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On Efficient Channel Modeling for Video Transmission over Cognitive Radio Networks

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Abstract This paper investigates the problem of video transmission over cognitive radio networks with the objective of maintaining continuous video playback while gracefully degrading the quality of the reconstructed video sequences, if needed. We focus on modeling the channel availability to secondary users, which is a major limiting factor on the continuity of the streaming process. A Markov chain model for the channels availability in an M-channels system is developed. This model is used to estimate the likelihood of transmission interruptions a secondary user might experience due to the loss of a channel to a primary user. We also propose a joint adaptive mechanism where a simple source rate control scheme is integrated with an adaptive playback approach to reduce the impact of channels relocation/unavailability on the streaming process of active secondary users. Simulations and numerical investigations demonstrate the correctness of the proposed channel model. Simulation results also indicate that instants of playback buffer starvation at the secondary user ends could be avoided only when the hybrid approach is employed.

Keywords Video streaming · cognitive radio networks · wireless channels

1 Introduction

In spite of the continuous advances in wireless communications and the movement towards 4G and 5G technologies, which is expected to result in an increase in the offered data rates, there is still a continuously increasing demand

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for more spectrum. The limited usable radio frequencies make spectrum bands not only scarce but very expensive as well. The situation is further aggravated by the proliferation of bandwidth-hungry applications, like video streaming applications. Such an increasing demand for spectrum has caused frequency bands to be sold at auctions for prices that could reach in billions of dollars. However, those billions-worth frequency bands are not efficiently utilized. For instance, studies have estimated that 80% of frequencies below 3 GHz in crowded areas like Manhattan and Washington D.C. are underutilized [1].

Cognitive radio (CR) is an intelligent wireless technology that was first introduced in [2] and currently is widely recognized as a promising solution for the spectrum scarcity problem [3]. CR wireless systems are characterized by their awareness to the surrounding radio frequency (RF) environments. They are also known for their capability to adapt their internal states according to the statistical variations in the environment with the objective of providing reliable communications while efficiently utilizing the available spectrum. This is done by the adaptation of tunable transmission parameters including transmission power, carrier frequency, and the modulation schemes. In CR systems, to efficiently utilize the available spectrum, non-license holders are allowed to temporarily use certain frequency bands when they are not occupied by their primary users (PUs) [4]. However, the spectrum must be immediately vacated when demanded by its PU. This requires the relocation of the traffic of secondary users (SUs) using this channel to other available channels, if any. Clearly, such an act introduces transmission delays that could be very severe for SUs with time sensitive applications. Let alone, worst case scenarios when there are no available channels at the moment of relocation and possibly for some consecutive periods of time. Challenges associated with such dynamic nature of CR systems are reviewed in [5]. Researchers have been trying to optimize realizable CR systems, and therefore different aspects of CR have been investigated in the literature. This includes infrastructured versus infrastructure-less networks, spectrum sensing and management, spectrum access techniques, cross-layer optimization, scheduling algorithms for SUs, medium access control (MAC) protocols, security, etc. [3–5].

The difficulties facing video streaming applications over CR networks are twofold. First, the challenges facing video transmission over wireless channels that typically stem from the time-varying nature of wireless channels and aggravated by the strict quality of service requirements mandated by the nature of video streaming applications [6]. Such applications are not only time-sensitive and bandwidth-hungry applications but are also intolerable to delay variations and transmission errors, which may cause packet losses and hence the loss of video frames. When lost frames are needed to decode other dependent frames, this leads to error propagation which, in severe scenarios, leads to interrupted video. Therefore, the conditions of the channel granted to the SUs have a major impact on the efficiency of the streaming process. Elaborated, the unreliability of wireless channels can cause unexpected variations in the number of correctly received and decoded video frames in the playback buffer on the SU side. Losing video frames will lead to scenarios in which the number of correctly received and decoded frames is less than the number of played-back frames at any interval of time, which in turn causes the playback buffer to starve [7].

Several techniques to maintain continuous video playback over wireless channels have been investigated in the literature. This includes source and channel rate control [8], layered coding (LC) [9], error concealment [10] and adaptive playback (AP) [11, 12]. Under bad channel conditions, source rate control and layered coding could be used to achieve faster transmission rates by reducing the encoder data rate (i.e., using smaller frame sizes to represent the video sequences) at the expense of degraded video quality [7]. This results in reducing starvation instants at which the playback buffer runs out of video frames and as a result, the client experiences reduced interruption in the playback process. More specifically, source rate control should be implemented in a way that guarantees gradual variations in the quality of the reconstructed video and hence, does not negatively affect the viewer experience. Error concealment and adaptive playback are two techniques that can also help in reducing starvation instants at the playback buffer at the end user side. In adaptive playback, the playback rate is varied according to the instantaneous occupancy of the playback buffer [11] while simple error concealment mechanisms can fictitiously reduce starvation instants by duplicating selected frames in the playback buffer.

Secondly, when video sequences are streamed over CR networks, the challenges are greatly increased since the availability of the wireless channels to SUs is of a stochastic nature. This problem has been tackled by several researchers in the literature. In [13], a centralized channel allocation scheme is proposed to enable the provisioning of video services to the SUs. The authors in [14] investigated the problem of channel allocation between cognitive video receivers with the objective of maximizing the overall network throughput. On the other hand, in [15], a decentralized cross-layer control scheme is proposed to maximize the network throughput. Also, in [16], the authors formulated a stochastic programming model for the problem of relay-assisted downlink multiuser video streaming in a CR cellular network. Video streaming over multi-hop CR networks has been addressed in [17] where a mixed integer nonlinear optimization problem was formulated to maximize the overall received video quality. The problem of video streaming in a femtocell CR network was investigated in [18] where a stochastic programming framework was used to obtain the optimal solutions in the case of non-interfering femto-base stations.

This paper investigates the problem of video transmission over cognitive radio networks with the objective of enhancing the viewing experience of cognitive video users. This is done through graceful degradation of the quality of the reconstructed video. Such graceful degradation was made possible by maintaining continuous video playback through the proper modeling of channel(s) availability to SUs. A Markov chain (MC) model for the availability of channels to SUs in an $M-$channels system is developed. This model is used to estimate the likelihood of transmission interruptions an SU might experience due to the loss of a channel to a PU. In addition, a hybrid solution that jointly integrates source rate control and adaptive playback is proposed to overcome possible starvation instants at the playback buffer.

The rest of the paper is organized as follows: Section 2 briefly discusses the architecture of the cognitive video streaming system considered in this study. The mathematical model is presented in Section 3. Section 4 presents the numerical investigations and simulation results, and then discusses the findings of the paper. Finally, Section 5 concludes the paper.

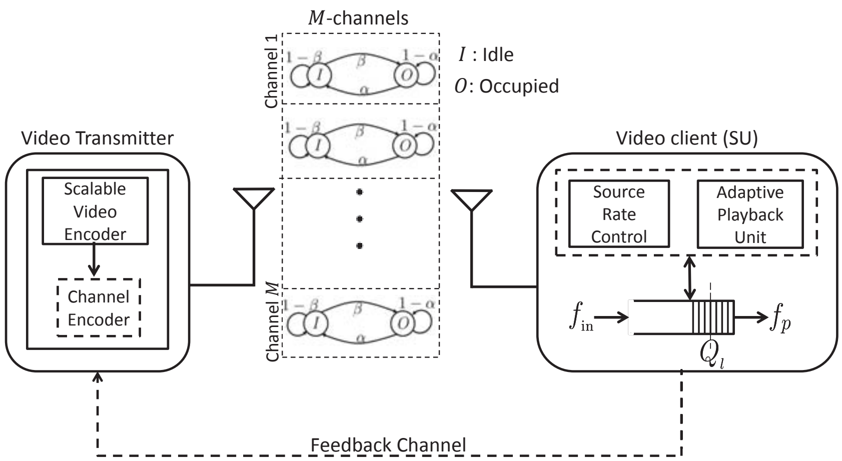

Fig. 1 Architecture of the cognitive video streaming system.

2 System Model

We consider the video streaming system shown in Figure 1. In this system, a video transmitter delivers real-time or archived video to the mobile SUs via one or more of the M PUs channels. We assume that the streamed video sequences are encoded using a scalable video encoder such as H.264/MPEG4-AVC and hence, can be rate-controlled without the need for transcoding [19]. The SU is assumed to continuously monitor the occupancy of its playback buffer in addition to the quality of the assigned channel. We also assume that the video encoder is capable of adjusting its parameters to meet the required rate as computed by the joint rate control algorithm. Based on the monitored occupancy and the channel quality, the SU determines the appropriate source rate for the next frame as well as the playback rate. Information about the next frame size is fed back to the video transmitter over a reliable feedback channel. Because such control packets are considerably small, they can be adequately protected through forward error correction (FEC) alone, ensuring that the feedback channel is effectively error-free. We assume that each of the primary channels fluctuates according to a 2-state continuous-time Markov chain (CTMC), where state g is the good state and state b is the bad state. Hence, p_g is the bit error rate (BER) during the good state and p_b is the BER during the bad state. The sojourn times for the good and bad states are exponentially distributed with means λ and μ, respectively.

In this study, we consider a slotted channel availability model in which a PU channel switches from being "available" (idle) to "busy" (occupied) or remaining idle and vice versa according to the 2-state discrete-time Markov chain (DTMC) shown in Figure 2. When a PU channel is idle, it could be used by a SU. In the DTMC in Figure 2, state O represents the unavailability of the channel (i.e., an occupied channel or the presence of the PU) and state I represents the availability of the channel (i.e., an idle channel or the absence of the PU). For this simple 2-state DTMC, the one-step transition probability matrix is given by:

$$P = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix}, \tag{1}$$

where $\alpha = p_{OI}$ is the transition probability from state O to state I, $\beta = p_{\mathrm{IO}}$

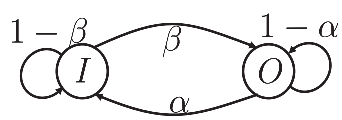

Fig. 2 The availability model of "one" primary channel to a SU.

is the transition probability from state I to O and $1-\alpha$ and $1-\beta$ are the self-transition probabilities for state O and I, respectively. Let $\pi = [\pi_O \ \pi_I]$ be the steady-state probability mass vector of the 2-state channel in Figure 2, which is simply obtained from:

$$[\pi_O \ \pi_I] \times \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix} = [\pi_O \ \pi_I],$$

where π_I is the steady-state probability that the channel is in state I (i.e., channel is idle and hence, available to the SU) and π_O is the steady-state probability that the channel is in state O (i.e., channel is busy).

3 Analysis of the Channel Availability Model

As mentioned earlier, a major challenge of video streaming over CR systems is the interruptions in data transmission experienced by the SUs as a result of the PUs requesting immediate access to their channels while they are occupied by the SUs. Such interruption to SUs transmission can be avoided if the transmission is reallocated to another "available" (idle) channel(s). Such reassignment of idle channels to active SUs is not always possible, and depends on the availability of such channels. In addition, channel reassignment introduces extra delays that are typically undesirable in time sensitive applications like video streaming. This clearly adds to the well-known challenges faced by video streaming applications over wireless channels which are characterized by their time-varying nature, in terms of bandwidth, delay and packet loss rates.

Several studies have proposed a variety of solutions to mitigate the impact of the time-varying nature and the limited bandwidth of wireless channels on the streaming process [7, 8, 20]. Yet mitigation of the effects of channel availability and their reassignments on the streaming process over cognitive radio networks is not yet properly addressed in the current literature. Therefore, in what follows, we try to introduce a simple yet useful mathematical model that describes the channel availability to SUs, hoping that such a model will assist in avoiding transmission interruptions through proper resource allocation, according to the importance of SUs time-sensitive information.

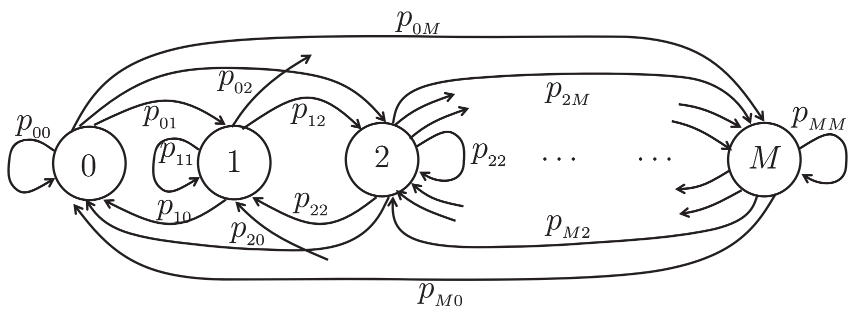

Fig. 3 The Markov chain that governs the availability model of all $M-$channels.

We first start by discussing the details of finding the probability of having $n \in [0,\ M]$ idle channels that can be used by the SUs. This is achieved by extending the 2-state channel model in Figure 2 to obtain the discrete-time multi-state Markov chain in Figure 3. Therefore, in the MC in Figure 3, a state $n \in [0,\ M]$ represents the number of available PUs channels to be used by one or more of the SUs. Thus, the objective now is to obtain the transition probabilities, and hence the steady state probabilities, that describe the availability of a number of PUs channels, which also indicates the total number of idle PUs in the spectrum. It is now worth noting the difference between the MC in Figure 3 and that in Figure 2. The states of the MC in Figure 3 represent the number of idle channels available to SUs while the states of the MC in Figure 2 represent the availability of one channel. More importantly, the steady state transition probabilities can always be used by the SU as an indication on how many channels will be available next based on our knowledge of how many channels are available at any time. This can clearly help an SU to decide and probably adapt different transmission parameters that could typically help in maintaining continuous playback on the receiver side.

Let N_{ac} be the random variable that represents the number of available (idle) channels at steady state. Obviously, the probability that $N_{ac} = n$ is given by:

$$\Pr[N_{ac} = n] = \binom{M}{n} \pi_I^n (1-\pi_I)^{M-n}, \tag{2}$$

where M is the total number of primary channels in the spectrum, which is also equal to the number of primary users. Let P be the 1-step transition probability matrix that represents the M-channels system. Since the Markov chain in Figure 3 is homogeneous, P can be written as:

$$P = \begin{bmatrix} p_{00} & p_{01} & p_{02} & \cdots & p_{0M} \\ p_{10} & p_{11} & p_{12} & \cdots & p_{1M} \\ p_{20} & p_{21} & p_{22} & \cdots & p_{2M} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{M0} & p_{M1} & p_{M2} & \cdots & p_{MM} \end{bmatrix},$$

where p_{ij} is the transition probability from state i to state j for $i, j = 0,\ 1,\ \ldots,\ M$. Elements of P are functions of the four possible transitions, namely, idle to busy, busy to idle, busy to busy or idle to idle (according to the 2-state MC in Figure 2). Therefore, each of the elements, p_{ij}, in the matrix P could be expressed as a combination of four different probabilities: $\beta,\ 1-\beta, \alpha$, and $1-\alpha$, and can be generalized as follows:

$$p_{ij} = \begin{cases} \sum_{k=0}^{\frac{M}{2}} \binom{M-i}{j-i+k} \alpha^{j-i+k} (1-\alpha)^{M-j-k} \binom{i}{i-k} (1-\beta)^{i-k} \beta^k, i = j = \frac{M}{2},\ M \text{ is even} \\ \sum_{k=0}^{\frac{M}{2}-1} \binom{M-i}{j-i+k} \alpha^{j-i+k} (1-\alpha)^{M-j-k} \binom{i}{i-k} (1-\beta)^{i-k} \beta^k,\ \forall i = j,\ i,\ j \notin \{0,\ M,\ \frac{M}{2}\},\ M \text{ is even} \\ \sum_{k=0}^{\frac{M}{2}-1} \binom{M-i}{j-i+k} \alpha^{j-i+k} (1-\alpha)^{M-j-k} \binom{i}{i-k} (1-\beta)^{i-k} \beta^k,\ \forall i \neq j,\ i,\ j \notin \{0,\ M\},\ M \text{ is even} \\ \sum_{k=0}^{\frac{M-1}{2}} \binom{M-i}{j-i+k} \alpha^{j-i+k} (1-\alpha)^{M-j-k} \binom{i}{i-k} (1-\beta)^{i-k} \beta^k,\ \forall i \leq j,\ i,\ j \notin \{0,\ M\},\ M \text{ is odd} \\ \sum_{k=0}^{\frac{M-1}{2}} \binom{M-i}{k} \alpha^{k} (1-\alpha)^{M-i-k} \binom{i}{j-k} (1-\beta)^{j-k} \beta^{i-j+k},\ \forall i > j,\ i,\ j \notin \{0,\ M\},\ M \text{ is odd} \\ \binom{M-i}{(M-i)\left(\frac{j}{M}\right)} \alpha^{\frac{j(M-i)}{M}} (1-\alpha)^{\frac{(M-j)(M-i)}{M}} \binom{i}{ij/M} (1-\beta)^{j\left(\frac{i}{M}\right)} \beta^{(M-j)\frac{i}{M}},\ \forall j,\ i \in \{0,\ M\}. \end{cases} \tag{3}$$

Now, let $\gamma_n,\ n \in [0,\ M]$ represent the steady-state probability of having n idle channels. The steady state probability mass function (pmf) vector $\Gamma = [\gamma_0\ \gamma_1\ \gamma_2\ \ldots\ \gamma_M]$ can be obtained by solving $\sum_{n=0}^{M} \gamma_n = 1$ and $\Gamma = \Gamma P$.

4 Simulations Results and Numerical Investigations

In this section, we verify the usefulness of the proposed channel availability model using simulations and numerical investigations. Then, using MATLAB©

simulations, we study the efficacy of the proposed hybrid adaptive video streaming model based on the proposed channel availability model.

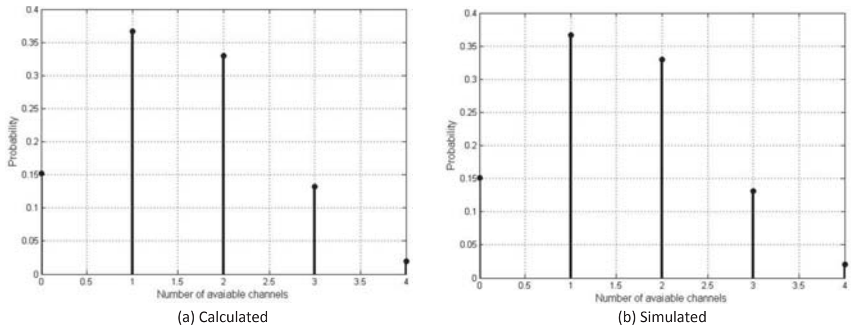

Fig. 4 pmf of the number of available channels, ($M = 4,\ \alpha = 0.3,\ \beta = 0.5$).

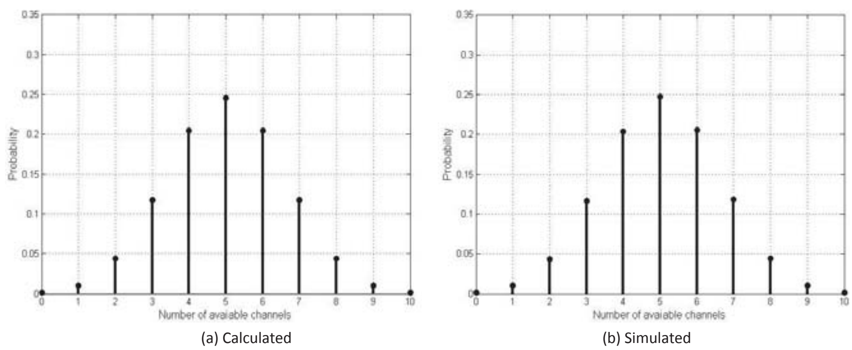

Fig. 5 pmf of the number of available channels, ($M = 10,\ \alpha = 0.5,\ \beta = 0.5$).

Figures 4 and 5 show the pmf of the number of available channels as calculated using Equation 3 and by averaging 10^5 runs of the simulation model. Specifically, Figure 4(a) shows the pmf of the number of available channels as calculated using Equation 3 while Figure 4(b) shows the same probability using the simulation model for $M = 4,\ \alpha = 0.3$ and $\beta = 0.5$ in both cases. Similarly, Figure 5(a) shows the pmf of the number of available channels as calculated using Equation 3 for $M = 10,\ \alpha = 0.5$ and $\beta = 0.5$, while Figure 5(b) shows the same probability by averaging 10^5 runs of the simulation model. It is obvious that the figures obtained using the simulation model are in full agreement with these obtained by calculations, which validates the obtained formula in Equation 3.

In this section, we also investigate by simulations the impact of the unavailability of channels and their reassignment to SUs on the video streaming process. To do so, a MATLAB SimEvents model that represents the behavior a CR network was developed. In this model, different scenarios with different number of primary channels and different numbers of SUs were considered. It is important to note that the number of SUs was always kept less than or equal to the number of the PUs. In addition, it is assumed that SUs are only allowed to access idle channels. Moreover, perfect sensing is assumed and as a result, an SU will immediately vacate a used channel once its PU gets active. Hence, when none of the PUs channels are available, the video transmission of a SU will be interrupted. This is of severe impact on the continuity of the playback process since once started it cannot be stopped. If such a situation persists, noting that video frames are drained from the playback buffer at a constant rate, the playback buffer will starve. Therefore, it is highly recommended to predict which channels will be available and reallocate the SU traffic to these channels, if any, to avoid buffer starvations and hence, avoid playback interruptions. Finally, in our simulations, different trace files for different video sequences obtained from [21] and [22] were used. Details of these video sequences will be provided as needed.

The encoded Common Interchange Format (CIF) ten-minute "Sony Demo sequence" is first transmitted over the previously mentioned CR simulation model with 3 PUs (i.e., 3 channels) and 1 SU. The video file is streamed from a secondary transmitter to the CR user. Transmission and network delays were both taken into considerations. The availability of each of the PUs channels is modeled by the Markov chain shown in Figure 2 with different values for the parameters α and β used in the simulations. The quality of the received video is controlled using a hybrid solution that jointly integrates a source rate controller with adaptive playback [11]. This is done according to the instantaneous occupancy of the playback buffer at the receiver side. To avoid starvation instants when there are no video frames in the playback buffer, it is desirable to maintain the number of correctly received and decoded video frames in the buffer at or around a specific threshold. Buffer underflow is the situation in which the instantaneous number of frames in the playback buffer is below that threshold. Selection of such a threshold depends on the channel availability to SUs, quality of the allocated channel, and the video content. It is important to note that selection of such a threshold is out of the scope of this study. Underflow situations could result due to different reasons that could happen individually or jointly. These reasons could be channel unavailability, length of time periods a channel is available for the SU, bad channel quality, or when the amount of the transmitted information is beyond the channel capability, etc. Recall that video applications typically require high data rates with strict upper bounds on delays, delay jitter, and packet losses. Therefore, in underflow situations, the proposed adaptive scheme reduces the amount of transmitted information through a source rate control mechanism.

Figure 6 depicts the buffer occupancy for the case of 1 cognitive user and 3 primary users (i.e., 3 primary channels) for $\alpha = 0.35$ and $\beta = 0.5$. In this case, video frames are transmitted over one channel at a time even if there are

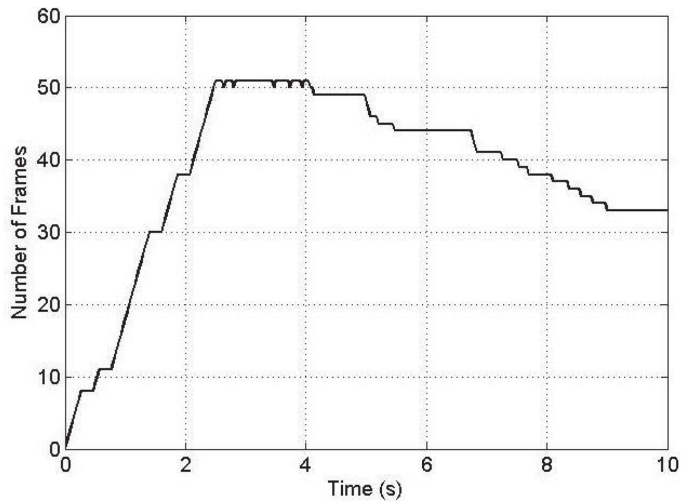

Fig. 6 Receiver buffer occupancy, (1 SU, 3 PUs, $\alpha = 0.35$, $\beta = 0.5$).

more channels available. Such a situation will be addressed shortly. Moreover, video frames will not be transmitted only when all channels are busy.

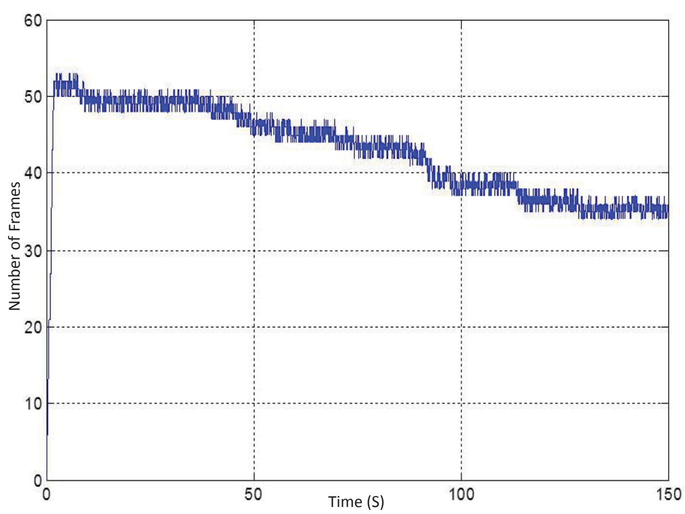

Fig. 7 Receiver buffer occupancy, (1 SU, 4 PUs, $\alpha = 0.6$, $\beta = 0.4$).

Figure 7 depicts the buffer occupancy for the case of 1 cognitive user and 4 primary users (i.e., 4 primary channels) for $\alpha = 0.6$ and $\beta = 0.4$. Similarly, video frames are transmitted over one channel at a time. In addition, video frames are not transmitted only when all of the four channels are busy. Comparing the buffer occupancy in this case with the previous case, it is obvious that as the number of primary channels increases for the same number of SUs, the playback buffer builds up faster and hence continuous video playback can be maintained with the proper channel assignment. It is also important to note that Figures 6 and 7 indicate that even with the number of primary channels larger than the number of cognitive users, there is still a decreasing trend in the buffer occupancy. Such trend depends on the fraction of time the cognitive user can access the primary channels. Therefore, there is a clear need for other techniques rather than just transmitting on channels when available.

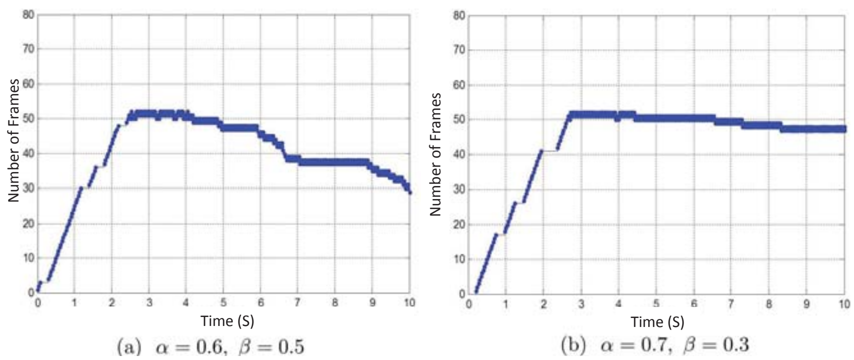

Fig. 8 Impact of channel availability on the receiver buffer occupancy (1 SU, 3 PUs).

To investigate the impact of the channel availability on the continuity of the video playback, simulations were carried out for different values of the channel parameters α and β. Figure 8 depicts the buffer occupancy for the case of 1 cognitive user and 3 primary users (i.e., 3 primary channels) for 2 pairs of values of α and β. Figure 8(b) shows that as the transition probability from busy to idle (α) increases, the buffer occupancy increases. The same is observed when the transition probability from idle to busy (β) decreases.

To exploit the possibility of using multiple channels, as offered by the CR technology, we relax the restriction of transmitting video frames over only one channel, even if more than one channel is available. Figure 9 depicts the buffer occupancy for two different scenarios. First, Figure 9(a) shows the buffer occupancy for the case of 1 SU and 3 PU channels, while Figure 9(b) shows the buffer occupancy for the case of 1 SU and 4 PU channels. As expected, this figure shows that as the number of PU channels increases, the buffer occupancy is enhanced, which is expected to help in maintaining continuous video playback at the SU. It is also important to note that there will always be a decreasing/fluctuating trend in the buffer occupancy as time goes by. This is simply explained by the fact the some of the channels used by the SU will be lost due to the activity of their PUs. The occupancy will also be affected

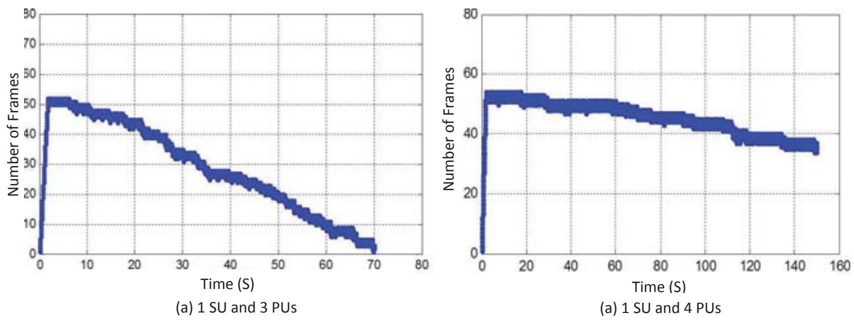

Fig. 9 Impact of channel assignment on the occupancy of the playback buffer.

when the transmitted frames are of considerable sizes due to the activity of the video sequence.

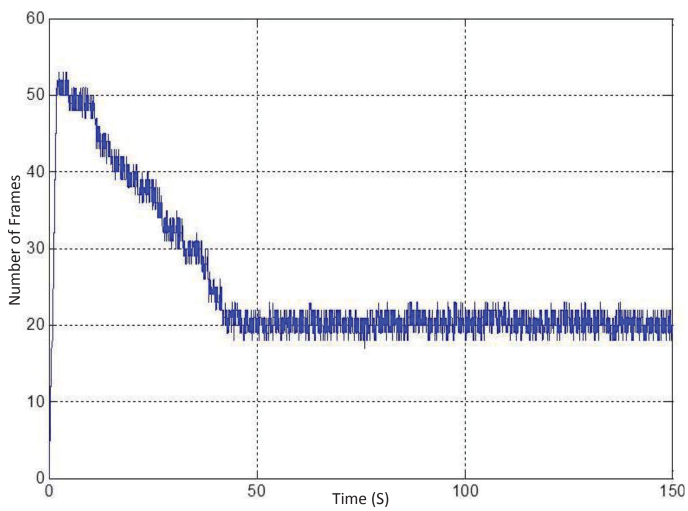

Fig. 10 Receiver buffer occupancy using the proposed hybrid rate control and adaptive playback scheme.

It is important to note that there are sometimes unavoidable situations in which all channels are busy, and in such cases no video frames could be transmitted. The impact of such cases on the streaming process could be contained through building the playback buffer with enough number of frames that guarantees continuous playback until a channel (or more) becomes available. Figure 10 shows the achieved receiver buffer occupancy using the proposed hybrid rate control and adaptive playback scheme. The figure shows that buffer starvation can be avoided and hence, the goal of continuous video playback may be achieved. In more detail, the quality of the reconstructed video is adapted based on the number of frames available at the playback buffer using two possible techniques: rate control and adaptive playback. If the number of frames in the buffer is less than the predefined threshold, the size of each video frame and the playback rate are reduced accordingly. In our simulations, the threshold is arbitrarily set to 20 frames. If there are less than 20 frames in the playback buffer, the size of each frame is reduced to speed up the frame transmission rate, which typically results in degradation in the perceptual quality. The playback rate is also reduced from 30 frames per second (fps) to 22.5 fps. The results shown in Figure 6 prove that the buffer is not likely to starve and hence, achieves the goal of maintaining a continuous video playback.

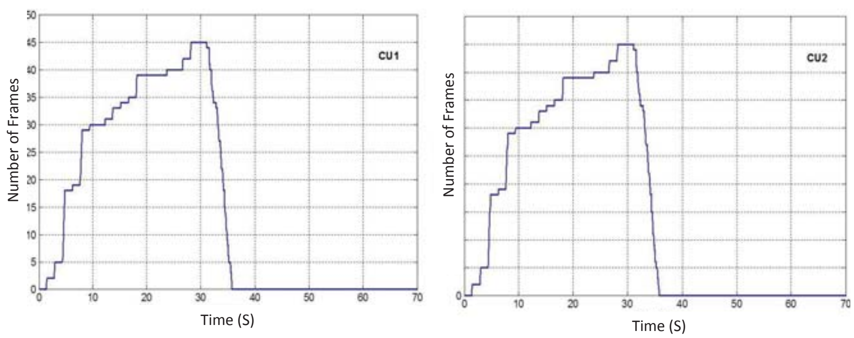

Fig. 11 Receiver buffer occupancy, (2 SU, 4 PUs, $\alpha = 0.6,\ \beta = 0.4$).

Hence, we investigate the possibility of assigning multiple channels, as also offered by the cognitive radio technology, among different SUs and hence, improving the viewing quality on the SUs end. To do so, we simulated several scenarios. Figure 10 shows the buffer occupancy of the playback buffers of two SUs for the case of 2 SUs and 4 primary users with the $\alpha = 0.6$ and $\beta = 0.4$. In this scenario, we considered a simple assignment mechanism. In more detail, if two or four channels are available, then each of the SUs gets an equal share of the channels. If three channels are available, each SU gets one of the channels and the third one is assigned in a round robin time division fashion to the two users. Similarly, if only one channel is available, this channel is also assigned in a round robin fashion among the two contending SUs. Please note that more sophisticated channel assignment scenarios are also possible and will be considered in our future work. This could include assignments based on the dynamics of the playback buffer along with the channel quality as experienced by the SUs, in addition to the importance of the transmitted information and their deadlines.

5 Conclusions

In this paper, the channel availability of the primary users channels to the secondary users was represented by a finite-state Markov chain (FSMC) model. A closed-form expression that characterizes this availability was also obtained and verified. In addition, a simple hybrid rate control and adaptive playback scheme was proposed and used. Simulation results demonstrated the efficacy of this simple rate control mechanism in limiting the fluctuations in the occupancy of the playback buffer that could arise due to the unavailability of channels and/or the time-varying nature of the channels, if any. The impact of the number of PUs channel in addition to their parameters on the buffer occupancy was also investigated. Finally, channel assignment between SUs was considered in our study.

In a future work, more complex scenarios in channel assignment among the SUs will be studied. Also, efficient scheduling schemes will be developed to ensure continuous video playback for all cognitive users in the system. The hybrid rate control mechanism will be extended through the integration of other alternative solutions such as layered coding, error concealment, and adaptive modulation.

References

1. "New America Foundation @ONLINE." `https://www.newamerica.org/publications/policy/end_spectrum_scarcity`. Accessed: 6 March 2015.
2. J. Mitola, *Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio.* PhD thesis, Royal Institute of Technology (KTH), 2000.
3. S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, pp. 201–220, Feb 2005.
4. A. Amraoui, B. Benmammar, F. Krief, and F. Bendimerad, "Intelligent wireless communication system using cognitive radio," *International Journal of Distributed and Parallel Systems (IJDPS)*, vol. 3, pp. 91–104, March 2012.
5. T. Nguyen, V. F. Villain, and Y. L. Guillou, "Cognitive radio RF: Overview and challenges," *VLSI Design*, vol. 3, 2012.
6. M. Lindeberg, S. Kristiansen, T. Plagemann, and V. Goebel, "Challenges and techniques for video streaming over mobile ad hoc networks," *Multimedia Systems*, vol. 17, no. 1, pp. 51–82, 2011.
7. M. Hassan, L. Atzori, and M. Krunz, "Video transport over wireless channels: A cycle-based approach for rate control," in *Proceedings of the 12th Annual ACM International Conference on Multimedia*, MULTIMEDIA '04, (New York, NY, USA), pp. 916–923, ACM, 2004.
8. M. Hassan and M. Krunz, "Video streaming over wireless packet networks: An occupancy-based rate adaptation perspective," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 17, pp. 1017–1027, Aug 2007.
9. Y. chi Lee, J. Kim, Y. Altunbasak, and R. M. Mersereau, "Layered coded vs. multiple description coded video over error-prone networks," in *Signal Processing: Image Communication*, pp. 337–356, 2003.
10. Y. Wang and Q.-F. Zhu, "Error control and concealment for video communication: a review," *Proceedings of the IEEE*, vol. 86, pp. 974–997, May 1998.
11. M. Hassan and M. Krunz, "A playback-adaptive approach for video streaming over wireless networks," in *Global Telecommunications Conference, 2005. GLOBECOM '05. IEEE*, vol. 6, pp. 5 pp.–3691, Dec 2005.

12. M. Kalman, E. Steinbach, and B. Girod, "Adaptive media playout for low-delay video streaming over error-prone channels," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 14, pp. 841–851, June 2004.
13. D. Hu and S. Mao, "On cooperative relay networks with video applications," *arXiv preprint*, Oct. 2012.
14. S. Li, T. H. Luan, and X. Shen, "Channel allocation for smooth video delivery over cognitive radio networks," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, pp. 1–5, Dec 2010.
15. H. Xu and B. Li, "Resource allocation with flexible channel cooperation in cognitive radio networks," *IEEE Transactions on Mobile Computing*, vol. 12, pp. 957–970, May 2013.
16. Y. Xu, D. Hu, and S. Mao, "Relay-assisted multiuser video streaming in cognitive radio networks," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 24, pp. 1758–1770, Oct 2014.
17. D. Hu and S. Mao, "Streaming scalable videos over multi-hop cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 9, pp. 3501–3511, November 2010.
18. D. Hu and S. Mao, "On medium grain scalable video streaming over femtocell cognitive radio networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, pp. 641–651, April 2012.
19. D. Marpe, T. Wiegand, and G. J. Sullivan, "The H.264/MPEG4 advanced video coding standard and its applications," *IEEE Communications Magazine*, vol. 44, pp. 134–143, Aug 2006.
20. M. Hassan and T. Landolsi, "A retransmission-based scheme for video streaming over wireless channels," in *Wirel. Commun. Mob. Comput.*, vol. 10, p. 511521, April 2009.
21. P. Seeling and M. Reisslein, "Video transport evaluation with H.264 video traces," *IEEE Communications Surveys Tutorials*, vol. 14, pp. 1142–1165, Fourth 2012.
22. R. Gupta, A. Pulipaka, P. Seeling, L. J. Karam, and M. Reisslein, "H.264 coarse grain scalable (CGS) and medium grain scalable (MGS) encoded video: A trace based traffic and quality evaluation," *IEEE Transactions on Broadcasting*, vol. 58, pp. 428–439, Sept 2012.