Optimal Resource Allocation for Video Streaming over Cognitive Radio Networks
Bo Guan and Yifeng He

Department of Electrical and Computer Engineering
Ryerson University, Toronto, Canada

Abstract—Cognitive Radio (CR) is a new paradigm in wireless communications to enhance utilization of limited spectrum resources. In this paper, we investigate the resource allocation problem for video streaming over spectrum underlay cognitive radio networks where secondary users and primary users transmit data simultaneously in a common frequency band. We formulate the resource allocation problem into an optimization problem, which jointly optimizes the source rate, the transmission rate, and the transmission power at each secondary session to provide QoS guarantee to the video streaming sessions. The optimization problem is formulated into a Geometric Programming (GP) problem, which can be solved efficiently. In the simulations, we demonstrate that the proposed scheme can achieve a lower Packet Loss Rate (PLR) and queuing delay, thus leading to a higher video quality for the video streaming sessions, compared to the uniform scheme.

I. INTRODUCTION
The emerging high-speed wireless access technologies and the requirements of different wireless applications are expected to create a huge demand on spectral resources in the next generation wireless systems. Achieving high spectrum utilization is, therefore, one of the most critical research objectives in designing wireless communication systems today. In fact, as discussed in a report by Federal Communication Commission (FCC) on spectrum usage, the spectrum utilization varies from 15% to 85%, depending on the geographical area [1]. Therefore, there is an increasing interest in developing efficient methods for spectrum management and sharing. Cognitive Radio (CR) is a new paradigm in wireless communications to enhance utilization of limited spectrum resources. It is defined as a radio that is able to utilize available side information, in a decentralized paradigm, in order to efficiently use the radio spectrum left unused by licensed systems. CR techniques exploit spectrum opportunities in space, time, frequency while protecting users of the primary network (who are referred to as primary users) from excessive interference due to spectrum access from the users of secondary networks (who are referred to as secondary users). Meanwhile, Code Division Multiple Access (CDMA) has been adopted as multiple access technology for 3G and beyond due to its advantages such as universal frequency reuse, soft handoff, inherent diversity, and high spectrum efficiency [2]. Multimedia services over IP-based CDMA wireless networks will be one of the key applications in cognitive radio field.

Secondary users can access the spectrum owned by the primary network provider using spectrum overlay or spectrum underlay [3, 4]. In the spectrum overlay scheme, secondary users are only allowed to access the spectrum channels of the primary network that are not being used by primary users. In the spectrum underlay scheme, primary users and secondary users can transmit data simultaneously over the same channel as long as the aggregated interference generated by secondary users are below an acceptable threshold [5].

Compared to spectrum overlay, the advantage of spectrum underlay is that the secondary users can directly access the licensed spectrum without considering the behaviours of the primary users. In the spectrum underlay scheme, the transmission power and transmission rate of each secondary user become critically important in order to guarantee the interference to the primary network below an acceptable threshold.

It is challenging to obtain a high quality for video streaming over spectrum underlay cognitive radio networks. First, the secondary users need to carefully select their transmission power and transmission rate to guarantee that they do not generate an unacceptable interference to the primary users. Second, the secondary users suffer from the interferences from both the primary users and the other secondary users, which may corrupt the video packets.

Co-existence study between CDMA and cognitive radio has already attracted attention of researchers [6, 7]. Resource allocation problems in cognitive radio network need to ensure that the primary users are protected against the interferences from the secondary users, which is not considered in the resource allocation problems in traditional wireless networks [8]. The problem of channel and power allocation for secondary users in a cellular cognitive radio network was addressed in [9], in which the authors proposed a heuristic-based two-phase resource allocation scheme. In [10], the problem of dynamic spectrum access with Quality of Service (QoS) guarantee for secondary users was studied under an interference temperature constraint for primary users. In [11], a user removal algorithm based on the tree-pruning algorithm was proposed to satisfy QoS constraints for secondary users and interference temperature constraints for primary users. The proposed algorithm in [11] is however computationally expensive.

In this paper, we investigate the resource allocation problem for video streaming over spectrum underlay cognitive wireless networks. Specifically, we jointly optimize the source rate, the transmission rate, and the transmission power at each
secondary video session to provide QoS guarantee to the delivery of video streams. The optimization problem is formulated into a Geometric Programming (GP), which can be solved efficiently.

The remainder of this paper is organized as follows. In Section II, we present the system models. In Section III, we formulate and solve the resource allocation problem for video streaming over spectrum underlay cognitive wireless networks. The simulation results are presented in Section IV, and the conclusions are drawn in Section V.

II. SYSTEM MODELS

We consider the hierarchical spectrum sharing problem in a spectrum underlay cognitive wireless network where several secondary users and primary users transmit data in a common frequency band (e.g., as in a CDMA-based wireless network) [12]. A communication session is established between a pair of users who wish to communicate with each other. The communication sessions between the primary users are referred to as primary sessions, and the communication sessions between the secondary users are referred to as secondary sessions. The transmission setting considered in this paper is illustrated in Fig. 1. The set of primary sessions is denoted by \( M \), and the set of the secondary sessions is denoted by \( N \). In this paper, we assume that all the secondary sessions in the set \( N \) are video streaming sessions and they are all single-hop sessions. We may extend the study to video streaming over multi-hop secondary sessions in the future.

Simultaneous communications of primary sessions and secondary sessions will interfere with each other. We will optimize the resource allocation to guarantee that: 1) the interference received at the receiving nodes of the primary sessions should be below an acceptable level, and 2) the secondary sessions (e.g., video streaming sessions) should meet the QoS requirements.

A. Queuing Model

Each secondary session consists of a sender and a receiver. The sender captures and encodes the live video, and then transmits the compressed stream to the receiver. The block diagram of the sender of the secondary session \( m (\forall m \in M) \) is shown in Fig. 2. An M/M/1 queuing system [13] is used to buffer the compressed video streams before they are transmitted to the receiver via the wireless channel. The compressed video packets enter the M/M/1 queue at a source rate \( S_m \). The video packets are scheduled based on First-In-First-Out (FIFO) order, and are transmitted to the receiver at the transmission rate \( R_m \) with the transmission power \( P_m \).

Let \( l_m \) denote the average packet length at the sender of the secondary session \( m \). The packet arrival rate \( r_m \) to the M/M/1 queue is given by \( r_m = S_m/l_m \), and the packet departure rate out of the M/M/1 queue is given by \( \mu_m = R_m/l_m \). The M/M/1 queue needs to satisfy the follow condition in order to be stable [13]:

\[
\tau_m \leq \mu_m, \quad \forall m \in M, \tag{1}
\]

where \( M \) is the set of the secondary sessions.

In the M/M/1 queuing system, the tail probability is defined as the probability that the number of packets in the system is larger than a threshold \( \epsilon_m \) [13]. Let the threshold \( \epsilon_m \) represent the length of the queue at the secondary session \( m \). The tail probability represents the packet drop probability due to queue overflow. The tail probability \( p^c_m \) at the secondary session \( m \) is given by [13]

\[
p^c_m = p_r(N_m > \epsilon_m) = \left( \frac{r_m}{\mu_m} \right)^{\epsilon_m+1}, \forall m \in M, \tag{2}
\]

where \( N_m \) is a random variable representing the number of the packets in the M/M/1 queuing system of secondary session \( m \).

B. CDMA Model

In the transmission setting as shown in Fig. 1, multiple primary sessions and secondary sessions share the common channel using CDMA technology.

In the CDMA model, the spread-spectrum bandwidth is denoted by \( W \), the power spectrum density of the Additive White Gaussian Noise (AWGN) is denoted by \( N_0 \). The channel gain from the sender of link \( j \) to the receiver of link \( m \) is denoted by \( g_{jm} \). The received Bit-Energy-to-Interference-Density Ratio (BEIDR) at the receiver of the secondary session \( m \) is denoted by \( y_m \), which is given by [14]

\[
y_m = \left( \frac{W}{R_m} \right) \left( \frac{g_{mm} l_m^2}{\delta(\sum_{j \in M, j \neq m} g_{jm} p_j + \sum_{k \in N} g_{km} p_k) + N_0 W} \right), \quad \forall m \in M, \tag{3}
\]
where $\delta$ is the orthogonally factor representing Multiple Access Interference (MAI) from the imperfect orthogonal spreading codes.

We assume Binary Phase Shift Keying (BPSK) modulation is used in the CDMA system. The Bit Error Rate (BER) at the secondary session $m$ is given by

$$e_m = Q(\sqrt{2y_m}), \forall m \in M,$$  

where $Q(x)$ is a Q-function [15].

If a packet is received in error, it will be dropped at the receiver. We assume that the bit errors occur independently in a packet. Therefore the Packet Loss Rate (PLR) due to transmission errors at the secondary session $m$ is then given by

$$P^{PLR}_m = 1 - (1 - e_m)^{L_m}, \forall m \in M,$$  

where $L_m$ is the number of bits for the packet at the secondary session $m$.

C. QoS Metrics

We examine two QoS metrics, the PLR and the queuing delay, at each secondary session. The PLR consists of the congestion PLR due to queue overflow and the transmission PLR due to transmission errors. The PLR of the packets at the secondary session $m$, denoted by $P^{PLR}_m$, is given by

$$P^{PLR}_m = 1 - (1 - P_u^m)(1 - P^{m}_m)$$

$$= 1 - \left(1 - \left(\frac{\tau_m}{\mu_m}\right)^{(\epsilon_m + 1)}\right)\left(1 - Q(\sqrt{2y_m})\right)^L, \forall m \in M.$$  

The queuing delay of a packet is defined as the duration from the time when packet arrives in the M/M/1 queuing system to the time when the packet leaves the M/M/1 queuing system. In the M/M/1 queuing model, the queuing delay $D_m$ of the packets at the secondary session $m$ is given by [13]

$$D_m = \frac{1/\mu_m}{1-\tau_m/\mu_m}, \forall m \in M.$$  

III. OPTIMAL RESOURCE ALLOCATION

A. Problem Formulation

We optimize the resource allocation to provide QoS guarantee for video streaming at the secondary sessions, while guaranteeing that the interference from the secondary sessions to the primary sessions should be lower than the tolerable threshold.

The quality of the encoded video at the secondary session $m$ is higher if the source rate $S_m$ is higher, or equivalently the reciprocal of the source rate, $1/S_m$, is lower. Therefore, we set the objective of the resource optimization problem to minimize the weighted sum of the reciprocals of the source rates of all secondary sessions, mathematically expressed by

$$f_{obj} = \sum_{m \in M} \frac{k_m}{S_m},$$

where $k_m$ denotes the quality weight for the secondary session $m$, and $\sum_{m \in M} k_m = 1$. We can enable quality differentiation among the video sessions in the set $M$ by assigning different quality weights. The video session with a higher quality weight can be allocated a higher source rate, thus leading to a higher video quality.

The resource optimization problem can be stated as: to minimize the weighted sum of the reciprocals of the source rates of all secondary sessions, by optimizing the source rate, the transmission rate, and the transmission power at each secondary session, subject to the power constraints, the requirements of the congestion PLR, the transmission BER, and tolerable interference at the primary receiving points, respectively. Mathematically, the problem is formulated as follows.

Minimize $f(S,R,P)$ subject to

$$Q(\sqrt{2y_m}) \leq e_{th}, \forall m \in M,$$

$$y_m = \left(\frac{W}{R_m}\right)\left(\frac{\theta mm_p}{\delta \sum_{j \in M, j \neq m} \theta jm_p + \Sigma_{k \in N} \theta km_p + N_d}\right), \forall m \in M,$$

where $S$ is the vector of the source rates of all secondary sessions, $R$ is the vector of the transmission rates of all secondary sessions, $P$ is the vector of the transmission powers of all secondary sessions, $e_{th}$ is the threshold of BER, $P_{th}$ is the threshold of congestion PLR, $P_{max}$ is the maximum transmission power at the secondary session, and $l_k$ is the interference threshold tolerable by the receiving point of the primary session $k$.

$Q$ function is a monotonically decreasing function. Therefore we can convert the constraints, $Q(\sqrt{2y_m}) \leq e_{th}$ and $y_m = \left(\frac{W}{R_m}\right)\left(\frac{\theta mm_p}{\delta \sum_{j \in M, j \neq m} \theta jm_p + \Sigma_{k \in N} \theta km_p + N_d}\right), \forall m \in M,$ to an equivalent form

$$\left(\frac{W}{R_m}\right)\left(\frac{\theta mm_p}{\delta \sum_{j \in M, j \neq m} \theta jm_p + \Sigma_{k \in N} \theta km_p + N_d}\right) \geq \frac{(Q^{-1}(e_{th}))^2}{2},$$

where $Q^{-1}(x)$ is the inverse $Q$-function [15]. After the conversion, the optimization problem (8) is changed to the following equivalent form:
In the optimization problem (9), to an equivalent form:

\[
\text{minimize}_{S,R,P} \sum_{m \in M} \frac{k_m}{s_m} \tag{9}
\]
subject to

\[
\left( \frac{W}{R_m} \right) \left( \delta \left( \sum_{j \in M, j \neq m} g_j m_j P_j + \sum_{k \in K} g_k m_k P_k \right) \right) \geq \frac{(q^{-1}(e_{th}))^2}{2}, \quad \forall m \in M,
\]

\[
\mu_m = R_m / L_m, \quad \forall m \in M,
\]

\[
\tau_m = S_m / L_m, \quad \forall m \in M,
\]

\[
\frac{\tau_m}{\mu_m} \frac{(e_{th})}{(e_{th})} \leq P_{th}, \quad \forall m \in M,
\]

\[
\tau_m \leq \mu_m, \quad \forall m \in M,
\]

\[
0 \leq \sum_{m \in M} g_m m_k P_m \leq I_k, \quad \forall k \in N,
\]

\[
R_m > 0, \quad \forall m \in M,
\]

\[
S_m > 0, \quad \forall m \in M.
\]

Let \( \omega_{th} = \frac{(q^{-1}(e_{th}))^2}{2} \) representing the threshold of the received BEIDR. If the received BEIDR at the receiver of a secondary session is larger than \( \omega_{th} \), the BER of the secondary session will be less than \( e_{th} \).

In the optimization problem (9), the first constraint is equivalent to \( q^{-1}(e_{th})^2 \). The constraint \( \sum_{m \in M} g_m m_k P_m \leq I_k \), requires that the packets at the secondary session be no less than the threshold \( P_{th} \). The second constraint, \( \tau_m = S_m / L_m \), represents packet arrival rate to the M/M/1 queue. The third constraint, \( \mu_m = R_m / L_m \), represents packet departure rate out of the M/M/1 queue. The fourth constraint, \( \frac{\tau_m}{\mu_m} \frac{(e_{th})}{(e_{th})} \leq P_{th} \), requires that the packet departure rate at the sender of the secondary session be no less than the packet arrival rate to the M/M/1 queue.

The fourth constraint, \( \frac{\tau_m}{\mu_m} \frac{(e_{th})}{(e_{th})} \leq P_{th} \), requires to admit the secondary sessions based on the available resources in the wireless network. Our work focuses on the resource allocation for the admitted secondary sessions.

B. Optimal Solution

We convert the first constraint:

\[
\left( \frac{W}{R_m} \right) \left( \delta \left( \sum_{j \in M, j \neq m} g_j m_j P_j + \sum_{k \in K} g_k m_k P_k \right) \right) \geq \frac{(q^{-1}(e_{th}))^2}{2}, \quad \forall m \in M,
\]

\[
\omega_{th} R_m \sum_{j \in M, j \neq m} g_j m_j P_j + \omega_{th} R_m \delta \sum_{k \in K} g_k m_k P_k \leq 1.
\]

The constraint \( \frac{\tau_m}{\mu_m} \frac{(e_{th})}{(e_{th})} \leq P_{th} \) is equivalent to \( \sum_{m \in M} g_m m_k P_m \leq I_k \). Therefore, the optimization problem (9) is then converted to the following equivalent form:

\[
\text{minimize}_{S,R,P} \sum_{m \in M} \frac{k_m}{s_m} \tag{10}
\]
subject to

\[
\delta \omega_{th} R_m \sum_{j \in M, j \neq m} g_j m_j P_j + \omega_{th} R_m \delta \sum_{k \in K} g_k m_k P_k + N_0 W \leq 1, \quad \forall m \in M,
\]

\[
P_{th} \left( \frac{S_m}{R_m} \right) \frac{(e_{th})}{(e_{th})} \leq 1, \quad \forall m \in M,
\]

\[
S_m (R_m)^{-1} \leq 1, \quad \forall m \in M,
\]

\[
I_k \delta \sum_{m \in M} g_m m_k P_m \leq 1, \quad \forall k \in N,
\]

\[
0 \leq P_m \leq P_{max}, \quad \forall m \in M,
\]

\[
R_m > 0, \quad \forall m \in M,
\]

\[
S_m > 0, \quad \forall m \in M.
\]

In the optimization problem (10), the objective function and the left side of the first constraint are polynomials \([16]\), the left sides of the second, third, and fourth constraints are monomials \([16]\). Therefore the optimization problem is a geometric programming problem \([16]\). The GP problem can be converted to a convex optimization problem based on a logarithmic change of variables and a logarithmic transformation of the objective and constraint functions \([16]\). The convex optimization problem can be then solved efficiently using the interior-point methods \([17]\).

The proposed resource optimization algorithm can be performed by the base station. In the initialization stage, the parameters \( (W, J, N_0) \) are obtained by the base station, the parameters \( (e_{th}, P_{th}, P_{max}) \) are set by the administrator, the parameters \( (L_m, C_m, G_{mj}) \) are provided by the sender of the primary session \( m \), the parameters \( (P_k, I_k) \) are provided by the sender of the primary session \( k \). The base station collects the parameters, computes the optimal source rate, transmission rate, and transmission power for each secondary session by solving the optimization problem (10), and then feeds them back to the sender of each secondary session, respectively. The sender of each secondary session performs video streaming using the optimal source rate, transmission rate, and transmission power.

C. Discussion

The number of the primary sessions and the secondary sessions may change dynamically in a cell area of the CDMA wireless network. The solution to handle the session dynamics is to divide the time evenly into multiple time slots and perform the resource optimization during each time slot, in which we assume that the number of sessions remain unchanged.

During the time when the traffic load is high, the source rate of the secondary session may be too low to support a video streaming session. Therefore, an admission control policy is needed to admit the secondary sessions based on the available resources in the wireless network. Our work focuses on the resource allocation for the admitted secondary sessions. The admission control is complementary to our work.
IV. SIMULATIONS

We consider a circle area of the CDMA wireless network, which consists of one base station, one primary user, and 4 secondary users. The network setting is shown in Fig. 1. The radius of the circle area is 1000 m. The base station is located at the centre, while the primary and secondary users are randomly placed inside the circle area. We assume that there are one primary session and two secondary sessions. The primary session is the uplink connectivity from a primary user to the base station. The two secondary sessions are all single-hop video streaming sessions.

In CDMA model, we set the channel bandwidth \( W = 10 \) MHz, the orthogonally factor \( \delta = 0.1 \), and the noise power spectrum density \( N_0 = 10^{-13} \) W/Hz. The maximum transmission power is set to 1.0 \( W \) for all secondary sessions. The channel gain from the sender of link \( j \) to the receiver of link \( m \) is given by \( g_{jm} = 10^5 / d_{jm}^4 \), where \( d_{jm} \) is the distance from the sender of link \( j \) to the receiver of link \( m \). We set the interference threshold at the primary receiving point to \( 10^{-7} W \). The transmission power at the primary user is set to 0.5 \( W \). In the M/M/1 queuing model, we set the average packet length to 1000 bits, and the queue length to 20 packets, for all secondary sessions. In the setting of QoS thresholds, we set the threshold of transmission BER \( e_{th} = 10^{-6} \), the threshold of congestion PLR \( P_{th} = 0.01 \). At each video session, the Foreman CIF sequence is encoded using Joint Scalable Video Model (JSVM) video codec [18].

We compare the performances for each secondary session between the proposed scheme, in which the source rate, the transmission rate, and the transmission power for each secondary session are optimized by solving the optimization problem (10), and the uniform scheme, in which the source rate, the transmission rate, and the transmission power are uniformly allocated in two secondary sessions, respectively. In order for fair comparison, the resources consumed in the two schemes are set to the same. In other words, the sum of the source rates, the sum of the transmission rates, and the sum of the transmission powers, of the two secondary sessions, are all equal in the two schemes.

The comparison of the PLR between the two schemes is shown in Fig. 3. The proposed scheme achieves the same PLR 1.1% in both secondary sessions. The proposed scheme provides PLR guarantee to all video sessions by optimally utilizing the resources. On the other hand, the uniform scheme does not allocate the resources appropriately, thus causing a high PLR at the secondary session 1.

The comparison of the queuing delay between the two schemes is shown in Fig. 4. The queuing delay in both sessions in the proposed scheme is 10.61 ms, which is much lower than that in the uniform scheme. The proposed scheme
The resource allocation problem into an optimization problem, which jointly optimizes the source rate, the transmission rate, and the transmission power at each secondary session to minimize the weighted sum of the reciprocals of the source rates of all secondary sessions. The optimization problem is formulated into a GP problem, which can be converted to a convex optimization problem and then be solved efficiently. In the simulations, we demonstrate that the proposed scheme can provide QoS guarantee, thus achieving a higher video quality for the video streaming sessions, compared to the uniform scheme.

![Graph](image)

Fig. 6. Variation of video source rates with the quality weight of secondary session 1

The comparison of frame PSNR of the Foreman CIF sequence between the proposed scheme and the uniform scheme is shown in Fig. 5. We do not use any error concealment at the video decoder. Due to the encoding dependency, a lost frame will cause the remaining frames in the same Group of Pictures (GOP) undecodable, which is called error propagation. The PSNR comparison for the secondary session 1 is shown in Fig. 5(a), from which we can see much more undecodable frames in the uniform scheme than those in the proposed scheme. This is due to a much higher PLR in the uniform scheme than that in the proposed scheme. The average PSNR in the secondary session 1 is 36.506 dB in the proposed scheme, and 30.368 dB in the uniform scheme, respectively. The PSNR comparison for the secondary session 2 is shown in Fig. 5(b). The proposed scheme and the uniform schemes have a close source rate and a close PLR in the secondary session 2. Therefore, they have a similar average PSNR. The average PSNR in the secondary session 2 is 36.994 dB in the proposed scheme, and 36.250 dB in the uniform scheme, respectively.

We show the impact of the quality weight in Fig. 6. The sum of the quality weights of the two secondary sessions is equal to 1. When the quality weight of the secondary session 1 is increased from 0.05 to 0.95, the optimal source rate of the secondary session 1 is increased from 144.5 Kbps to 585.9 Kbps, while the optimal source rate of the secondary session 2 is decreased from 615.5 Kbps to 201.5 Kbps, as shown in Fig. 6. A higher source rate leads to a higher quality of the encoded video. Therefore, the video quality of a video session can be adjusted by changing the corresponding quality weight.

V. CONCLUSIONS

In this paper, we optimize the resource allocation for video streaming over spectrum underlay cognitive radio networks. Specifically, we formulate the resource allocation problem into an optimization problem, which jointly optimizes the source rate, the transmission rate, and the transmission power at each secondary session to minimize the weighted sum of the reciprocals of the source rates of all secondary sessions. The optimization problem is formulated into a GP problem, which can be converted to a convex optimization problem and then be solved efficiently. In the simulations, we demonstrate that the proposed scheme can provide QoS guarantee, thus achieving a higher video quality for the video streaming sessions, compared to the uniform scheme.