	Demand of UAV_j.
B_j	Backhaul bandwidth.
f^η	the rank of item f.
η	the skewness of the popularity distribution.
C_{b_j}	The energy cost for sending beacons of UAV_j.
C_{q_j}	is the energy cost for providing QoS of UAV_j.
C_{h_j}	is the energy cost for caching content of UAV_j.
C_{s_j}	is the energy consumed to switch the state of transceiver of UAV_j.
CP	Content Provider.
UAV	Unmanned Aerial Vehicle.

Way-point mobility model to cover a specific area. Each UAVs send a beacon to the ground users to announce its presence during a specific period of duration ξ . The UAVs choose their beaconing period durations to maximize the probability of encountering a mobile device on the ground and send periodic beacon advertising his availability for users on the ground. The beacon/idle cycle is periodically repeated every time slot T during a time window: $m = L \times T$. However UAVs should define their beaconing periods strategically in order to maximize their encounter rate with the ground users. They should avoid battery depletion resulting from maintaining useless beaconing in the absence of contact opportunities. The first encounter follows an exponential distribution with a random parameter λ. In order for a UAV j to encounter first the ground users at time ξ, the following conditions must hold: the UAV has to be beaconing at ξ. The encounters need to be happen while UAV j competitors are inactive. In other words, all encounters of other UAVs happen before the times instant ξ_j must be unsuccessful. Consequently, the successful contact probability is given by the following equation:

$$P_{srv_j} = \sum_{g=1}^{G} \left[P(T_j \leq T_g) + P(T_j \geq T_g) P_{slp_g} \right] P_{bcn_j} \quad (1)$$

We define the probability of UAV_j beaconing while encountering for the first time the destination within $[0, m]$:

$$\begin{aligned} P_{bcn_j} &= \sum_{s=0}^{l-1} \left(\int_{sT}^{sT+\xi_j} \lambda_j e^{-\lambda_j x} dx \right) \\ &= -\frac{e^{-\lambda T} (e^{-m\lambda_j} - e^{-\lambda_j (m+\xi_j)} - 1 + e^{-\lambda_j \xi_j})}{e^{\lambda_j T} - 1} \end{aligned} \quad (2)$$

For a UAV j, the probability of being idle is given by the following equation:

$$\begin{aligned} P_{slp_j} &= \sum_{s=0}^{l-1} \left(\int_{sT+\xi_j}^{(s+1)T} \lambda_j e^{-\lambda_j x} dx \right) \\ &= \frac{e^{-\lambda_j T} (-e^{-\lambda_j (m+\xi_j)} + e^{-\lambda_j (m+T)} + e^{-\lambda_j \xi_j} - e^{-\lambda_j T})}{e^{\lambda_j T} - 1} \end{aligned} \quad (3)$$

The probability that UAV j encounters first the ground destination without accounting for its state (probing/idle) is expressed as follows:

$$P(T_j \leq T_g) = \frac{\lambda_g e^{-m(\lambda_g + \lambda_j)} + (-\lambda_g - \lambda_j) e^{-\lambda_g m} + \lambda_j}{\lambda_j + \lambda_g} \quad (4)$$

And finally, we define the probability that UAV j encounters first the ground destination without accounting for its state:

$$P(T_j \geq T_g) = \frac{\lambda_j e^{-m(\lambda_g + \lambda_j)} + (-\lambda_g - \lambda_j) e^{-\lambda_j m} + \lambda_g}{\lambda_j + \lambda_g} \quad (5)$$

C. Demand model

The ground users demand are affected by three market parameters service fee, beaconing duration and QoS. The linear demand function is [17][18][19]:

$$\begin{aligned} d_j =& D_j^0 - \rho_j^j p_{s_j} + \delta_j^j \xi_j + \alpha_j^j p_{c_j} + \sigma_j^j q_{s_j} \\ &+ \sum_{g=1, g \neq j}^{G} (\rho_j^g p_{s_g} - \delta_j^g \xi_g + \alpha_j^g p_{c_g} - \sigma_j^g q_{s_g}) \end{aligned} \quad (6)$$

The parameter D_j^0 expresses the potential demand of ground users. ρ_j^g, δ_j^g, α_j^g and σ_j^g are positive parameters representing respectively the responsiveness of UAV_j to fee p_{s_g}, beaconing period ξ_g, fee p_{c_g} and QoS q_{s_g} of UAV_g. For UAV_j, the demand d_j is decreasing in the fee it charges, p_{s_j}, p_{c_g}, and increase in the fee charged by its opponent, p_{s_g}, p_{c_g}, $g \neq j$. The analogous relationship holds in QoS and beaconing period, in this case D_j is increasing in q_{s_j} (resp. ξ_j) and decreasing in q_{s_g} (resp. ξ_g).

Assumption 1 *The sensitivity ρ verifies:*

$$\rho_j^j \geq \sum_{g=1, g \neq j}^{G} \rho_j^g$$

The sensitivity δ verifies:

$$\delta_j^j \geq \sum_{g=1, g \neq j}^{G} \delta_j^g$$

The sensitivity σ verifies:

$$\sigma_j^j \geq \sum_{g=1, g\neq j}^{G} \sigma_j^g$$

The sensitivity α verifies:

$$\alpha_j^j \geq \sum_{g=1, g\neq j}^{G} \alpha_j^g$$

Assumption 1 will be needed to ensure the uniqueness of the resulting equilibrium. It is furthermore a reasonable condition, in that Assumption 1 implies that the influence of an UAV fee (resp. beaconing duration) is significantly greater on its observed demand than the fees of its opponents.

D. Utility function

The utility U_j of UAV_j is the difference between the obtained reward and the associated costs

$$\begin{aligned} U_j = &\sum_{f=1}^{F} \Theta_f \{(p_{s_j} - p_{t_j})(1 - h_{jf}) P_{srv_j} d_j \\ &+ (p_{s_j} + p_{c_j} - \mu_j) h_{jf} P_{srv_j} d_j\} \\ &- \frac{(C_{b_j}\xi_j + C_{q_j} q_{s_j} + C_{h_j} \sum_{f=1}^{F} h_{jf} + C_{s_j}) l}{m} \\ &- \vartheta_j (F - \sum_{f=1}^{F} h_{jf}) B_j \end{aligned} \tag{7}$$

$\sum_{f=1}^{F} \Theta_f (p_{s_j} - p_{t_j})(1 - h_{jf}) P_{srv_j} d_j$ is the revenue of UAV_j by serving the request demand $\sum_{f=1}^{F} \Theta_f (1 - h_{jf}) P_{srv_j} d_j$. $\mu_j \sum_{f=1}^{F} \Theta_f h_{jf} P_{srv_j} d_j$ is the caching fee paid by the UAV_j when serving the demand $\sum_{f=1}^{F} \Theta_f h_{jf} P_{srv_j} d_j$ of the item f from its cache. Each ground user requests an item, which is selected independently according to a discrete distribution Θ_f where $1 \leq f \leq F$, and F is the library size. We assume that the item f is requested by their popularity, characterized by Zipf popularity distribution Θ_f [20] [21] [22]. The Zipf popularity distribution of item f is defined by $\Theta_f = A^{-1} f^{-\eta}$, where $A = \sum_{f=1}^{F} f^{-\eta}$, f^{η} is the rank of item f, and η is the skewness of the popularity distribution. $\frac{(C_{b_j}\xi_j + C_{q_j} q_{s_j} + C_{h_j} \sum_{f=1}^{F} h_{jf} + C_{s_j}) l}{m}$ is the energy consumed. $\vartheta_j (F - \sum_{f=1}^{F} h_{jf}) B_j$ is a fee paid by UAV_j. B_j is the backhaul bandwidth required by the UAV_j. The backhaul bandwidth B_j of UAV_j is expressed as [23] [24] [25]

$$B_j = (F - \sum_{f=1}^{F} h_{jf})(P_{srv_j} d_j + q_{s_j}^2) \tag{8}$$

Then, the utility function is given by

$$\begin{aligned} U_j = &\sum_{f=1}^{F} \Theta_f \{(p_{s_j} - p_{t_j})(1 - h_{jf}) P_{srv_j} d_j \\ &+ (p_{s_j} + p_{c_j} - \mu_j) h_{jf} P_{srv_j} d_j\} \\ &- \frac{(C_{b_j}\xi_j + C_{q_j} q_{s_j} + C_{h_j} \sum_{f=1}^{F} h_{jf} + C_{s_j}) l}{m} \\ &- \vartheta_j (F - \sum_{f=1}^{F} h_{jf})(P_{srv_j} d_j + q_{s_j}^2) \end{aligned} \tag{9}$$

sectionGame analysis Let $\psi = \left[\mathscr{G}, \left\{P_{s_j}, Q_{s_j}, \Xi_j, P_{c_j}\right\}, \{U_j(.)\}\right]$ denote the non-cooperative game (NPQBPG), where $\mathscr{G}$={1, ..., G} is the set of UAVs, P_{s_j} is the network access fee strategy set of UAV_j, Q_{s_j} is the QoS strategy set of UAV_j, Ξ_f is the beconing strategy set of UAV_j, P_{c_j} is the content access fee strategy set of UAV_j, and $U_j(.)$ is the utility function of UAV_j. We assume that the strategy spaces P_{s_j}, Q_{s_j}, Ξ_j and P_{c_j} of each UAV_j are compact and convex sets with maximum and minimum constraints. Thus, for each UAV_j we consider as respective strategy spaces the closed intervals: $P_{s_j} = \left[\underline{p}_{s_j}, \overline{p}_{s_j}\right]$, $Q_{s_j} = \left[\underline{q}_{s_j}, \overline{q}_{s_j}\right]$, $\Xi_j = \left[\underline{\xi}_j, \overline{\xi}_j\right]$ and $P_{c_j} = \left[\underline{p}_{c_j}, \overline{p}_{c_j}\right]$. Let the fee vector $p_s = (p_{s_1}, ..., p_{s_G})^T \in P_s^G = P_{s_1} \times P_{s_2} \times ... \times P_{s_G}$, QoS vector $q_s = (q_{s_1}, ..., q_{s_G})^T \in Q_s^G = Q_{s_1} \times Q_{s_2} \times ... \times Q_{s_G}$, beconing vector $\Xi = (\xi_1, ..., \xi_G)^T \in \Xi^G = \Xi_1 \times \Xi_2 \times ... \times \Xi_G$, fee vector $p_c = (p_{c_1}, ..., p_{c_G})^T \in P_c^G = P_{c_1} \times P_{c_2} \times ... \times P_{c_G}$,

E. Fee game

A $NPQBCG$ in fee p_s is defined for fixed $\mathbf{q}_s \in Q_s$, $\xi \in \Xi$, $\mathbf{p}_c \in P_c$ as $\Psi(\mathbf{q}_s, \xi, \mathbf{p}_c) = [G, \{P_{s_j}\}, \{U_j(., \mathbf{q}_s, \xi, \mathbf{p}_c)\}]$.

Definition 1 *A fee vector $\mathbf{p_s}^* = (p_{s_1}^*, ..., p_{s_G}^*)$ is a Nash equilibrium of the NPQBG $\Psi(\mathbf{q}_s, \xi, \mathbf{p}_c))$ if:*

$$\begin{aligned} &\forall (j, p_{s_j}) \in (G, P_{s_j}), \\ &U_j(p_{s_j}^*, \mathbf{p}_{s_{-j}}^*, \mathbf{q}_s, \xi, \mathbf{p}_c) \geq U_j(p_{s_j}, \mathbf{p}_{s_{-j}}^*, \mathbf{q}_s, \xi, \mathbf{p}_c) \end{aligned} \tag{10}$$

Theorem 1 *For each $\mathbf{q}_s \in Q_s$, $\xi \in \Xi$, $\mathbf{p}_c \in P_c$ the game $[G, \{P_{s_j}\}, \{U_j(., \mathbf{q}_s, \xi, \mathbf{p}_c)\}]$ admit a unique Nash equilibrium.*

$$\frac{\partial^2 U_j}{\partial p_{s_j}^2} = -2\rho_j^j P_{srv_j} \leq 0 \tag{11}$$

The second derivative of the utility function is negative, then the utility function is thus concave, which ensures existence of a Nash equilibrium point in the game $\Psi(\mathbf{q}_s, \xi, \mathbf{p}_c)$.

We use the following proposition that holds for a concave game [26]: If a concave game satisfies the dominance solvability condition :

$$-\frac{\partial^2 U_j}{\partial p_{s_j}^2} \geq \sum_{g=1, g\neq j}^{G} \left| \frac{\partial^2 U_j}{\partial p_{s_j} \partial p_{s_g}} \right|. \tag{12}$$

then the game $\Psi(\mathbf{q}_s, \xi, \mathbf{p}_c)$ admits a unique Nash equilibrium.

The mixed partial derivative is written as:

$$\frac{\partial^2 U_j}{\partial p_{s_j} \partial p_{s_g}} = \rho_j^g P_{srv_j} \tag{13}$$

Then,

$$-\frac{\partial^2 U_j}{\partial p_{s_j}^2} - \sum_{g=1,g\neq j}^{G} \left|\frac{\partial^2 U_j}{\partial p_{s_j}\partial p_{s_g}}\right| = P_{srv_j}(\rho_j^j - \sum_{g=1,g\neq j}^{G} \rho_j^g) \geq 0 \quad (14)$$

Thus, the game $\Psi(\mathbf{q}_s, \xi, \mathbf{p}_c)$ admits a unique Nash equilibrium point.

F. Beaconing duration game

A $NPQBCG$ in beaconing duration ξ is defined for fixed $\mathbf{p}_s \in P_s$, $\mathbf{q}_s \in Q_s$ and $\mathbf{p}_c \in P_c$ as $\Psi(\mathbf{p}_s, \mathbf{q}_s, \mathbf{p}_c) = [G, \{\xi_j\}, \{U_j(\mathbf{p}_s, \mathbf{q}_s, ., \mathbf{p}_c)\}]$.

Definition 2 *A beaconing vector $\xi^* = (\xi_1^*, ..., \xi_G^*)$ is a Nash equilibrium of the $NPQBCG$ $\Psi(\mathbf{p}_s, \mathbf{q}_s, \mathbf{p}_c)$ if:*

$$\begin{aligned} &\forall (j, \xi_j) \in (G, \Xi_j),\\ &U_j(\mathbf{p}_s, \mathbf{q}_s, \xi_j^*, \xi_{-j}^*, \mathbf{p}_c) \geq U_j(\mathbf{p}_s, \mathbf{q}_s, \xi_j, \xi_{-j}^*, \mathbf{p}_c) \end{aligned} \quad (15)$$

Theorem 2 *For each $\mathbf{q}_s \in Q_s$, $\mathbf{p}_s \in P_s$ and $\mathbf{p}_c \in P_c$, the game $[G, \{\xi_j\}, \{U_j(\mathbf{p}, \mathbf{q}_s, .)\}]$ admit a unique Nash equilibrium.*

$$\begin{aligned} \frac{\partial^2 U_j}{\partial \xi_j^2} =& (u_j - \nu_j(F - \sum_{f=1}^{F} h_{jf}))\\ &\times \frac{e^{-\lambda_j(\xi_j+T)}(e^{-\lambda_j m} - 1)(-2\delta_j^i + d_j\lambda_j)}{e^{\lambda_j T} - 1} \end{aligned} \quad (16)$$

where $u_j = \sum_{f=1}^{F} \Theta_f\{(p_{s_j} - p_{t_j})(1 - h_{jf}) + (p_{s_j} + p_{c_j} - \mu_j)h_{jf}\}$.

we assume $u_j \geq \nu_j(F - \sum_{f=1}^{F} h_{jf})$ and $e^{-\lambda_j m} \leq 1$ then,

$$\frac{\partial^2 U_j}{\partial \xi_j^2} \leq 0 \quad (17)$$

The second derivative of the utility function is negative, then the utility function is thus concave, which ensures existence of a Nash equilibrium in the game $\Psi(\mathbf{p}_s, \mathbf{q}_s, \mathbf{p}_c)$.

We use the following proposition that holds for a concave game [26]: If a concave game satisfies the dominance solvability condition :

$$-\frac{\partial^2 U_j}{\partial \xi_j^2} \geq \sum_{g=1,g\neq j}^{G} \left|\frac{\partial^2 U_j}{\partial \xi_j \partial \xi_g}\right| \quad (18)$$

then the game $\Psi(\mathbf{p}_s, \mathbf{q}_s, \mathbf{p}_c)$ admits a unique Nash equilibrium point.

The mixed partial is written as:

$$\begin{aligned} \frac{\partial^2 U_j}{\partial \xi_j \partial \xi_g} =& -\frac{P(T_j > T_n)\lambda_j e^{-\lambda_j T}(e^{\lambda_j m} - 1)\lambda_g e^{\lambda_g T}}{(e^{\lambda_j T} - 1)}\\ &\times (e^{-\lambda_g m} - 1)(u_j - \nu_j(F - \sum_{f=1}^{F} h_{jf}))d_j e^{-\lambda_j \xi_j - \lambda_g \xi_g}\\ &+ \frac{\lambda_j e^{-\lambda_j T}(e^{\lambda_j m} - 1)\delta_j^g(u_j - \nu_j(F - \sum_{f=1}^{F} h_{jf}))e^{-\lambda_j \xi_j}}{e^{\lambda_j T} - 1}\\ &+ \frac{\delta_j^j(u_j - \nu_j(F - \sum_{f=1}^{F} h_{jf}))\lambda_g e^{\lambda_g T}(e^{-\lambda_g m} - 1)e^{\lambda_g \xi_n}}{e^{-\lambda_g} - 1} \end{aligned} \quad (19)$$

then,

$$\begin{aligned} &-\frac{\partial^2 U_j}{\partial \xi_j^2} - \sum_{g=1,g\neq j}^{G} \left|\frac{\partial^2 U_j}{\partial \xi_j \partial \xi_g}\right| = \frac{\lambda_j e^{-\lambda_j(T+\xi_j)}(e^{-\lambda_j m} - 1)}{e^{\lambda_j T} - 1}\\ &\times (u_j - \nu_j(F - \sum_{f=1}^{F} h_{jf}))(2\delta_j^j - \sum_{g=1,g\neq j}^{G} \delta_j^g)\\ &+ \frac{e^{-\lambda_j \xi_j}(e^{-\lambda_j m} - 1)}{e^{\lambda_j T} - 1} u_j - \nu_j(F - \sum_{f=1}^{F} h_{jf})d_j\\ &\times (-\lambda_j^2 e^{-\lambda_j \xi_j} + \lambda_j e^{-\lambda_j T} \sum_{g=1,g\neq j}^{G} P(T_j > T_g)\lambda_n\\ &\times (e^{-\lambda_g m} - 1)e^{-\lambda_g \xi_g} \frac{e^{\lambda_g T}}{e^{\lambda_g} - 1}\\ &+ \delta_j^j(u_j - \nu_j(F - \sum_{f=1}^{F} h_{jf}))(\frac{\lambda_j e^{-\lambda_j(T+\xi_j)}(e^{-\lambda_j m} - 1)}{e^{\lambda_j T} - 1}\\ &- \sum_{g=1,g\neq j}^{G} \frac{\lambda_g e^{\lambda_g(T-\xi_g)}(e^{-\lambda_g m} - 1)}{e^{\lambda_g} - 1}) \geq 0 \end{aligned} \quad (20)$$

Thus, the game $\Psi(\mathbf{p}_s, \mathbf{q}_s, \mathbf{p}_c)$ admits a unique Nash equilibrium point.

G. Quality of service game

A $NPQBCG$ in QoS is defined for fixed $\mathbf{p}_s \in P_s$, $\xi \in \Xi$ and $\mathbf{p}_c \in P_c$ as $\Psi(\mathbf{p}_s, \xi, \mathbf{p}_c) = [G, \{Q_{s_j}\}, \{U_j(\mathbf{p}_s, ., \xi, \mathbf{p}_c\}]$.

Definition 3 *A QoS vector $\mathbf{q}_s^* = (q_{s_1}^*, ..., q_{s_G}^*)$ is a Nash equilibrium of the $NPQBCG$ $\Psi(\mathbf{p}_s, \xi, \mathbf{p}_c)$ if*

$$\begin{aligned} &\forall (j, q_{s_j}) \in (G, Q_{s_j}),\\ &U_j(\mathbf{p}_s, q_{s_j}^*, \mathbf{q}_{s_{-j}}^*, \xi, \mathbf{p}_c) \geq U_j(\mathbf{p}_s, q_{s_j}, \mathbf{q}_{s_{-j}}^*, \xi, \mathbf{p}_c) \end{aligned}$$

Theorem 3 *For each $\mathbf{p} \in P_s$, $\xi \in \Xi$ and $\mathbf{p}_c \in P_c$ the game $[G, \{Q_{s_j}\}, \{U_j(\mathbf{p}, ., \xi, \mathbf{p}_c\}]$ admits a unique Nash equilibrium.*

$$\frac{\partial^2 U_j}{\partial q_{s_j}^2} = -2\nu_j(F - \sum_{f=1}^{F} h_{jf}) \leq 0 \quad (21)$$

the utility function is concave, which ensures existence of a Nash equilibrium point in the game $\Psi(\mathbf{p}, \xi, \mathbf{p}_c)$.

In order to prove uniqueness, we follow, [27], and define the weighted sum of user utility functions.

$$\psi(\mathbf{q}_s, \mathbf{x}) = \sum_{j=1}^{G} x_j U_j(q_{s_j}, \mathbf{q}_{s_{-j}}) \quad (22)$$

The pseudo-gradient of (22) is given by:

$$v(\mathbf{q}_s, \mathbf{x}) = \left[x_1 \nabla U_1(q_{s_1}, q_{s_{-1}}), ..., x_G \nabla U_G(q_{s_G}, \mathbf{q}_{s_{-G}})\right]^T \quad (23)$$

The Jacobian matrix J of the pseudo-gradient (w.r.t.q) is written:

$$J = \begin{pmatrix} x_1\frac{\partial^2 U_1}{\partial q_{s_1}^2} & x_1\frac{\partial^2 U_1}{\partial q_{s_1}\partial q_{s_2}} & . & . & . & x_1\frac{\partial^2 U_1}{\partial q_{s_1}\partial q_{s_G}} \\ x_2\frac{\partial^2 U_2}{\partial q_{s_2}\partial q_{s_1}} & x_2\frac{\partial^2 U_2}{\partial q_{s_2}^2} & . & . & . & x_2\frac{\partial^2 U_2}{\partial q_{s_2}\partial q_{s_G}} \\ . & . & . & & & . \\ . & . & & . & & . \\ . & . & & & . & . \\ x_G\frac{\partial^2 U_G}{\partial q_{s_G}\partial q_{s_1}} & x_G\frac{\partial^2 U_G}{\partial q_{s_G}\partial q_{s_2}} & . & . & . & x_G\frac{\partial^2 U_G}{\partial q_{s_G}^2} \end{pmatrix}$$

$$= \begin{pmatrix} \Lambda_1 & 0 & . & . & . & 0 \\ 0 & \Lambda_2 & . & . & . & 0 \\ . & . & . & & & . \\ . & . & & . & & . \\ . & . & & & . & . \\ 0 & 0 & . & . & . & \Lambda_G \end{pmatrix}$$

where $\Lambda_i = -2x_i\nu_i(F - \sum_{f=1}^{F} h_{if})$, $i = 1, ..., G$.

Thus, J is a diagonal matrix with negative diagonal elements. This implies that J is negative definite. Henceforth $[J + J^T]$ is also negative definite, and according to Theorem (6) in, [27], the weighted sum of the utility functions $\psi(q_s, x)$ is diagonally strictly concave. Thus, the game $G(\mathbf{p}, \xi)$ admits a unique Nash equilibrium point is unique.

H. Fee P_c game

A $NPQBCG$ in fee p_c is defined for fixed $\mathbf{p}_s \in P_s$, $\mathbf{q}_s \in Q_s$ and $\xi \in \Xi$ as $\Psi(\mathbf{p}_c, \mathbf{q}_s, \xi) = [G, \{P_{s_j}\}, \{U_j(\mathbf{p}_s, \mathbf{q}_s, \xi, .)\}]$.

Definition 4 *A fee vector $\mathbf{p_c}^* = (p_{c_1}^*, ..., p_{c_G}^*)$ is a Nash equilibrium of the $NPQBCG$ $\Psi(\mathbf{p}_s, \mathbf{q}_s, \xi)$ if:*

$$\begin{aligned} &\forall (j, p_{c_j}) \in (G, P_{c_j}), \\ &U_j(\mathbf{p}_s, \mathbf{q}_s, \xi, p_{c_j}^*, \mathbf{p}_{c_{-j}}^*) \geq U_j(\mathbf{p}_s, \mathbf{q}_s, \xi, p_{c_j}, \mathbf{p}_{c_{-j}}^*) \end{aligned} \quad (24)$$

Theorem 4 *For each $\mathbf{p}_s \in P_s$, $\mathbf{q}_s \in Q_s$ and $\xi \in \Xi$ the game $[G, \{P_{s_j}\}, \{U_j(\mathbf{p}_s, \mathbf{q}_s, \xi, .)\}]$ admit a unique Nash equilibrium.*

$$\frac{\partial^2 U_j}{\partial p_{c_j}^2} = -2\alpha_j^j P_{srv_j} \sum_{f=1}^{F} \Theta_f h_{jf} \leq 0 \quad (25)$$

The second derivative of the utility function is negative, then the utility function is thus concave, which ensures existence of a Nash equilibrium point in the game $\Psi(\mathbf{q}_s, \xi, \mathbf{p}_c)$.

We use the following proposition that holds for a concave game [26] : If a concave game satisfies the dominance solvability condition :

$$-\frac{\partial^2 U_j}{\partial p_{c_j}^2} \geq \sum_{g=1, g\neq j}^{G} \left| \frac{\partial^2 U_j}{\partial p_{c_j}\partial p_{c_g}} \right| \quad (26)$$

then the game $\Psi(\mathbf{p}_s, \mathbf{q}_s, \xi)$ admits a unique Nash equilibrium.

The mixed partial is written as:

$$\frac{\partial^2 U_j}{\partial p_{c_j}\partial p_{c_g}} = \alpha_j^g P_{srv_j} \sum_{f=1}^{F} \Theta_f h_{jf} \quad (27)$$

Then,

$$-\frac{\partial^2 U_j}{\partial p_{c_j}^2} - \sum_{g=1, g\neq j}^{G} \left| \frac{\partial^2 U_j}{\partial p_{c_j}\partial p_{c_g}} \right| = (2\alpha_j^j - \sum_{g=1, g\neq j}^{G} \alpha_j^g) \times P_{srv_j} \sum_{f=1}^{F} \Theta_f h_{jf} \geq 0 \quad (28)$$

Thus, the game $\Psi(\mathbf{p}_s, \mathbf{q}_s, \xi)$ admits a unique Nash equilibrium point.

I. Learning Nash equilibrium

The problem presented in this document respects the uniqueness of equilibrium of NASH. After step Nash's uniqueness of equilibrium comes the second step on how to design an algorithm that converges to this equilibrium.

The fundamentals of the best dynamic response schemes, which can lead to a Nash equilibrium can be represented according to the following description: Let G be a non-cooperative strategic game. Maximizing utility by UAV's response strategy by considering the strategies of other UAVs is the best. The importance of best response is useful if the game converges to a stable state ie Nash equilibrium.

A better dynamic response scheme is formed by a sequence of steps, the next step of each UAV is based on a policy applied by these competitors to previous steps, it has integrated into its process to update its policy. At the start, the first round begins with an arbitrary choice by UAV of its best response. To achieve Nash equilibrium, the following algorithm represents the Best Response learning steps that each UAV performs.

Algorithm 1 Best response Algorithm

1: Initialize vectors $x(0) = [x_1(0), ..., x_g(0)]$ randomly;
2: **For each** UAV_g, $g \in \mathscr{G}$ at time instant t computes:
- $x_g(t+1) = \underset{x_g \in X_g}{\text{argmax}} \, (U_g(x(t)))$.

3: **If** $\forall g \in \mathscr{G}$, $|x_g(t+1) - x_g(t)| < \epsilon$, then STOP.
4: **Else**, $t \leftarrow t + 1$ and go to step (2)

Such as:

- x refers to the vector price p_c, vector price p_s, vector q_s or vector ξ.
- X_g refers to the policy profile price, QoS or beconing.

IV. NUMRICAL RESULTS

In this section, our experiments are conducted using MATLAB as a numerical simulation tool. In which the performance and efficiency of the proposed non-cooperative model are analyzed by considering two UAVs competing with each other for mobile users on the ground during a fixed period. The main objective of this work is to analyze the effect of many different parameters, such as service access rate, caching cost, QoS, and beaconing.

The analysis of funding for the implementation of the proposed approach shows that the best response algorithm

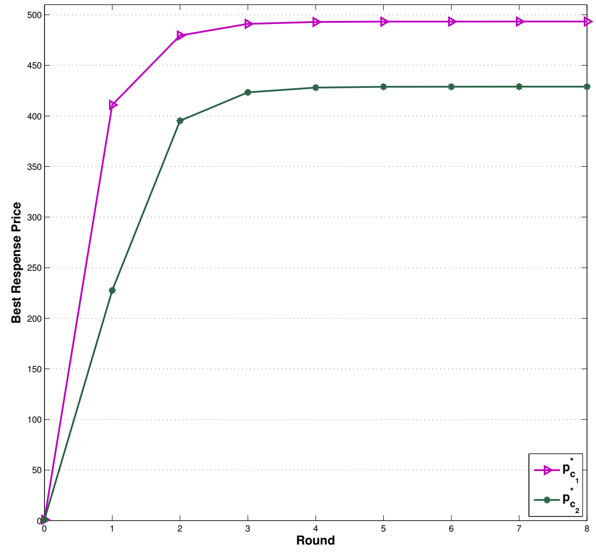

Fig. 2. Convergence of the content access fee p_c.

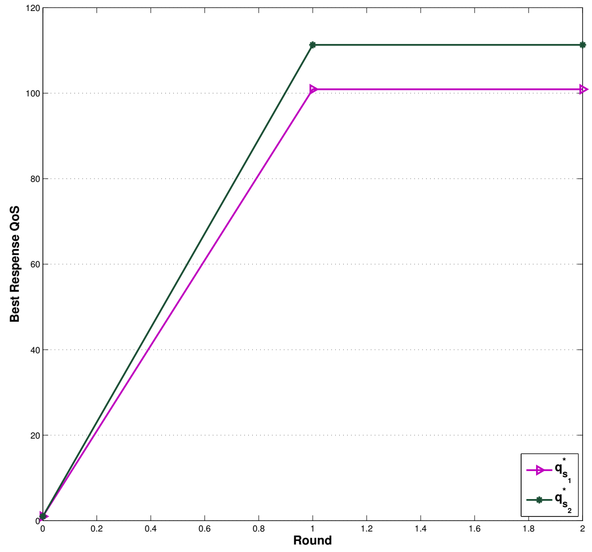

Fig. 4. Convergence of the quality of service q_s.

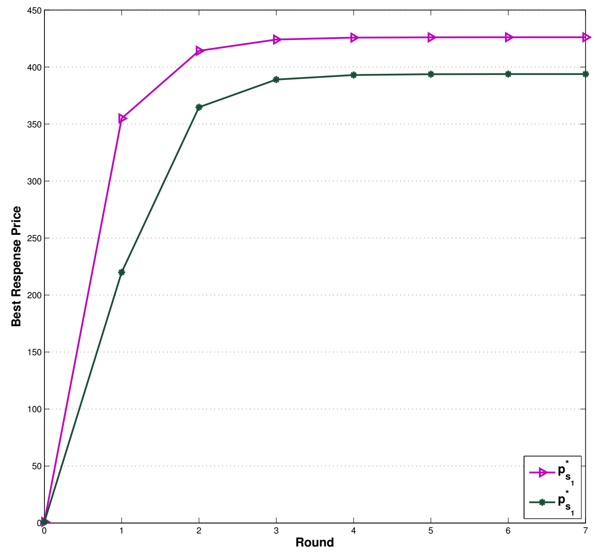

Fig. 3. Convergence of the network access fee p_s.

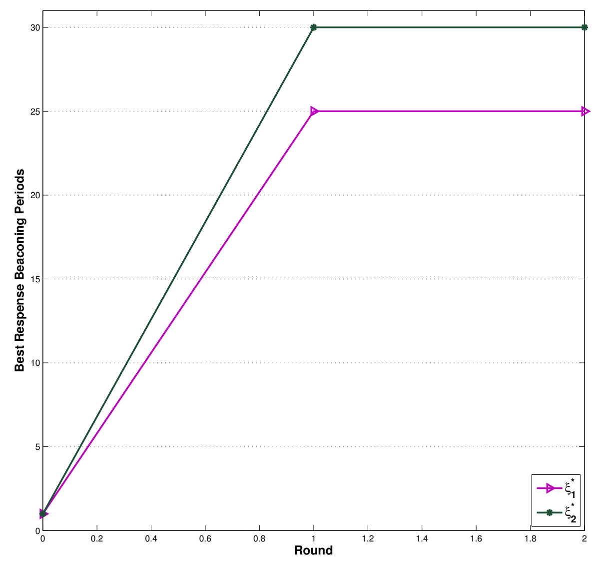

Fig. 5. Convergence of the beaconing periods ξ.

converges to the Nash equilibrium for fee, QoS, and beaconing periods. More importantly, we can see that with the best response algorithm, the UAV based network as expected converge quickly to the state represented by the Nash equilibrium. Figures 2, 3, 4 and 5 provide a constructive proof for the existence and uniqueness of equilibria in this setting, especially for equilibrium fee, QoS, and beaconing periods.

Both Figures 6 and 7 illustrate the fee of both network access and the content access in the equilibrium state as in function of the number of F elements. That is, as the number of elements increases, then the number of cached elements increase as well. In addition, as the number of cached content increases, so do the caching costs. Accordingly, the UAVs will increase their fee to cover the increased cost of caching services. This conclusion is somewhat intuitive because a drone-based antenna system generates significant profits with a better pricing strategy. Furthermore, there is an effect of the number of elements F on the beaconing periods as shown in 8. As a result, the beaconing period of the proposed model increases as F increases; this is because a larger number of elements allow more content to be cached so as to easily fulfill end-users requests.

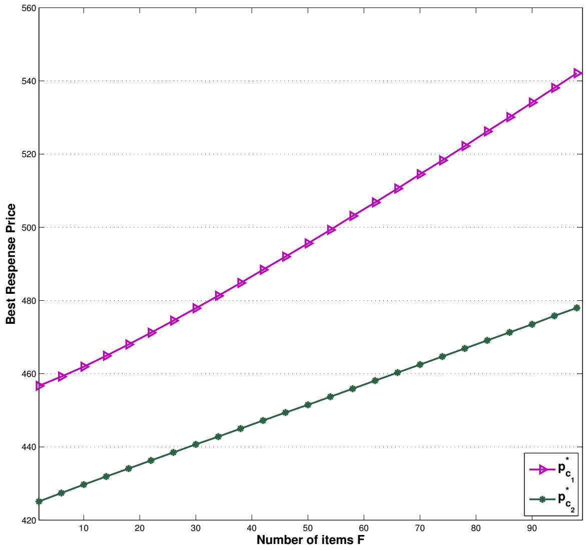

Fig. 6. Impacts of the number of items F on the content access fee.

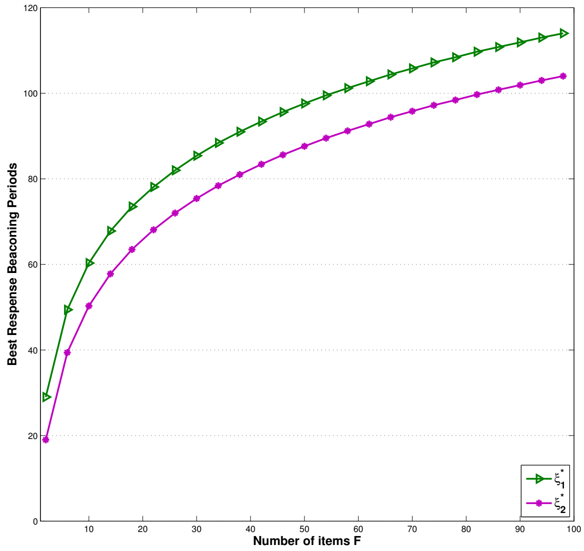

Fig. 8. Impacts of the number of items F on the beaconing periods.

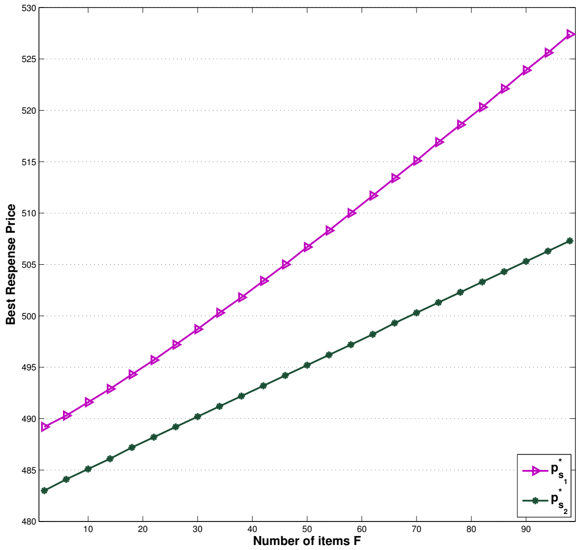

Fig. 7. Impacts of the number of items F on the network access fee.

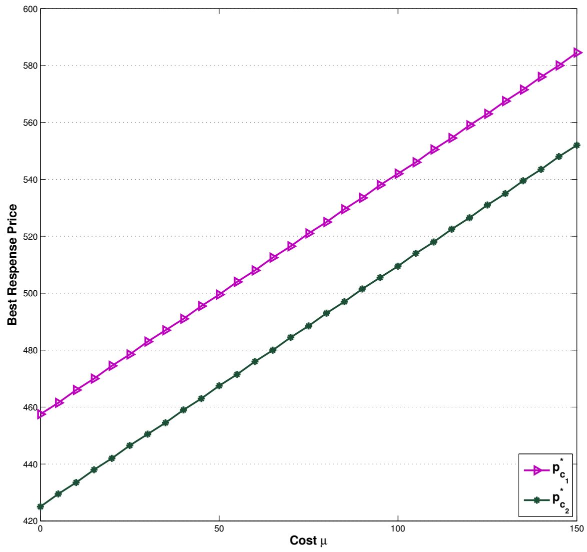

Fig. 9. Content access fee at different fixed cost μ

In the same line, Figures 9 and 10 illustrate the access fee of both network and content for different values of caching cost, respectively. Of course, the Nash equilibrium fee is found to be minimal with a low caching cost, and from a certain value of caching cost, the network access fee and content access fee increase. One reason for this is that once the caching cost becomes expensive, the UAVs are forced to raise their fee to compensate the caching fee increases.

Figures 11 and 12 show the impact of beaconing duration on both network access fee and content access fee. As the beaconing duration increases the network access fee and content access fee increases. The main reason is that the beaconing duration increases when the energy cost increases as well. Consequently, the UAV-based data communication in wireless sensor networks raise when the network access fee and the content access fee increase in order to compensate the increase in the energy cost.

Figures 13, 14 and 15 show the influence of backhaul bandwidth cost on network access fee, content access fee and QoS. In this respect, network access fee and content access fee increases, as the bandwidth cost gets higher. In the same manner, we note that the quality of service is decreasing with

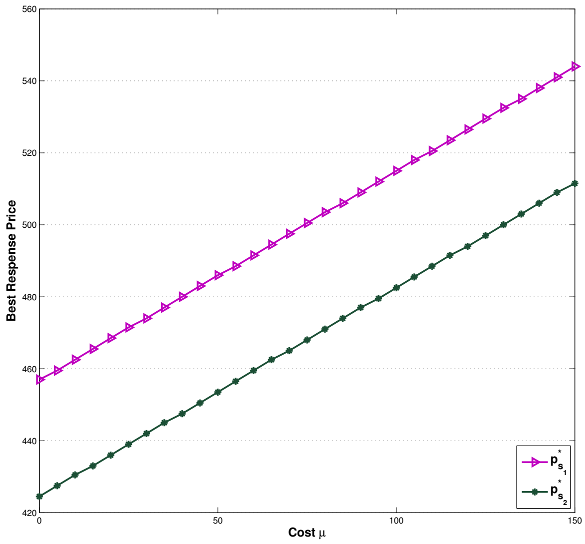

Fig. 10. Network access fee at different fixed cost μ.

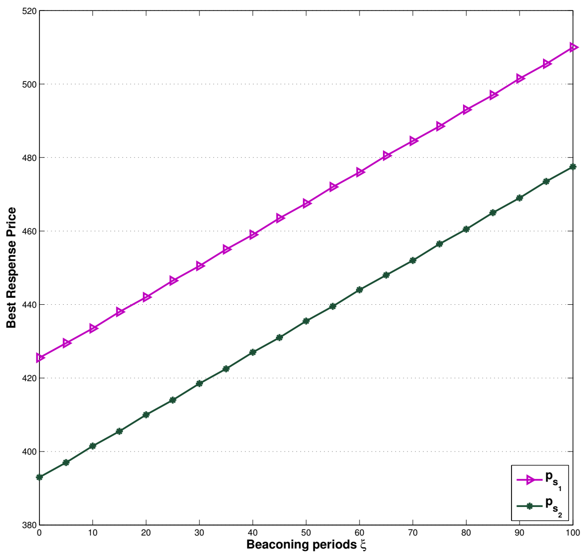

Fig. 11. Network access fee versus beaconing periods

the bandwidth cost. For a given bandwidth cost determined by the network provider, the UAV-based network provider is forced to decrease its fees and improve its QoS. This strategy would cause the demand for end-users requests to increase. However, as bandwidth cost increases, the UAV-based network needs to slightly increase the fee and decreases the QoS to compensate the expected increase in the bandwidth cost.

Figures 16 and 17 illustrate the influence of energy cost on the beaconing duration and QoS. Generally, as the energy cost increases, the beaconing duration and QoS decreases. Most obviously, increasing energy cost leads to lower incentives

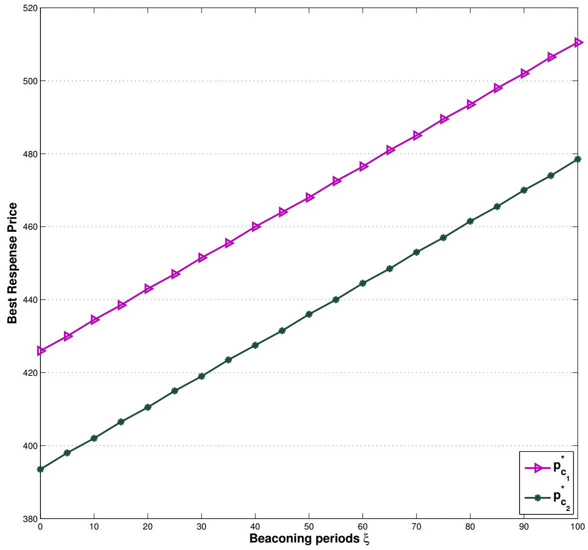

Fig. 12. Content access fee versus beaconing periods ξ.

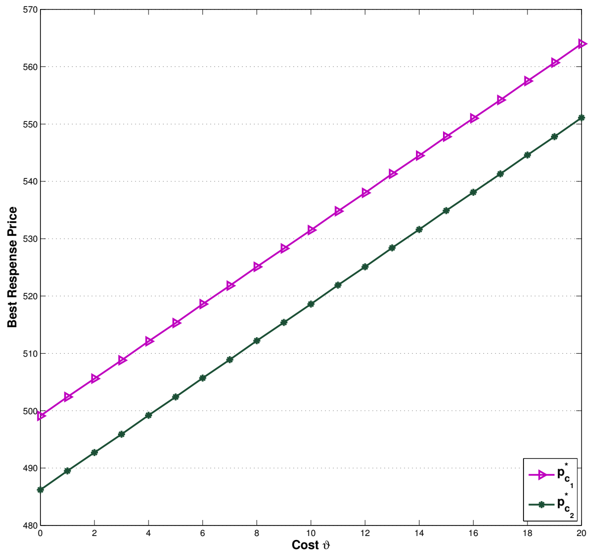

Fig. 13. Content access fee varies with the cost ϑ

to invest for UAVs providers in bandwidth, QoS and mobile beacon to better serve ground users.

In light of the above results of the numerical simulation, caching the popular contents in intermediate nodes has, to our knowledge, never been considered. Thus, we have demonstrated that caching-based architecture is the most cost-effective solution to increase the reliability of UAV-based communication.

V. Conclusion

With the ongoing development of smart cities, using UAVs as a flying relay is expected to be the most important element

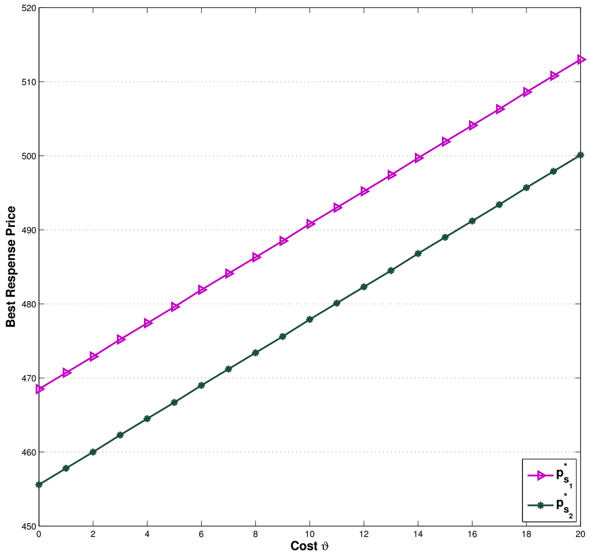

Fig. 14. Network access fee varies with the cost ϑ

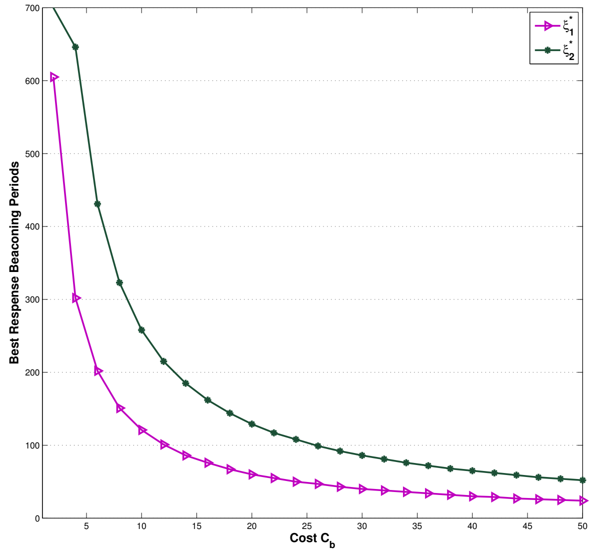

Fig. 16. The impact of the energy cost C_b on the beaconing periods.

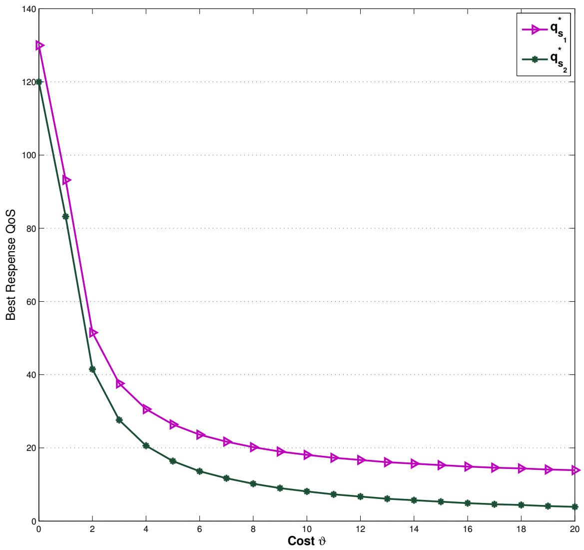

Fig. 15. Quality of service varies with the cost ϑ

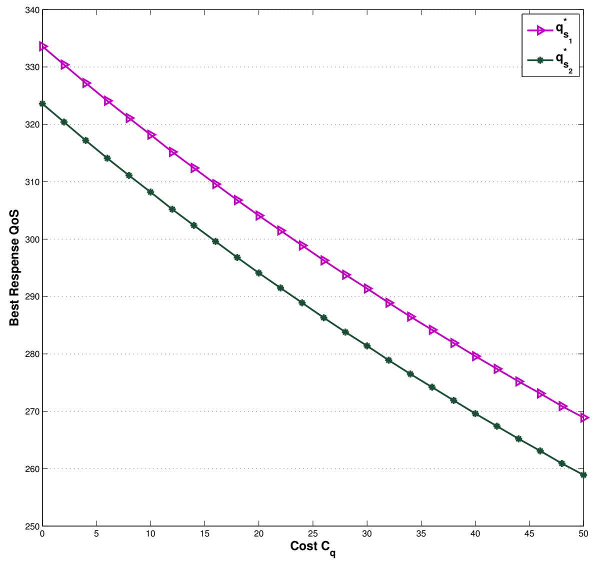

Fig. 17. The impact of the energy cost C_q on the quality of service.

that will ensure the future success of reliable and robust communication systems. In this paper, we highlight the role of game theory models in designing and deployment of UAV-supported 5G network to assist and forward information to the mobile devices in full duplex. To this aim, we formulate the competition among UAVs as primary components of non-cooperative game to determine the optimal solution with the property that no single UAV can obtain a higher expected payoff. Our analysis focuses on several indicators such as beaconing time, fee to support caching of data, and QoS requirements. In this respect, we need to conduct a comprehensive analysis of this competitive game among drones to prove the existence and uniqueness of Nash equilibrium that maximizes network coverage to mobile ground-based units. More importantly, a Bertrand game model with fairness concern is established, and its equilibrium fee is derived and analyzed. More practically, numerical experiments are carried out to investigate the factors, which affect the drones' strategies. When it comes to adopting a competitive strategy, theoretical analysis and simulation results show that QoS standards, fee option and competition policy have a significant influence on the expected profits. As a future work, we propose a new

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Mohamed El Amrani received the Ph.D. degrees from University Sultan Moulay Slimane, Morocco, in 2021. His research interests include network economics, network security, applications of game theory in wireless networks, and radio resource management.

Hamid Garmani is a Professor of computer science in the Faculty of Sciences and Techniques, Sultan Moulay Slimane University, Morocco. His research interests include network economics, network security, applications of game theory in wireless networks, and radio resource management.

Driss Ait Omar is a Professor of computer science in the Faculty of Sciences and Techniques, Sultan Moulay Slimane University, Morocco. His research interests include network economics, network security, applications of game theory in wireless networks, and radio resource management.

Mohamed Ouaskou is a PhD student at the Faculty of Sciences and Technology, University Sultan Moulay Slimane, Morocco. His research interests include network economics and applications of game theory in wireless networks.

Abdelkarim Ait Temghart is a PhD student at the Faculty of Sciences and Technology, University Sultan Moulay Slimane, Morocco. His research interests include network economics and applications of game theory in wireless networks.

Mohamed Baslam is a Professor of computer science in the Faculty of Sciences and Technology, Sultan Moulay Slimane University, Morocco. His current research interests include performance evaluation and optimization of networks based on game-theoretic and queuing models, applications in communication/transportation and social networks, such as wireless flexible networks, bio-inspired and self-organizing networks, and economic models of the Internet and yield management.