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Channel Allocation for Smooth Video Delivery over Cognitive Radio Networks

Sanying Li, Tom H. Luan, Xuemin (Sherman) Shen
Department of Electrical and Computer Engineering
University of Waterloo, Waterloo, ON, Canada, N2L 3G1
Email: {s68li, hluan, xshen}@bcr.uwaterloo.ca

Abstract—To address the impact of the network dynamics on video streaming, the playout buffer is typically deployed at the receiver. With different buffer storage, users thus have different tolerance to the network dynamics. In this paper, we exploit this feature for channel allocation in cognitive radio (CR) networks. We first model the channel availability as an on-off process which is stochastically known. Based on the bandwidth capacity and the specific buffer storage of users, we then intelligently allocate the channels to maximize the overall network throughput while providing users with the smooth video playback, which is formulated as an optimization framework. Given the channel conditions and the video packet storage in the playout buffer, we propose a centralized scheme for provisioning the superior video service to users. Simulation results confirm that by exploiting the playout buffer of users, the proposed channel allocation scheme is robust against intense network dynamics and provides users with the elongated smooth video playback.

I. INTRODUCTION

In this paper, we investigate how to provide the large-scale Video-on-Demand (VoD) service, like YouTube, over the cognitive radio (CR) networks. Compared with the data transfer applications, video streaming like VoD is characterized by the strong time sensitivity and inelastic bandwidth requirements; the video packets must be downloaded and available at the video decoder before their playback time to allow an undis
torted video reconstruction. Nevertheless, the CR networks are typically highly dynamic which poses significant challenges to the smooth video streaming. Specifically, in CR networks, primary users (PUs) normally behave in a purely random and unpredictable fashion, making the channel spectrum opportunities for secondary users (SUs) highly variable. Coupled with the dynamic channel status and internal transmission contentions among themselves, the downlink throughput of SUs is extraordinarily turbulent and intensely changing all the time, which severely affects the quality of the video playback.

There is extensive literature striving to provision guaranteed quality-of-service (QoS) [1] to users in the dynamic CR networks. [2] describes a live video streaming system over the infrastructure-based CR networks, in which multiple video flows are delivered to different groups of users via the dynamic CR networks. To provide high-quality video streaming with the minimal video distortion, they propose a cross-layer optimizer of the network which exploits three dimensions of the system: coding rate, channel selection and channel sharing. [3] also studies the resource allocation for real-time streaming in CR networks. Unlike [2], [3] focuses on the uplink where users compete for the channel access for video upload. Based on the buffer storage of SUs and their channel status, the base station performs the channel scheduling and power allocation to minimize the packet loss of SUs caused by the buffer overflow. In [4], a game-theoretic framework is proposed to address the selfish behavior of users in the video streaming. [5] studies the QoS provision in an OFDMA network, where two groups of users, the best-effort (BE) and the real-time (RT) users, compete for the channel access. As a result, an optimization framework is proposed to achieve the maximal throughput of the network while satisfying the specific QoS requirements of different users.

Existing works mainly focus on the live video multicasting [2] where the users are synchronized in the video playback. As a contrast, in the VoD system, users are non-synchronized; they subscribe to different video clips and are different in the progress of playback. Therefore, users are diverse in the packet storage of the playout buffer as shown in Fig. 1. The playout buffer is deployed at the receiver to absorb the network dynamics. With different packet storage in the playout buffer, users have different tolerance to the network dynamics. In this work, we exploit this diversity and propose the buffer-oriented channel allocation. Given the packet storage of the playout buffer and channel status, we first evaluate the video quality of users in terms of the smoothness of video playback. Using this information as the input, we then model the channel allocation as an optimization framework to maximize the overall throughput, while providing the VoD users with guaranteed video quality. Based on the optimization framework, we finally devise a centralized VoD system for the optimal use of channels.

The remainder of this paper is as follows. We first introduce the system model in Section II. Section III formulates the optimization problem for the large-scale CR-based VoD service, and Section IV proposes an approximate solution of the optimization problem via a heuristic algorithm. Section V
provides the simulation results for performance evaluation, and Section VI closes this paper with conclusions and future works.

II. SYSTEM MODEL

We consider an infrastructure-based single-hop CR network as shown in Fig. 1 where there exists a central base station (BS) to coordinate the transmission. The overall spectrum band of the network is composed of $N$ orthogonal channels indexed by $n$ ($n = 1, 2, \ldots, N$) and each channel is allocated to one PU also indexed by $n$. Let $M$ denote the number of secondary users indexed by $m$ ($m = 1, 2, \ldots, M$).

Let $\tau$ denote the maximal time duration which the PUs could tolerate in presence of the interference from SUs. To avoid the interference from SUs to PUs, we slot the system time into discrete intervals of $\tau$. In each time slot, SUs monitor channels actively and are allowed to transmit only when the channel is sensed idle. Every $L = T/\tau$ time slots, namely a channel allocation epoch, the BS allocates channel spectrum to SUs according to their specific QoS requirements and channel status. In the ensuing $L$ time slots, SUs then transmit in a distributed manner based on the allocation. The design of the channel allocation will be detailed later.

**Channel Availability** At each time slot, the availability of each channel $n$ is abstracted by an ON-OFF model where the channel is in “ON” state if the PU $n$ is online, and “OFF” state otherwise. Let $\pi_{0,n}$ denote the limiting probability that channel $n$ is in “OFF” state and available for SUs to use. Based on accumulated observations, we assume that $\pi_{0,n}$ is known.

**MAC Scheme** We deploy the $p$-persistent MAC to coordinate the transmissions of SUs upon the same channel. As such, in each slot, when a channel $n$ is sensed idle, each SU allocated to this channel will issue a request for video or data transmission with probability $p_n$. If no collision happens, the SU sending the request would be rendered for transmission in the ensuing slot time $\tau$.

**Channel Model** We assume that each SU $m$ is able to measure its SNR upon channel $n$, denoted by $\rho_{m,n}$. Within the channel allocation epoch time $T$, $\rho_{m,n}$ is assumed unchanged. Let $c_{m,n}$ denote the achievable transmission rate at which the SU $m$ could transmit or receive over channel $n$. According to the Shannon capacity, we have $c_{m,n} = \frac{1}{2} \log_2 (1 + \rho_{m,n})$.

**QoS Requirements** We consider two groups of SUs: VoD users with the video delivery and best effort (BE) users with the data transfer. The VoD users download the subscribed video clips from remote video servers through the BS using the CR interface. The BE users also communicate with the central BS using the same CR interface as VoD users, but with both uplink and downlink transmissions. Let $M_{\text{VoD}}$ denote the number of VoD users indexed from 1 to $M_{\text{VoD}}$. Let $M_{\text{BE}}$ denote the number of BE users indexed from $M_{\text{VoD}} + 1$ to $M$.

The QoS requirements of BE users are represented by the mean throughput of the uplink and downlink transmissions. For any BE user $m$, let $D_m$ denote the demanded average transmission rate. Let $d_m$ denote the mean upload and download rate of the BE user $m$. Mathematically, the QoS requirement of BE users is specified as $d_m \geq D_m$, $m = M_{\text{VoD}} + 1, \ldots, M$.

The QoS of each VoD user $m$ is guaranteed by upper bounding $P_m$ as $P_m \leq \epsilon$, $m = 1, \ldots, M_{\text{VoD}}$, where $0 < \epsilon < 1$ represents the level of playback smoothness. For ease of exposition, we assume $\epsilon$ to be constant and the same for all the users. It is, however, easy to extend by differentiating $\epsilon$ and QoS requirements for different VoD users.

III. OPTIMAL VO D STREAMING OVER CR NETWORKS

In this section, we first describe the system architecture, and then present the optimal channel allocation in details.

A. Description of System Protocol

Fig. 2 depicts the basic structure of the VoD system which operates iteratively at the interval of channel allocation epochs ($L$ slots). Each epoch is composed of two phases:

**Beacon period:** The beacon period is at the beginning of each epoch, as shown in Fig. 2. Within this period, the system first collects the 3-tuple profile of each SU $m$, including the current buffer stage $\Delta_m$, video playback rate (mean and variance of inter-departure time $r$ and $v_t$) and the measured SNR $\rho_{m,n}$ upon each channel $n$. After that, the BS performs the optimal channel allocation as follows: based on the user profile, the BS first calculates the Shannon capacity of users
upon each channel, and then figures out the video quality of VoD users in (1) and acquired throughput of BE users. Based on the data rate and QoS requirements of SUs, the BS optimally allocates the channel to SUs, which will be described later, and then broadcasts the allocation to SUs at the end of the beacon period.

Transmission period: After the beacon period, each SU monitors the availability of the channel which it is assigned to at every slot \( \tau \) and competes for the transmission opportunities using the \( p \)-persistent MAC once the channel is sensed idle.

### B. Optimal Channel Allocation

We formulate the optimal channel allocation of BS in the beacon period. Our goal is to maximize the overall system throughput, while satisfying the QoS requirements of both VoD and BE users, i.e.,

\[
\max_{a_{m,n}} \sum_{m=1}^{M} d_{m}
\]

s.t. \( p_{m} \leq \epsilon \), \( m = 1, ..., M_{\text{VoD}} \),

\[
d_{m} \geq D_{m}, \quad m = M_{\text{VoD}} + 1, ..., M,
\]

\[
\sum_{n=1}^{N} a_{m,n} = 1, \quad m = 1, 2, ..., M,
\]

where \( a_{m,n} \) is binary with \( a_{m,n} = 1 \) if channel \( n \) is allocated to user \( m \), and 0 otherwise. The last constraint of (2) dictates that each SU could only be assigned to one channel in each channel allocation epoch. To solve (2), in what follows, we represent \( p_{m} \) and \( d_{m} \) by the channel allocation \( a_{m,n} \).

Let \( M_{n} \) denote the number of SUs allocated to channel \( n \), mathematically, \( M_{n} = \sum_{m=1}^{M} a_{m,n} \). With the knowledge of \( a_{m,n} \), the probability that a SU \( m \) transmits successfully over channel \( n \) in each slot is \( P_{\text{suc},n} = p_{n} (1 - p_{n})^{M_{n}-1} \pi_{0,n} \). By setting \( p_{n} = 1/M_{n} \), we have the maximum \( P_{\text{suc},n} \) and the throughput accordingly.

Let \( x_{m,n} \) denote the time between two consecutive transmission slots of SU \( m \) on channel \( n \), as shown in Fig. 3. As the SU contends for the transmission opportunities using the \( p \)-persistent MAC scheme, we have the probability mass function of \( x_{m,n} \) as

\[
P \left\{ x_{m,n} = i \tau + \frac{1}{c_{m,n}} \right\} = P_{\text{suc},n} (1 - P_{\text{suc},n})^{i}. \tag{3}
\]

As shown in Fig. 3, given the capacity of user \( m \) on channel \( n \) to be \( c_{m,n} \), within one slot \( \tau \), there could be a spurt of \( c_{m,n} \tau \) packets uploaded or downloaded by user \( m \) through channel \( n \). In this spurt of packets, the interval between any two consecutive packets is \( 1/c_{m,n} \). The expected interval between the current spurt and the next spurt is \( E[x_{m,n}] \). Therefore, the mean interval time between the consecutive downloaded packets is

\[
\frac{1}{d_{m,n}} = \frac{c_{m,n} \tau - 1}{c_{m,n} \cdot c_{m,n} \tau} + E[x_{m,n}] = \frac{1}{P_{\text{suc},n} c_{m,n}}. \tag{4}
\]

The variance of the inter-arrival time of video packets over channel \( n \) to VoD user \( m \) is

\[
v_{m,n} = \frac{c_{m,n} \tau (1 - P_{\text{suc},n}) (2 - P_{\text{suc},n}) - (1 - P_{\text{suc},n})^{2}}{P_{\text{suc},n}^{2} c_{m,n}}, \tag{5}
\]

Given the channel allocation represented by \( a_{m,n} \), the integrated mean of transmission rate and the variance of the inter-arrival time of the video packets of user \( m \) are, respectively,

\[
d_{m} = \sum_{n=1}^{N} a_{m,n} \cdot d_{m,n}, \quad v_{m} = \sum_{n=1}^{N} a_{m,n} \cdot v_{m,n}. \tag{6}
\]

Substituting (6) into (1), we are able to evaluate the video performance of VoD users, and finally obtain the optimal channel allocation by solving (2).

### IV. Heuristic Algorithm

Since (2) is a nonlinear integer programming problem, it may be impossible to be solved for the real-time channel allocation, especially when the number of SUs scales to a large number. In this section, we propose a utility-based heuristic algorithm to determine the channel allocation by rendering SUs differentiated service according to their specific QoS requirements and contribution to the overall utility.

Fig. 4 shows the pseudo code of the heuristic algorithm which is composed of two parts. The first part is to allocate channels to VoD users subject to their QoS requirements. To this end, we first evaluate the urgency of download for VoD users according to their buffer storage, as in line 2, and then ranking channels in terms of the frozen probability of VoD users over each channel, as in lines 3-5. After that, we allocate channels to users according to the stringency of QoS requirements since line 6. From line 9 to line 19, each VoD user is allocated to the channel on which the user has the relatively small frozen probability; more importantly, the channel should be still available to be allocated to more VoD users without violating the QoS of users previously allocated to the channel. If no channels are available while some users still have not been allocated, we relax the QoS requirement of users by enlarging \( \epsilon \) (line 21) and then continue the allocation.

After all the VoD users are accommodated, we allocate the channels to BE users in the second part of the algorithm. As BE users have relatively loose QoS requirements, the emphasis is to enhance the system throughput. To this end, we first evaluate the download rates of BE users over each channel in lines 2-4 of part II, and then sort the rates in the descending order in line 5. The channel is allocated to a BE user from line 9 to line 19 if the user has comparatively large throughput over this channel and more importantly by inserting the BE user to this channel the QoS of VoD users specified in the constraints of (2) are not violated. If there is no such allocation, we relax the QoS requirement of VoD users by enlarging \( \epsilon \) (line 21) and then continue the allocation following line 9 to line 19.

### V. Simulation Results

We evaluate the performance of the proposed CR VoD system using a discrete time, event-driven simulator coded in C++. The default settings of the simulation are: \( M =

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Fig. 3. Inter-arrival time of video packets
I. VoD Users:

Define: \( k_n \) returns the first user ID in channel \( n \);
Define: \( F_n \) returns the availability of channel; \( F_n = \text{TRUE} \) if channel \( n \) is forbidden to be allocated to any more users, and otherwise, \( F_n = \text{FALSE} \);
Define: \( L \) is a queue which stores a list of VoD users;
Define: \( P \) is a queue which stores the frozen probability of VoD users on different channels;
1. Set \( F_n = \text{FALSE} \) for all channel \( n \); Set \( k_n = 0 \) for all channel \( n \); Insert all VoD users into \( L \);
2. Sort \( L \) in ascending order according to VoD users’ current storage of packets in their playout buffer;
3. for \( m \) in \( \{1, \ldots, M\} \) do
   4. Evaluate the frozen probability \( p_m,n \) on channel \( n \) for all \( n \in \{1, \ldots, N\} \); Sort \( p_m,n \) in ascending order and insert sorted \( p_m,n \) into a list \( P \);
5. end
6. while \( P \) is non-empty do
   7. Set \( i \) to be the VoD user ID and \( j \) to be the channel ID which the first frozen probability \( p_{i,j} \) in \( P \) associates with;
   8. if \( F_j = \text{FALSE} \) then
      9. if \( k_j = 0 \) then
         10. Set \( k_j \leftarrow i \); Set \( a_{i,j} \leftarrow 1 \); Erase \( p_{i,n} \) of user \( i \) for all channel \( n \in \{1, \ldots, N\} \) in \( P \);
      else
         11. Recalculate \( p_{i,j} \) with \( a_{i,j} = 1 \);
      end
      12. if \( p_{i,j} \leq \epsilon \) then
         13. Set \( a_{i,j} \leftarrow 1 \); Erase \( p_{i,n} \) of user \( i \) for all channel \( n \in \{1, \ldots, N\} \) in \( P \);
      else
         14. Set \( F_j \leftarrow \text{TRUE} \);
      end
      15. Move all \( p_{m,n} \), \( m \in \{1, \ldots, M\} \), to the end of queue \( P \);
   else
      16. \( \epsilon \leftarrow \epsilon + 0.01 \);
      17. Reset \( F_n = \text{FALSE} \) for all channel \( n \in \{1, \ldots, N\} \);
   end
5. end

II. BE Users:

Define: \( D \) is a queue which stores the download rate of BE users on different channels;
1. Set \( F_n \leftarrow \text{FALSE} \) for all channel \( n \);
2. for \( m \in \{M_{\text{BE}} + 1 \to M\} \) do
   3. Calculate the download rate \( d_{m,n} \) on channel \( n \) for all \( n \in \{1, \ldots, N\} \), given the VoD users’ allocation; Insert \( d_{m,n} \) into a list \( D \);
4. end
5. Sort \( D \) in the descending order;
6. while \( D \) is non-empty do
   7. Set \( i \) to be the BE user ID and \( j \) to be the channel ID which the first download rate \( d_{i,j} \) in \( D \) associates with;
      8. if \( F_j = \text{FALSE} \) then
         9. Set \( a_{i,j} \leftarrow 1 \); Erase \( d_{i,n} \) of user \( i \) for all channel \( n \in \{1, \ldots, N\} \) in \( D \);
         10. Recalculate and sort the remaining \( d_{m,n} \) in \( D \) with \( F_n = \text{FALSE} \) in the descending order;
      else
         11. Recalculate \( p_{i,j} \) with \( a_{i,j} = 1 \);
         12. if \( p_{i,j} \leq \epsilon \) then
            13. Set \( a_{i,j} \leftarrow 1 \); Erase \( d_{i,n} \) of user \( i \) for all channel \( n \in \{1, \ldots, N\} \) in \( D \);
            14. Recalculate and sort the remaining \( d_{m,n} \) in \( D \) with \( F_n = \text{FALSE} \) in the descending order;
         else
            15. Set \( F_j \leftarrow \text{TRUE} \);
            16. Move all \( d_{m,n} \), \( m \in \{1, \ldots, M\} \), to the end of queue \( D \);
         end
      end
   else
      17. \( \epsilon \leftarrow \epsilon + 0.01 \);
      18. Reset \( F_n \leftarrow \text{FALSE} \) for all channel \( n \in \{1, \ldots, N\} \);
      19. Recalculate remaining \( d_{m,n} \);
   end
5. end

Fig. 4. Proposed heuristic algorithm

50, \( N = 5, M_{\text{VoD}} = 20, \pi_{0,n} \in \{0.3, 0.4, 0.5, 0.6, 0.7\}, \tau = 10 \) ms, \( L = 50 \). Unless otherwise mentioned, the capacity of SUs on channels \( c_{m,n} \) is uniformly selected in the range of \([1000, 2000]\) pkts/sec within each channel allocation epoch. The tolerable frozen probability of VoD users \( \epsilon \) is set to 0.05. The throughput performance of BE users is evaluated by the percentage of BE users which download at a rate larger than 30 pkts/sec. For each scenario, we conduct 10 simulation runs with each run terminating at \( t = 150 \) seconds, and plot the mean results.

For evaluation purpose, all the VoD users use the same VBR video trace “Aladdin” from [7] but start the playback from different sections of the clip. As such, the statistics of the video playback rate are the same for all VoD users with the mean rate \( r = 30 \) pkts/sec and variance \( v_r = 102 \). The mean packet size is 630 Bytes for all users. In addition, each VoD user is associated with two system parameters: initial buffer storage and lifetime. The initial buffer storage represents the packet storages of VoD users at the start-up of their video playback when they join the system. It is fixed to 50 packets for all VoD users. The lifetime of each VoD user is uniformly distributed within the range of \([10, 30]\) seconds. Once its lifetime expires, a VoD user resets its playout buffer storage to the initial buffer storage, i.e., 50 packets, and selects a new lifetime, representing a new round of download. We simulate a dynamic network where VoD users dynamically join and depart from the network after watching the video clips. The lifetime of users is random as in real-world users may subscribe to videos of different length and they may quit in the middle of video playback.

In what follows, we tune the channel capacity of users and the portion of VoD users, respectively, to evaluate the performance of the proposed heuristic algorithm when the network resource is surplus or deficient. We compare the heuristic algorithm with another two heuristic schemes, namely the random allocation and the greedy allocation. For the random allocation, the SUs are randomly allocated to each channel every allocation epoch. Using the greedy allocation, each SU is allocated to the channel with the largest throughput, evaluated by the product of channel capacity \( c_{m,n} \) and channel idle probability \( \pi_{0,n} \).

Fig. 5 plots the performance of the users when enlarging the range of the channel capacity \( c_{m,n} \) with increased upper bound and fixed lower bound. As we can see in Fig. 5(a), the VoD users using the heuristic algorithm have much lower playback frozen probability compared with the random and greedy allocations. With increased upper bounds of the channel capacity and hence enhanced mean capacity, the frozen probability of VoD users in both random and greedy allocations reduces...
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In addition, the performance of random and greedy allocations when VoD users' population increases, as shown in Fig. 6(a). The throughput of BE users degrades when the network resource is insufficient. The reason is that, the heuristic algorithm gives high priority to users. However, without catering to the specific QoS requirements of users, the greedy allocation tends to allocate a crowd of users to certain channels with the high availability, resulting in high collision probability to users. This leads to the poor performance in terms of the playback frozen probability of VoD users and the percentage of the satisfied BE users, as indicated in Fig. 5(a) and Fig. 5(b).

Fig. 6 shows the impacts of VoD user's population on the performance of the heuristic algorithm with the total number of users fixed to be 50. As shown in Fig. 6(a), the playback frozen probability of the heuristic algorithm remains stable when VoD user's population increases, while in Fig. 6(b), the throughput performance of BE users degrades when the network resource is deficient. The reason is that, the heuristic algorithm gives high priority to VoD users. The total throughput degrades slightly when VoD users’ population increases, as shown in Fig. 6(c). In addition, the performance of random and greedy allocations remains the same because both random and greedy allocations do not differentiate VoD and BE users. Therefore, they are not sensitive to the change of VoD users’ population.

VI. CONCLUSION

We stress that the CR network is extraordinarily dynamic due to the opportunistic use of channels. This directly threatens to the smooth video playback of the users. To address this issue, we have proposed an optimal channel allocation framework in this paper. The proposed framework exploits the user diversity in terms of the tolerance to the network dynamics, and allocates the channels based on the required user specific video quality. For the future work, we intend to investigate the distributed channel allocation by allowing SUs to distributively select channels to transmit according to their QoS requirements. Without any central coordinations, the resulting channel allocation scheme would thus be more scalable.

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