AN AUCTION-BASED FRAMEWORK FOR MULTIMEDIA STREAMING OVER COGNITIVE RADIO NETWORKS

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ABSTRACT

Recently, many works have been proposed in the area of cognitive radio to efficiently utilize the spectrum for data communication. However, little effort has been made in content-aware multimedia applications over cognitive radio networks. In this paper, we study the multimedia streaming problem over cognitive radio networks. The uniquely scalable and delay-sensitive characteristics of multimedia data and the resulting impact on users' viewing experiences of multimedia content are explicitly involved in the utility functions, due to which the primary user and the secondary users can seamlessly switch among different quality levels to achieve the greatest utilities. Then, we formulate the spectrum allocation problem as an auction game and propose a distributively auction-based spectrum allocation scheme, which is spectrum allocation using Alternative Ascending Clock Auction (ACA-A). We prove that ACA-A is cheat-proof and can maximize the social welfare. Finally, simulation results are presented to demonstrate the efficiency of the proposed algorithms.

Index Terms— Multimedia, cognitive radio networks, auction, game theory, cheat-proof, social welfare.

1. INTRODUCTION

Cognitive radio is a technology that can enable the wireless devices to dynamically access the spectrum. In the literature, researchers have proposed various approaches to optimally share the spectrum using cognitive radio technologies in different scenarios. The authors in [1] proposed to use local bargaining to achieve distributed conflict-free spectrum assignment while those in [2] formulated the spectrum access problem as a noncooperative game and proposed a learning-based distributed algorithm to obtain the correlated equilibrium as a solution. Auction and pricing approaches were also proposed for efficient spectrum allocation [3]. In [4], auction mechanisms for spectrum sharing among a group of users was studied. A belief-assisted distributive double auction that maximizes both primary and secondary users' revenues was proposed in [5].

While these game theoretic approaches have achieved promising results, they cannot be directly used in content-aware multimedia applications since they are designed for data communications but do not explicitly consider the characteristics of the video content and the resulting impact on video quality. In this paper, we specifically consider the unique characteristics of multimedia content and study multimedia streaming over cognitive radio networks, where there is one primary user and N secondary users. In this problem, the objective of the primary user is to maximize his/her revenue by choosing either to self-utilize the spectrum or to sell the spectrum to the secondary users, while the objective of each secondary user is to maximize the payoff by competing with other secondary users to buy the spectrum for streaming. We propose an auction-based framework to distributively and efficiently allocate the spectrum for multimedia streaming. We prove and demonstrate with simulation results that the proposed approach is cheat-proof and can maximize the social welfare.

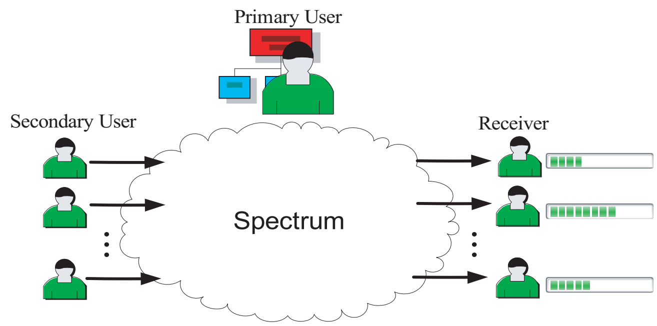

Fig. 1. The system model.

The rest of this paper is organized as follows. In Section 2, we introduce the system model and the utility function. In Section 3, we present the problem formulation and the proposed spectrum allocation scheme. In Section 4, we provide a detailed analysis of the proposed schemes. Finally, we illustrate the simulation results in Section 5 and draw conclusions in Section 6.

2. SYSTEM MODEL AND UTILITY FUNCTION

2.1. System Model

As shown in Figure 1, we consider a multimedia cognitive network with one primary user (PU) and N secondary users (SUs), u_1, u_2, ..., u_N. The PU can choose to utilize the spectrum himself/herself or to sell the available spectrum to SUs who are willing to buy spectrum for streaming multimedia data. In this case, once the PU announces the availability of spectrum, SUs will compete with each other to buy the spectrum. Then, the PU allocates bandwidth to SUs and each SU transmits multimedia streams to the corresponding receiver using the allocated bandwidth. We assume that each SU has a corresponding receiver with a buffer long enough for real-time playback. Now, the problem becomes how and when the PU sells the spectrum as well as how and when the SUs compete with each other to buy the spectrum.

2.2. Secondary Users' Utility Function

In general, a SU u_i can gain by successfully transmitting the video to the corresponding receiver. On the other hand, u_i needs to pay for the used spectrum to transmit video, and the payment is determined by the amount of the used spectrum and its unit price. Therefore, given the bit-rate r_i, the buffer occupancy at the corresponding receiver B_i, the allocated bandwidth W_i, and the unit price λ, the utility function of u_i can be defined as

$$U_i(r_i, B_i, W_i, \lambda) = \mathcal{F}(r_i, B_i, W_i) - \mathcal{G}(\lambda, W_i), \quad (1)$$

where $\mathcal{F}(r_i, B_i, W_i)$ is the gain, and $\mathcal{G}(\lambda, W_i)$ is the cost. Here, we assume that the source video is compressed using scalable video codec with source rate $\{\zeta_i^1, ..., \zeta_i^{N_r}\}$, which means $r_i \in \{\zeta_i^1, ..., \zeta_i^{N_r}\}$.

Generally speaking, since the cost of u_i is larger if the bandwidth W_i is larger, the function $\mathcal{G}$ should be a monotonically increasing function of W_i. Without loss of generality, we assume that the cost function is linear, which means

$$\mathcal{G}(\lambda, W_i) = \lambda W_i. \quad (2)$$

Since two most important factors that reflect the degree of satisfaction of the receiver's video viewing experience are visual quality and delay, we argue that the gain is determined by the visual quality of the transmitted video and the corresponding receiver's buffer occupancy, which is shown as follows:

$$\mathcal{F}(r_i, B_i, W_i) = \alpha \ln\left(\frac{PSNR_i(r_i)}{PSNR_i(\zeta_i^{N_r})}\right) + \beta \ln\left(\frac{B_i + \tau\frac{W_i}{r_i} + \theta}{B_i + \theta}\right), \quad (3)$$

where α and β are two parameters controlling the balance between the first term and the second term, $\zeta_i^{N_r}$ is the maximal rate, τ is the transmission duration, $B_i + \tau\frac{W_i}{r_i}$ is the buffer occupancy after transmission, and θ is a system parameter which excludes the possibility of zero denominator.

Combining (1)-(3), the utility of u_i becomes

$$\begin{aligned} U_i(r_i, B_i, W_i, \lambda) &= \alpha \ln\left(\frac{PSNR_i(r_i)}{PSNR_i(\zeta_i^{N_r})}\right) \\ &+ \beta \ln\left(\frac{B_i + \tau\frac{W_i}{r_i} + \theta}{B_i + \theta}\right) - \lambda W_i. \quad (4) \end{aligned}$$

2.3. Primary User's Utility Function

Since the PU can choose either to utilize the spectrum himself/herself or to sell the spectrum to SUs, the utility of PU should be the maximum between the profit ($\mathcal{F}_p(W)$) that he/she can obtain if he/she choose to self-utilize the spectrum and the payment ($P(W)$) that he/she can obtain if he/she choose to sell the spectrum to SUs, i.e.

$$U_p(W) = \max(\mathcal{F}_p(W), P(W)), \quad (5)$$

where W is the total bandwidth.

From the above equation, we can see that the PU can at least obtain a profit $\mathcal{F}_p(W)$. Therefore, the PU should not sell the spectrum to SUs if $P(W) < \mathcal{F}_p(W)$. Let λ^0 stand for the lowest unit price (reserve price) at which the PU is willing to sell the spectrum to SUs, then

$$\lambda^0 = \frac{\mathcal{F}_p(W)}{W}. \quad (6)$$

3. SPECTRUM AUCTION GAME

In this section, we will discuss how the PU should sell the spectrum. There are two possible approaches, centralized approach and distributed approach. In the centralized approach, the PU knows exactly all the private information of each SU. In such a case, the PU can allocate the spectrum based on some criteria, such as maximizing social welfare or proportional fairness.

However, in general, the SUs can be geographically distributed in many places, it is therefore not feasible for the PU to collect all the private information of each SU. Moreover, since the SUs are selfish, e.g., they tend to overclaim/underclaim what they may need, they will not truly report their private information if cheating can improve their utilities. In this paper, we propose distributed spectrum allocation schemes based on auction theory [6]. An auction is a decentralized mechanism for allocating resources, where there is an auctioneer and several bidders. The auction procedures can be described as follows: the auctioneer announces a price, the bidders report to the auctioneer their demands at that price, and the auctioneer raises the price until the total demand meets the supply. In our spectrum allocation problem, the PU is the auctioneer and the SUs are the bidders.

3.1. Spectrum Allocation Using Alternative Ascending Clock Auction (ACA-A)

When the PU announces the reserve price λ^0, each SU submits his/her optimal bid W_i^0 by computing

$$(W_i^0, r_i^0) = \arg \max_{(W_i, r_i)} U_i(r_i, B_i, W_i, \lambda^0). \quad (7)$$

Then, the PU sums up all the bids $W_{total}^0 = \sum_i W_i^0$ and compares W_{total}^0 with W. If $W_{total}^0 \leq W$, the PU concludes the auction and chooses to utilize the spectrum himself/herself. Otherwise, the PU sets $\lambda^{t+1} = \lambda^t + \delta$, $t = t + 1$, and announces λ^t

to all the SUs. Then, each SU submits his/her optimal bid W_i^t to the PU by calculating

$$(W_i^t, r_i^t) = \arg\max_{(W_i,r_i)} U_i(r_i, B_i, W_i, \lambda^t). \quad (8)$$

After collecting all the bids, the PU compares the total bid W_{total}^t with the available bandwidth W. If $W_{total}^t > W$, the auction is not concluded. The PU computes the *cumulative clinch*, which is the amount of bandwidth that the user is guaranteed to win at clock t, for each SU using

$$C_i^t = \max(0, W - \sum_{j\neq i} W_j^t), \quad (9)$$

and continues the auction until $W_{total}^t \leq W$. Let the final clock index be L. As λ increases discretely, we may have $W_{total}^t < W$ and do not fully utilize the bandwidth. To make sure that $W_{total}^t = W$, we modify W_i^L by introducing proportional rationing [6]. Then, the final cumulative clinch of u_i is given by

$$C_i^L = W_i^L + \frac{W_i^{L-1} - W_i^L}{\sum_i W_i^{L-1} - \sum_i W_i^L}[W - \sum_i W_i^L], \quad (10)$$

with $\sum_i C_i^L = W$.

Finally, the rate allocated to u_i is $W_i^\star = C_i^L$ and the utility of u_i is computed by

$$U_i^\star = \alpha \ln\left(\frac{PSNR_i(r_i^L)}{PSNR_i(\zeta_i^{N_r})}\right) + \beta \ln\left(\frac{B_i + \tau\frac{W_i^\star}{r_i^L} + \theta}{B_i + \theta}\right) - P_i^\star, \quad (11)$$

where $P_i^\star = C_i^0\lambda^0 + \sum_{t=1}^{L} \lambda^t(C_i^t - C_i^{t-1})$ is the payment.

4. ANALYSIS OF THE SPECTRUM AUCTION GAME

According to (4), we can see that for any fixed r_i, the utility function $U_i(r_i, B_i, W_i, \lambda)$ is a concave function in terms of W_i. By taking the derivative of U_i over W_i, we have

$$\frac{\partial U_i}{\partial W_i} = \frac{\beta\frac{\tau}{r_i}}{B_i + \frac{\tau}{r_i}W_i + \theta} - \lambda. \quad (12)$$

Therefore, for any fixed r_i, $U_i(r_i, B_i, W_i, \lambda)$ achieves the maximal value at

$$W_i^\star(r_i, \lambda) = \min\left(W, \max\left(0, \frac{\beta}{\lambda} - \frac{B_i + \theta}{\tau} r_i\right)\right). \quad (13)$$

By substituting (13) back to the utility function, we can find the optimal $r_i^\star$ that maximizes the utility function

$$r_i^\star(\lambda) = \arg\max_{r_i} f(r_i, \lambda), \quad (14)$$

where $f(r_i, \lambda)$ is defined in (15).

Then, the optimal $W_i^\star$ that achieves the maximal utility becomes

$$W_i^\star(\lambda) = \min\left(W, \max\left(0, \frac{\beta}{\lambda} - \frac{B_i + \theta}{\tau} r_i^\star(\lambda)\right)\right), \quad (16)$$

where $r_i^\star(\lambda)$ is defined in (14).

In the following ***Theorem 1*** and ***2***, we prove that the proposed ACA-A algorithm is cheat-proof and can maximize social welfare. Therefore, ACA-A is a good solution to multimedia cognitive radio networks.

Theorem 1: In ACA-A algorithm, reporting true optimal demand at every clock is a mutually best response for every user, i.e. ACA-A algorithm is cheat-proof.

Proof: Due to page limitation, we show the proof in the supplementary information [7].

Theorem 2: When δ is sufficiently small, ACA-A will converge to $(W_1^\star, r_1^\star, ..., W_N^\star, r_N^\star)$, which maximizes the social welfare, i.e. $(W_1^\star, r_1^\star, ..., W_N^\star, r_N^\star)$ is the solution to the following optimization problem

$$\max_{(W_i,r_i\forall i)} \sum_{i=1}^{N}\left[\alpha\ln\left(\frac{PSNR_i(r_i)}{PSNR_i(\zeta_i^{N_r})}\right) + \beta\ln\left(\frac{B_i + \tau\frac{W_i}{r_i} + \theta}{B_i + \theta}\right)\right],$$
$$s.t.\ 0 \leq W_i \leq W, \forall i = 1, ..., N,$$
$$\sum_{i=1}^{N} W_i = W. \quad (17)$$

Proof: Due to page limitation, we show the proof in the supplementary information [7].

5. SIMULATION RESULTS

In order to evaluate the proposed spectrum allocation scheme, we conduct simulation on real video data. Five video sequences: Akiyo, Carphone, Foreman, Football, and Mobile in QCIF format, are tested. Notice that these video sequences include slow, medium or fast motion, and smooth or complex scene. We use the state-of-art scalable video codec (JSVM 9.17) to encode the video sequences [8]. By utilizing the SNR scalability, we compress each video sequence at three different quality layers. We compare the proposed ACA-A with two approaches: the dual-based optimization algorithm that maximizes social welfare, which is denoted as DBOA [9], and the second-price sealed-bid auction that has the cheat-proof property, which is denoted as SPSBA [10].

We first evaluate the cheat-proof performance of DBOA and ACA-A. We assume that the SU u_3 who transmits Foreman will cheat while other users are honest. We assume that u_3 reports a false demand $\tilde{W}_3^t$ by scaling the optimal demand W_3^t with a factor k, i.e. $\tilde{W}_3^t = \min(W, \max(0, kW_3^t))$. As shown in Figure 2, we can see that with DBOA, u_3 achieves the maximal utility when k is around 0.7. Therefore, all SUs have the incentive to report a smaller demand at every clock. In this case, the auction will conclude at a lower price. Thus, DBOA is not cheat-proof. However, with ACA-A, we can see that u_3 achieves the maximal utility

$$f(r_i,\lambda)=\begin{cases}\alpha\ln\left(\frac{PSNR_i(r_i)}{PSNR_i(\zeta_i^{N_r})}\right)+\beta\ln\left(B_i+\tau\frac{W}{r_i}+\theta\right)-\lambda W-\beta\ln\left(B_i+\theta\right), & \text{if } \frac{\beta}{\lambda}-\frac{B_i+\theta}{\tau}r_i>W;\\ \alpha\ln\left(\frac{PSNR_i(r_i)}{PSNR_i(\zeta_i^{N_r})}\right)+\beta\ln\left(\frac{\beta\tau}{\lambda r_i}\right)-\beta+\lambda\frac{B_i+\theta}{\tau}r_i-\beta\ln\left(B_i+\theta\right), & \text{if } 0\le\frac{\beta}{\lambda}-\frac{B_i+\theta}{\tau}r_i\le W;\\ \alpha\ln\left(\frac{PSNR_i(r_i)}{PSNR_i(\zeta_i^{N_r})}\right), & \text{if } \frac{\beta}{\lambda}-\frac{B_i+\theta}{\tau}r_i<0.\end{cases}\quad(15)$$

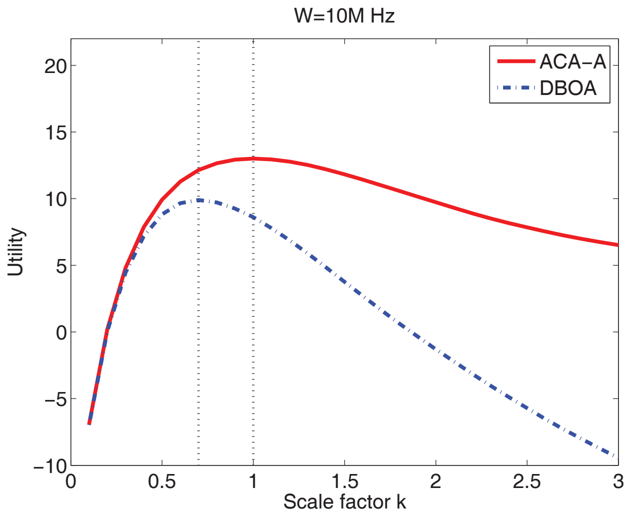

Fig. 2. The cheat-proof performance of ACA-A and DBOA algorithms.

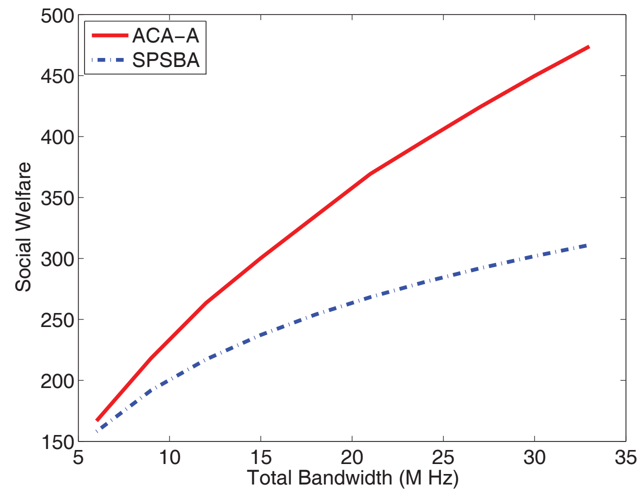

Fig. 3. The social welfare comparison between ACA-A and SPSBA algorithms.

when $k = 1$, which means that no SUs have the incentive to cheat since any cheating will lead to a lower utility. This simulation result verifies ***Theorem 1***.

Then, we compare ACA-A with SPSBA in terms of social welfare. The results are shown in Figure 3. We can see that ACA-A achieves a much higher social welfare compared with SPSBA. This is because with SPSBA, each SU can only choose to utilize the whole spectrum or not to utilize the spectrum. However, with ACA-A, each SU has the chance to utilize a fraction of the entire spectrum.

6. CONCLUSION

In this paper, we investigate the problem of multimedia streaming over cognitive radio networks and propose an auction-based scheme to distributively allocate the spectrum. We prove and demonstrate with simulation results that the proposed ACA-A algorithm can efficiently allocate the spectrum and achieve maximal social welfare. We also prove and verify with simulations that ACA-A is cheat-proof and can enforce the selfish secondary users to report their true demands at every clock. Furthermore, with the proposed schemes, the primary user and secondary users can seamlessly switch among different quality levels since the uniquely scalable and delay-sensitive characteristics of multimedia data and the resulting impact on users' viewing experiences of multimedia content are explicitly considered in the utility functions.

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