An Adaptive Channel Assignment Approach for Streaming of Scalable Video over Cognitive Radio Networks

Ala Eldin Omer, Mohamed S. Hassan, Mohamed El-Tarhuni
Department of Electrical Engineering
American University of Sharjah
Sharjah, UAE
{b00060370, mshassan, mtarhuni}@aus.edu

Abstract—In this study, a framework is proposed to stream different scalable videos from a base station to multiple secondary users over cognitive radio networks. The objective of this work is to ensure that the secondary users will enjoy continuous video playback with acceptable perceptual quality. To achieve such goal, a channel allocation algorithm is introduced to adaptively assign the available channels to the secondary users while taking into considerations their buffer occupancies. In addition, a streaming algorithm is devised to ensure the delivery of scalable video frames within the delay constraints with priority given to the base layers to guarantee the continuity of video playback. Moreover, the introduced algorithm adapts the employed modulation level based on the channel state information as fed-back by the secondary users. The simulation results show that the proposed streaming algorithms ensure the desirable fairness when allocating the channels between the secondary users. This in turn resulted in efficient usage of the available resources of the cognitive network which is demonstrated in the achieved PSNR of the reconstructed video streams with no interruptions in the playback process. We also showed that scalable video sequences outperform their single-layer counterparts in terms of the achieved video quality.

Keywords—Cognitive radio networks; video streaming; dynamic channel allocation; opportunistic access;

I. INTRODUCTION

The expansion of wireless services and applications is opposed by the shortage in radio spectrum that resulted from the static assignment of the available spectrum which in turn has led to spectrum underutilization. Opportunistic dynamic spectrum access (DSA) as a paradigm was first introduced in [1], [2]. In DSA, the licensed radio spectrum is made accessible to unlicensed users, called secondary users (SUs), when the licensed users, also called primary users (PUs), are idle. The absence of a PU from a specific frequency band at different points in time and space is called spectrum hole [3] which is a reserved portion of the spectrum that is not in use. Cognitive radio (CR) technology is a DSA technique that will help to overcome the expected radio spectrum scarcity problem and then efficiently and pervasively meet the increasing demand for new wireless services.

Multimedia streaming applications are bandwidth hungry applications that have dominated the wireless and wired networks’ traffic in the last decade. Recently, the delivery of multimedia applications to wireless end users was facilitated by the recent advances in wireless networks. However, video streaming over wireless and CR networks is faced with challenges of different types. First, and independent of the underlying network, challenges that stem from the stringent quality of service requirements (QoS) as demanded by the nature of the multimedia streams. In addition, video applications have heterogeneous traffic nature that differ not only in terms of video frames sizes but in terms of their dependency. Hence, deadlines and priority of video frames should be carefully considered to limit error propagation on the loss of a reference frame. Second, challenges that are introduced by the nature of wireless channels that known for their time varying nature with fluctuating signal-to-noise ratio (SNR), multipath fading and interference. Thirdly, CR channels are available to unlicensed users randomly and in an intermittent way depending on the behavior of primary users.

Several researches consider video streaming over CR networks. The problem of spectrum allocation in the case of unicast CR video transmission with one PU and $N$ SUs was formulated as auction game with three distributed allocation algorithms in [4]. A cross layer scheme with spectrum sharing and joint routing algorithm is introduced in [5] to enhance the overall throughput, subject to delay and sensitivity constraints using a prioritized queuing model. Video multicast over centralized CR network was considered in [6], where multiple video sequences are transmitted to a group of SUs. Video multicast over CR networks was also addressed in [7] by formulating an optimization problem that targets the improvement of video quality while guaranteeing a proportional fairness among the SUs.

A Markovian game problem with dynamic switching control was formulated in [8] to improve the resultant video quality of multiple SUs with different data rates. A two-state Markov model was used in [9] to model the channel to optimize the bit rate of the enhancement layers of the video frames under the available bandwidth constraints with
the objective of minimizing any possible fluctuations in the reconstructed quality. In [9], dynamic programming at the frame, GoP and scene level was used to solve the problem of optimal resource allocation. With the objective to maximize the overall network throughput while ensuring smooth video playback at the SUs, the channel availability to SUS was modeled as an on-off Markov process in [10]. In addition, the authors devised an optimization framework for channel allocation which takes into consideration the playback buffer storage of the SUS as well as the bandwidth capacity. Scalable video coding (SVC) was used in [11] to provide uninterrupted video playback at the SUS end. This is done by sending the base and enhancement layers in an overlay mode, while sending the base layer alone in underlay mode. Insertion of intra-coded frames was introduced as a technique to protect against the loss of the base layer so that to achieve an acceptable level of video quality.

In this paper, we propose an adaptive video streaming framework in which a CR base station (BS) delivers scalable video sequences to SUS over a CR spectrum that consists of N TDMA channels licensed to N PUs. The objective of the proposed adaptive scheme is to maximize the quality of the received video at the SUS end while maintaining continuous video playback. Therefore, the scheme opportunistically exploits any available channel or set of channels detected to be idle by the BS at regular intervals of time. To do so, the BS receives feedback information on a reverse reliable channel that includes the buffer occupancies of the different SUS in addition to the estimated SNRs of the different channels. The BS uses this feedback information to fairly allocate the available channels to the SUSs according to a proposed channel allocation algorithm. We also introduce a streaming algorithm that adaptively schedules the video frames on the allocated time slots with optimal bit-rate and adaptive modulation depending on the channel state and a target bit-error rate (BER). To reduce the impact of the dynamic nature of the CR network, scalable video sequences are considered in the proposed scheme to take advantage of the scalability feature of the video frames. Therefore, we also solve an optimization problem for video streaming for each SUS at the beginning of the available time slot(s). The output of this algorithm is the optimum number of the enhancement layers to be transmitted under a maximum bit budget and delay deadline constraints. Finally, we assume overlay mode of transmission where the primary and secondary users cannot simultaneously access the CR spectrum. Therefore, once a channel is declared idle by the BS, it will remain available until the end of a certain period of time with no interference to the PUs.

The rest of this paper is organized as follows. Section II discusses the details of the proposed scheme. Simulation results are discussed in Section III. Finally, Section IV summarizes the paper and outlines the future work.

II. OVERVIEW OF THE PROPOSED SCHEME

We consider an infrastructure-based CR network model with a base station that transmits a number of scalable encoded videos to multiple SUSs as shown in Figure 1. In this model, a SUS can use one or more of the PUs channels as long as they are not used by their PUs.

Figure 1: The proposed video streaming scenario.

The objective of the proposed CR video streaming scheme is to maintain the continuity of the video playback at the SUSs at acceptable perceptual quality. To achieve such a goal, two algorithms are introduced namely, channel allocation and streaming algorithms. First, it continuously senses the PUs spectrum to detect any available channels every T_idle duration. Then, it allocates the available channels to the SUSs based on their feedback information which includes their buffer occupancies and the CSI. While the channel allocation algorithm aims to guarantee fairness when allocating available channels between SUSs based on their feedback information, the streaming algorithm aims at the optimal scheduling of the video frames within the allocated slots to meet their deadlines while achieving the highest possible quality.

In the proposed model, the PU activity is modeled by a discrete-time two-state Markov chain with idle and active periods that are exponentially distributed. State “0” indicates that the PU is idle (i.e the corresponding channel is available to SUSs), while state “1” indicates that the PU is active and hence the corresponding channel is unavailable to SUSs. It is also assumed that there are N PUs (and hence N channels) the activities of which are independent. The activity of the n-th PU, n = 1, 2, . . . , N follows the transition probability matrix given by:

$$P_n = \begin{bmatrix} 1 - \alpha_n & \alpha_n \\ \beta_n & 1 - \beta_n \end{bmatrix},$$

and the steady-state probability that channel n is idle is $\pi_{0,n} = \beta_n / (\beta_n + \alpha_n)$. The channels are Rayleigh flat-fading channels with Additive White Gaussian Noise (AWGN) the condition of which does not change during one transmission slot and exhibits slowly varying SNR over multiple successive time slots. The
error-free bit rate for a given SNR is given by

\[ C = B \log_2 \left( 1 + \frac{kE_b}{N_0} \left( \alpha^2 \right) \right), \]  

(2)

where \( \alpha \) is a random variable that represents the channel gain and follows a Rayleigh distribution with a second moment \( \mathbb{E}[\alpha^2] = \omega \) and probability density function (pdf) given by [12]:

\[ P_{\alpha}(\alpha) = \frac{2\alpha}{\omega} \exp \left( -\frac{\alpha^2}{\omega} \right). \]  

(3)

The BER for the different modulation schemes (BPSK, 4-QAM, 16-QAM and 64-QAM) under Rayleigh flat-fading with AWGN, assuming coherent detection, are given by [13-15]:

\[ P_b = \begin{cases} \frac{4}{9} \left( 1 - \frac{1}{\sqrt{1+\gamma}} \right), & M = 2, 4 \\ \frac{4}{9} \left( 1 - \frac{1}{\sqrt{1+\gamma}} \right), & M = 16 \\ \frac{7}{16} \left( 1 - \frac{1}{\sqrt{1+\gamma}} \right), & M = 64. \end{cases} \]  

(4)

Adaptive modulation is employed to maximize the spectral efficiency to enable the representation of the video information at higher rates and hence achieve better perceptual quality at the SU end [13]. The modulation level is decided by the BS based on the fed back Channel State Information (CSI) to meet a predefined BER that is decided according to the sensitivity of the transmitted video information. When no channel coding is implemented, the effective bit rate \( C_e \) for modulation level \( M \) is given by:

\[ C_e = C \log_2 M, \]  

(5)

where \( C \) is the error-free data rate. As a result, the maximum bit budget available for a SU in the idle time of a PU is given by:

\[ B_{\text{max}} = T_{\text{idle}} C_e. \]  

(6)

In our system, the BS assigns a certain level of modulation \( (M = 2, 4, 16, \text{ and } 64) \) on the allocated channels based on the reported SNRs from the SUs to achieve a target BER. The highest modulation level that achieves the closest BER value to the target BER is used for sending the video frames on that channel.

The available channels are allocated to the SUs based on their feedback information, which includes their buffer occupancies as well as the measured SNR of different channels. In more details, the BS allocates the available channels to the SUs by comparing their buffer occupancies with a predefined occupancy threshold to determine the urgency of sending the video frames to the SUs. In the two special cases when all SUs have their buffer occupancies (denoted by \( \Delta_i, \forall i = 1, 2, \ldots, M \)) larger than or equal the threshold \( \Delta_{\text{th}} \), or all their buffer occupancies are below the threshold (i.e. underflowing), the BS allocates the available channels among the SUs in a Round Robin manner. For all other cases, the BS jointly considers the reported SNR of the different channels as seen by the SUs with their instantaneous buffer occupancies and allocates the channel(s) to SUs on which the best video quality can be attained. Once the a channel or more are assigned to a SU, the BS then solves an optimization problem for scheduling of the video frames under the maximum bit budget \( B_{\text{max}} \). This is done to optimally schedule the enhancement layers of the video frames along with their essential base layers to enhance the quality of the reconstructed video.

The raw video sequences are encoded using the H.264/SVC standard into one base layer and two enhancement layers with hierarchical B frame prediction [14]. It is assumed that the encoded video sequences are placed on a server located right at the CR base station. The dependency between the video frames extends to the enhancement layers similar to their counterparts in the base layer. The base layer provides the basic accepted quality level, whilst the quality can be improved by including more enhancement layers. The enhancement layers cannot be decoded without their corresponding base layers. Therefore, the base layers should be correctly received before their display deadline and the deadline of the dependent base layers of other frames as well enhancement layers that belong to their frames, otherwise, the dependent frames and corresponding enhancement layers become useless even if they are correctly received and decoded by their display times. Therefore, the streaming algorithm should satisfy the above characteristics when sending the video frames to ensure the continuity of the video playback at the maximum possible quality.

In what follows we briefly describe the employed streaming algorithm. Let \( f_i \) be the size of frame \( i \) in bits and let \( V \) be the number of frames a SU is about to transmit when one or more channels are granted to that user. Then, the total number of bits the SU will transmit is given by \( W = \sum_{i=1}^{V} f_i \). The streaming algorithm part in the streaming system compares \( W \) with \( B_{\text{max}} \) of the allocated channel(s) while taking into considerations the delay deadline constraints.

If that sum is less than \( B_{\text{max}} \), all frames from the base layer of the current GoP will be transmitted to guarantee the continuity of the playback. Otherwise, the algorithm transmits the maximum possible number of base layers then waits for the following available slot(s) with a new bit budget. Only after all the base frames of the currently transmitted GoP have been scheduled on the available slot(s), if there is still room for more transmission, then the algorithm assigns more of the enhancement layers after checking their sizes against what remains of the \( B_{\text{max}} \). Moreover, the quality that the enhancement-layer introduces is compared with a predefined quality threshold. If the enhancement in quality is equal to the threshold or above it, then the enhancement layer will be transmitted otherwise the attention is moved to
the base layers of the following GoP. Before the transmission of the enhancement layers, the streaming algorithm also checks that the needed base/enhancement layers are correctly received so that it guarantees the decoding of current transmission. If the enhancement-layer satisfies that criteria, it will be scheduled on the slot and the algorithm moves to the next enhancement layer(s) of next frame. If a frame is discarded, then all frames that depends on it will also be discarded. The algorithm moves to the next GoP after it finishes the first GoP and the process repeats until the end of the video sequence.

III. SIMULATION RESULTS

The proposed video streaming system over CR networks is implemented using the SimEvents discrete-event simulator in MATLAB. In our simulations, the BS transmits three different video sequences, that are Coarse Grained Scalability (CGS) encoded, to 3 secondary users denoted by SU1, SU2, and SU3, over 10 PUs channels that are opportunistically accessed according to the discrete-time two-state Markov chain model explained before. We used the H.264/SVC CGS encoded trace files for the Sony Demo, Star Wars I and Star Wars II video sequences in the simulations [15]. Each of the video sequences is encoded into one base layer and two enhancement layers with 352 × 288 resolution and playback rate of 30 frames per second. The GoP structure of the three layers is IBBBPBBBPBBBPBBB and is abbreviated as G16B3, with hierarchical dependency between the frames of each layer where B frames can be used as references to other B frames. The playback starts after receiving the first GoP. The error-free bit rate of each of the PU channels is \( C = 254 \) Kbps. We assume that the PUs channels change their state following the transition matrix \( P = \begin{bmatrix} 0.3 & 0.7 \\ 0.4 & 0.6 \end{bmatrix} \) with limiting probability \( \pi_{0,0} = 0.36 \).

To verify the fairness in the allocation of the available channels between the SUs, we first send the same video sequence “Star Wars I” to all SUs at a target BER= \( 10^{-7} \). Figure 2 shows the peak signal-to-noise ratio (PSNR) of the video sequence as received by the three SUs. The figure compares the PSNR with the maximum quality achieved when all layers are successfully received. We notice that the received video sequences show the same PSNR performance in average with slight degradation in quality in the first few frames. This is referred to the fact that the 2-nd enhancement layers of these frames were discarded as they did not meet the deadlines of their frames. When the 2-nd enhancement layers were received the PSNR jumped to about 48 dB. At some instants, the video quality suffers from more degradations and went down to 27 dB since both of the enhancement layers were discarded or received in error due to channel variations and the strict value of the BER. In such cases, the proposed streaming algorithms ensures the correct reception of the base layers of the video frames. This also explains the fact that there is no interruptions in the playback for all SUs since all base-layers of the video frames were correctly received which also proves the fairness in allocating the available channels between the SUs.

Next, we investigate the behavior of the proposed streaming scheme when different video sequences are requested by the different SUs. Figure 3 shows the resultant PSNR at a target BER \( 10^{-5} \) when the Sony Demo, Star Wars I, and Star Wars II video sequences are transmitted to SU1, SU2, and SU3, respectively. While Figure 3-(a) shows high PSNR values up to 59, it also shows slight degradation in the PSNR as a quality metric to because EL2 of an I frame was incorrectly received. Any slight degradation in the quality in Figure 3 results when EL1 and/or EL2 of the video frames are discarded by the streaming algorithm as they will not meet their deadlines or violate the upper limit on the available bit budget. Additionally, for the three test sequences, the figure compares the performance of the proposed scheme with the case when the sequences are transmitted as single-layer videos. This is very obvious in Figure 3-(b) which shows that the single-layer video received by SU2 is of PSNR values that are considerably less than those achieved for the same video sequence using the proposed adaptive scheme. The interruption in the playback process in Figures 3-(a) and 3-(c) results due the loss of the base layers of the video frames.

The number of the channels allocated to the SUs at the beginning of each time slot is shown in Figure 4 for two target BERs. The Sony Demo, Star Wars I, and Star Wars II video sequences are transmitted to SU1, SU2, and SU3, respectively. The figure indicates that SU1 is not allocated any more channels after the 2-nd second since its video frames are scheduled on the slots available on the first two seconds. Since the Sony Demo video sequence has the smallest frame sizes when compared to the other two video sequences, the BS continues allocating the available channels to SU2 and SU3 to avoid possible interruptions in their playback processes at their ends.

IV. CONCLUSION

We proposed an adaptive channel assignment scheme to stream scalable videos from a CR base station to multiple secondary users. A channel allocation algorithm and streaming algorithm were proposed to achieve the objective of non-interrupted playback at the SUs at acceptable perceptual quality. Moreover, the introduced algorithms adapted the employed modulation level based on the channel state information as feedback by the secondary users. Our results showed that the proposed algorithms ensured the desirable fairness in the allocation of the available channels between the SUs. This in turn resulted in efficient usage of the available resources of the cognitive network which was demonstrated in the achieved PSNR of the reconstructed video streams with no interruptions in the playback process. The simulation results also showed that streaming scalable video sequences...
with the proposed adaptive scheme outperforms their single-layer counterparts in terms of the achieved video quality.

REFERENCES

Figure 4: Channels’ allocation for the SUs.