QoE Driven Video Streaming over Cognitive Radio Networks for Multi-User with Single Channel Access

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1. Introduction

A study by Cisco indicates a drastic increase in mobile data and that almost 66% of the mobile data was video-related by 2015 [1]. Such dramatic increase in wireless video traffic, coupled with the depleting spectrum resource, poses great challenges to today's wireless networks. It is of great importance to improve the wireless network capacity by promoting more efficient use of spectrum, which can be accomplished by the cognitive radio (CR) technology. CR is an evolutionary technology for more efficient and flexible access to the radio spectrum. In a cognitive radio network (CRN), Cognitive Users (CUs) search for the unoccupied licensed spectrum of the Primary User (PU) network and then opportunistically access detected spectrum holes in an unobtrusive manner. CR has been recognized as an effective approach to support bandwidth-demanding mobile services such as wireless video streaming [2].

In the area of multimedia communications, subjective assessment methods have been studied intensively [3]. The International Telecommunication Union (ITU) has proposed standards on subjective assessment methods for various application scenarios [4]. For video transmission, quality of experience (QoE) is an effective subjective quality assessment model for the perceptual visual quality of video sequences. One of the most widely used QoE metric is the Mean Opinion Score (MOS) [5]. In the MOS model, the visual quality of a video sequence is not only dependent on the network environment such as packet loss rate, network delay, but also dependent on the content type. For example, under the same network conditions, the visual quality of video contents of fast motions (e.g., sports) is generally worse than that of video contents of slow motions (e.g., news). Since the ultimate goal of most multimedia communication services is to achieve high perceptual quality for viewers, it is desirable to incorporate QoE models in such applications.

In this paper, we address the challenging problem of downlink multi-user video streaming in CRNs. We consider a CRN consisting of one cognitive base station (CBS) and multiple CUs. Without loss of generality, we assume each CU can sense and access one channel at a time. The CUs cooperatively sense the PU signals on licensed channels and the CBS infers the licensed channel states based on the CU sensing results with an OR fusion rule. Once the idle channels are detected, the CBS then assigns them to active CUs for downlink multi-user video streaming. We incorporate the video assessment model proposed in [5], [6], aiming to maximize the CU QoE by optimal designs of spectrum sensing and access policies.

It is obviously a challenging problem to design the access polices for QoE-aware multi-user video streaming, due to the large number of design factors and the complex interactions that should be modeled in a cross- layer optimization framework. We propose a Hungarian method-based approach to achieve optimal solution to the channel assignment problem. Simulation results demonstrate the superior performance of the proposed methods in terms of the MOS that CUs can achieve under various network scenarios.

2. Problem Statement and Solution Algorithm

We consider a primary network operating on N1 orthogonal licensed channels. There is a CR network co-located with the primary network, consisting of a CBS supporting M1 CUs. The CUs sense the PUs' usage of the licensed channels and access the licensed channels in an opportunistic manner. We assume the CUs, when they are not receiving data, measure the SNRs of the PU transmissions over all the licensed channels and report the measured SNRs to the CBS through some feedback mechanism. Based on such feedback, the CBS then assigns those CUs with good channel conditions to sense each licensed channel, so as to improve the sensing performance. We consider the downlink multi-user video streaming scenario, where the CBS streams a video to each active CU using the license channels that are detected idle. We assume time is divided into a series of non-overlap GOP windows, each consisting of T time slots.

1) Formulation of Optimal Assignment Problem for Video Transmission (OAPVT).

We consider the QoE model named Mean Score Opinion (MOS) proposed in [6]. The MOS of CU i during time slot t, denoted by Ψ_{ij}^t, can be expressed as

$$\Psi_{ij}^t = \alpha + CT_i\gamma + (\beta + CT_i\delta)\ln(SBR_{ij}^t)$$
$$= \alpha + CT_i\gamma + (\beta + CT_i\delta)\ln\left(B_j \log_2\left(1 + SNR_{ij}^t\right)\right)$$

where α = 3.9860, β = 0.0919, γ = −5.8497, and δ = 0.9844 are constants, CTi is the Content Type of the video sequences required by CU i, Bj is the bandwidth of channel j in kbps, and SNR_{ij}^t is the SNR of the video signal using channel j measured at CU i at time slot t [6].

We assume that N2 channels are sensed as idle after the sensing phase, where N2 ≤ N1. We consider a general case where not all the CUs have data to receive at all times. Instead, the probability of a CU has data to receive at each GOP window is 0 ≤ ξ ≤ 1. The number of CUs that have data to receive in a GOP window is denoted as M2, where M2 ≤ M1. An M2 × N2 matrix Y is used to represent channel access assignment on time slot t, with the entry given as

$$y_{ij}^t = \begin{cases} 1, \text{assign channel } j \text{ to CU } i \text{ in time slot } t \\ 0, \text{otherwise.} \end{cases}$$

We consider the case where each CU can use at most one channel at each time slot due to hardware constraints, and each channel can be used by at most one CU at each time slot. We aim to maximize the expected average MOS of all the CUs during a GOP window by assigning the available channels.

$$\max : \sum_{i=1}^{M_2} \mathrm{E}\left[\frac{1}{T}\sum_{t=1}^{T}\Psi_i^t\right] = \frac{1}{T}\sum_{t=1}^{T}\sum_{i=1}^{M_2}\mathrm{E}\left[\Psi_i^t\right].$$

The above objective function can be maximized if we maximize the expected MOS increment of the M2 CUs during each time slot [2], which can be written as

$$\sum_{i=1}^{M_2}\mathrm{E}\left[\Psi_i^t\right] = \sum_{i=1}^{M_2}\sum_{j=1}^{N_2}\mathrm{E}\left[\Psi_{ij}^t\right]y_{ij}^t$$
$$= \sum_{i=1}^{M_2}\sum_{j=1}^{N_2}\left[\Pr\left(H_{0j}^t \mid s_j = 1\right)\phi_{ij}^t + \Pr\left(H_{1j}^t \mid s_j^t = 1\right)\theta_{ij}^t\right]y_{ij}^t,$$

where $s_j^t = 1$ indicates the channel is sensed as idle; $\Pr(H_{0j}^t)$ and $\Pr(H_{1j}^t)$ are the probability of channel j to be idle or busy at time slot t, respectively; $\Pr(H_{0j}^t \left| s_j^t = 1\right.)$ and $\Pr(H_{1j}^t \left| s_j^t = 1\right.)$ are the conditional probability for channel j to be idle or busy conditioned on the sensing result, respectively; μ_{ij}^t and ν_{ij}^t are the received SNR at CU i using channel j which is indeed idle or busy at time slot t, respectively; and

$$\Pr\left(H_{0j}^t \mid s_j^t = 1\right) = \frac{\left(1 - P_{f_j}^t\right)\Pr\left(H_{0j}^t\right)}{\left(1 - P_{d_j}^t\right)\Pr\left(H_{1j}^t\right) + \left(1 - P_{f_j}^t\right)\Pr\left(H_{0j}^t\right)}$$
$$\Pr\left(H_{1j}^t \mid s_j^t = 1\right) = 1 - \Pr\left(H_{0j}^t \mid s_j^t = 1\right)$$
$$\phi_{ij}^t = \alpha + CT_i\gamma + (\beta + CT_i\delta)\ln\left(B_j \log_2\left(1 + \mu_{ij}^t\right)\right)$$
$$\theta_{ij}^t = \alpha + CT_i\gamma + (\beta + CT_i\delta)\ln\left(B_j \log_2\left(1 + \nu_{ij}^t\right)\right)$$

Define ω_{ij}^t as

$$\omega_{ij}^t = \Pr\left(H_{0j}^t \mid s_j^t = 1\right)\phi_{ij}^t + \Pr\left(H_{1j}^t \mid s_j^t = 1\right)\theta_{ij}^t$$

The optimal channel access problem is formulated as

$$
\begin{aligned}
\max: & \sum_{i=1}^{M_2}\sum_{j=1}^{N_2}\omega_{ij}^t y_{ij}^t \\
\text{s.t.} & \sum_{j=1}^{N_2} y_{ij}^t \le 1, i \in \{1,\cdots,M_2\}, \\
& \sum_{i=1}^{M_2} y_{ij}^t \le 1,\ j \in \{1,\cdots,N_2\}, \\
& y_{ij}^t \in \{0,1\}, \forall\ i, j
\end{aligned}
$$

2) Solution Algorithm Based on Hungarian Method

In the OAPVT problem, each CU can use at most one channel and each channel can be used by at most one CU. Then, the OAPVT problem becomes a maximum weight matching problem in a bipartite graph that matches active CUs to available channels, while only one edge is allowed for any CU and channel and the edge weights are defined as ω_{ij}^t. This maximum weight matching problem can be effectively solved in polynomial time using the Hungarian method, and the solution is optimal.

The time complexity of using Hungarian method to solve the OAPVT problem is $\mathcal{O}\left((M_2+N_2)(M_2N_2)\right)$, where M_2+N_2 is the total number of vertices and M_2N_2 is the total number of possible edges in the bipartite graph representing the OAPVT problem.

3. Performance Evaluation

The performance of the proposed algorithm is validated with Matlab simulations. We assume the PUs and CUs are randomly distributed within the coverage of a CBS. Table I lists the values of the parameters used in the simulations. fs is the sampling frequency at the CUs for energy detection. We compare the proposed scheme with a benchmark scheme presented in [11], called Data Rate (DR) Driven, in which channels are assigned to end users to maximize the sum data rate of all users.

TABLE I
SIMULATION PARAMETERS

Parameters	*Value*	*Parameters*	*Value*
M_1	30	μ_{ij}^t	-25 dB to -15 dB
N_1	30	ν_{ij}^t	-80 dB to -60 dB
K	10^4	ς_{ij}^t	-30 dB to -10 dB
f_s	10^6 Hz	$\bar{P}_d$	0.95
T	100	$\max_j\left\{\Pr\left(H_{0j}^t\right)\right\}$	0.9
B_j	10^6 Hz		

Fig. 1 demonstrates the effect of the traffic load of CUs (i.e., ξ) on video quality. The average sum MOS achieved by the proposed scheme and the DR Driven scheme are plotted with 95% confidence intervals as error bars. As the CU traffic load increases, more channels are required. We can see that while the number of idle channels is greater than the number of active CUs, the average MOS sum of both schemes increases with ξ, and the performance gap between the two schemes grows larger.

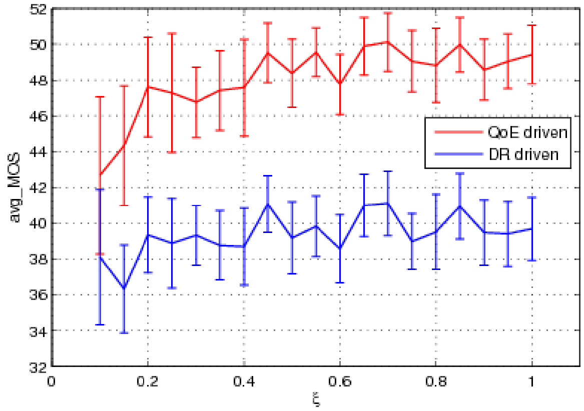

Fig. 1. Average MOS sum of the CUs over an entire GOP window, avg_Ψ, for different CU traffic loads ξ

In Fig. 2, we examine the impact of PU channel utilization and the SNR at the CUs on CU video quality. In the 3-D plots, the x-axis is the minimum channel idle probability, i.e., $\min_{i,j}\left\{\Pr\left(H_{0j}^{t}\right)\right\}$, and the y-axis is the minimum SNR of CUs, i.e., $\min_{i,j}\left\{\mu_{ij}^{t}\right\}$. It can be observed from the figure that as channel utilization is decreased, a channel has a higher probability of being at the idle state and there will be more channels available for CUs in the transmission phase. Thus, the average MOS sum of the CUs is improved.

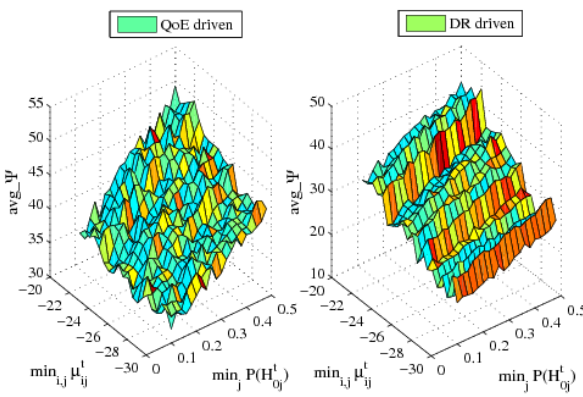

Fig. 2. Average MOS sum of the CUs over an entire GOP window vs. the minimum channel idle probability and the minimum SNR of CUs.

4. Conclusion

In this letter, we investigated the problem of QoE-aware video streaming over CRNs. The channel assignment problem was formulated as an IP and solved with the Hungarian Method to derive the optimal solution, where QoE is used as performance metric. We showed that the proposed algorithm achieves optimal solutions for channel access. The proposed scheme was validated with simulations.

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