Multimedia Multicast Service Provisioning in Cognitive Radio Networks

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***Abstract*—In this paper, we propose a design framework for achieving efficient multimedia multicast services in cognitive radio (CR) networks. The framework incorporates the characteristics of both heterogeneous network environment and the scalable video content. By adopting cooperative transmissions for the delivery of enhancement layer data, we can not only improve the achieved video quality but also protect the rights of subscribed secondary users. We also utilize network coding and superposition coding to achieve efficient multicast transmissions of the layered video packets in multi-channel CR networks. Numerical examples show the proposed framework can improve the average received data rate by up to 15%. When achieving the same video quality, the proposed framework can save 30% transmission time comparing with the scenario using direct transmission alone.**

keywords – Multimedia multicast, cognitive radio network, cooperative transmission

I. Introduction

[1] Multimedia services, such as video streaming, are becoming the dominant traffic type in today's communication networks. However, multimedia services consume a lot of network resources, and thus are challenging to provision in wireless networks. Cognitive radio networks, with the "built-in intelligence" for opportunistic transmissions, are regarded as a promising technology to achieve better utilization of radio resources. In this paper, we consider the multimedia services over cognitive radio networks. In particular, here we consider the multicast transmission, which is appropriate for delivering multimedia contents to a group of heterogeneous users.

Due to the unique features of cognitive radio network (e.g., dynamic and heterogenous channel availability [1]) and the high bandwidth requirements of multimedia services, it is still an open and challenging problem as how to efficiently utilize the network resources to achieve high-quality video services. F. Wang, et al. in [2] considers multimedia transmissions over cognitive radio networks with proper admission control and channel selection. S. Li, et al. in [3] investigates the impacts of the dynamic resources on the smooth video streaming in cognitive radio networks and proposes a centralized channel allocation algorithm to achieve superior video delivery by reducing the playback frozen probability. D. Hu, et al. in [5] addresses the scalable video multicast in cognitive radio network and proposes a cross-layer optimization and scheduling algorithm to achieve efficient video delivery and fair resource allocation. This work doesn't consider the heterogenous sets of available channels at different secondary users. F. Hou, et al. in [4] proposes a cooperative transmission mechanism, where throughput and fairness are the two performance measurements. D. Zhang, et al. in [6] discusses the advantages of network coding and superposition coding in multicast transmission.

In our paper, we address the problem of multimedia service provisioning in the context of a multi-channel cognitive radio network. Taking the channel heterogeneity among different secondary users and the feature of multicast transmission into account, we propose an effective framework for multimedia multicast services that incorporates cooperative transmission between users into direct transmission from the secondary base station. The main contributions of this study include

- *Framework description*: We propose and formulate a transmission framework for achieving high-quality multimedia multicast services in cognitive radio networks.
- *Algorithm design*: We design effective algorithms to solve the resource allocation problems and improve overall system performance. Simulation shows that the proposed framework can improve the average received data rate by up to 15%. With the same achieved video quality, the proposed framework can save 30% transmission time comparing with that without cooperative transmission.

II. Network Model

We consider a cognitive radio (CR) network coexisting with a primary network with L primary users. Each primary user owns a licensed channel and has the exclusive priority to access its owned channel. The CR network consists of a secondary base station (SBS) and N secondary users. We consider an overlay mode in which secondary users and SBS use a primary channel only when the channel is not used by the primary user.

Each secondary user can be referred as a node in the network, and hence we use the terms "node" and "secondary user" interchangeably. We consider the multimedia multicast services where the nodes in this network are divided into M multicast groups (MGs) based on the video content they subscribed such that each MG is composed of the nodes that subscribe to the same content. Let $N^m = \{n_i^m, 1 \leq i \leq$

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$|N^m|\}$, $m = 1, \cdots, M$, be the set of all nodes in MG m. The set of L primary channels is defined as $C = \{c_1, \cdots, c_L\}$.

Depending on the geographic locations of secondary users and the primary users' activities, the secondary users and SBS may have heterogeneous channel availabilities and conditions. Let the binary integer $a_i^m(l)$ and the real number $g_i^m(l)$ denote the availability and gain of channel c_l at node n_i^m, respectively. Similarly, $a^B(l)$ and $g^B(l)$ respectively denote the channel availability and condition of channel c_l at the SBS, where superscript B stands for "secondary Base station". The sets of channels available at the SBS and the node n_i^m are defined as C^B and C_i^m, respectively. Let $C^m = \cup_{i \in \mathcal{N}^m} C_i^m$, then the set of common channels between the SBS and MG m is denoted as $C^{m,B} = C^m \cap C^{\text{B}}$, which is the set of channels that SBS can use to multicast data to MG m.

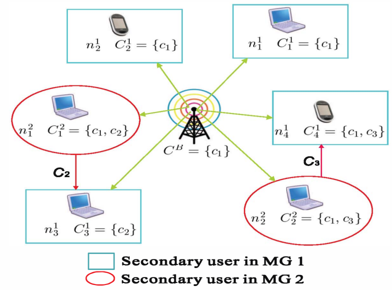

Fig. 1. The illustration of cooperative transmission for multicast service in heterogeneous cognitive radio network.

III. Framework Description

We consider multicast transmissions in cognitive radio network to achieve efficient multimedia services. We propose a framework to efficiently multicast layered video content, which includes the delivery of the base layer (BL) and enhancement layers (ELs). Here the BL is used to reconstruct video with basic quality, and the ELs are used to further refine the video quality. For the transmission of BL, our objective is to make sure the reception of all subscribed nodes due to its significance. For the transmission of ELs, we adopt the cooperative transmission (CT) to exploit the channel heterogeneity among multiple MGs.

Cooperative transmission has been widely studied for unicast service [7]. However, for multimedia multicast in cognitive radio network, little has been done in the literature. Figure 1 shows an example of cooperative transmission in a cognitive radio network composed of two MGs and six secondary users. At a particular time instance, channel c_1 is available at secondary users n_1^1, n_2^1, n_4^1, n_1^2, n_2^2, and the SBS, channel c_2 is available at secondary users n_3^1 and n_1^2, and channel c_3 is available at secondary users n_4^1 and n_2^2. The channel gains $g_i^m(l)$ of the same channel c_l can be different at different secondary users. Therefore, when the SBS multicasts data to MG 1 (called the targeted MG), some secondary users in the targeted MG may not successfully receive the information, either because the channel is not available at these nodes or the channel gains are too small. Meanwhile, it is possible that some secondary users in the non-targeted MG can receive the data, and hence they are potentially capable of forwarding the received information to the nodes in the targeted MG. As an example, consider the case $g_1^1(1) \approx g_2^1(1) \approx g_1^2(1) \approx g_2^2(1) \gg g_4^1(1)$. When SBS transmits to MG 1 using channel c_1, n_3^1 and n_4^1 will not receive the data. However, since n_1^2 and n_2^2 in MG 2 can receive the data, they can forward the information to nodes in the targeted MG 1. In addition, due to the heterogenous channel availability, channels c_2 and c_3, which are not available at the SBS, are available for the transmission between MGs. Specifically, secondary user n_1^2 can help n_3^1 using channel c_2 while n_2^2 can help n_4^1 using channel c_3. This is known as cooperative transmission (CT), in contrast to the direct transmission (DT) from the SBS.

In the proposed framework, we only adopt the cooperative transmission for the delivery of ELs. The delivery of BL information will only use direct transmission. The key reason for doing this is to protect the privilege of the subscribed users. Since the BL data is delivered through direct transmission from SBS to the nodes in the targeted MG, only subscribed users (i.e., nodes in the target MG) can receive the BL information. Nodes in other MGs can not reconstruct the video contents without the corresponding BL information even if they participate in the cooperative transmission for the ELs.

In the proposed framework, we also use the advanced coding techniques such as network coding and superposition coding to reduce the scheduling complexity and account for heterogenous channel conditions. With network coding, all encoded packets are equally important, thus the SBS does not need to differentiate packets when performing scheduling [8]. With superposition coding, the nodes with good channel conditions can successfully receive more packets such that it can have a larger probability to reconstruct video of higher quality [9]. In the following sections, we will formulate the resource allocation problem for the transmission of BL and ELs.

IV. Problem Formulation

A. Delivery of Base Layer Information

Since BL carries the basic information needed for video decoding, we should guarantee that all the subscribed users can receive the BL in time. With network coding, all packets are of equal importance, and hence the objective is translated into the reception of sufficient number of encoded packets. Specifically, let $D^{m,b}$ denote the total size (in terms of bits) of the encoded BL packets required for successfully reconstructing the BL information targeted to MG m. Therefore the remaining data required by node n_i^m at a particular time slot t is

$$R_i^{m,b}(t) = \max\left(0, D^{m,b} - \sum_{k=1}^{t-1} r_i^{m,b}(k)\right), \qquad (1)$$

where $r_i^{m,b}(k)$ is the BL data received by n_i^m at time slot k. The sum from $k = 1$ to $t - 1$ represents the BL data received before the time slot t. It is possible that the total received data before the time slot t is larger than $D^{m,b}$. Therefore, we use the *max* operator to bound the remaining data to zero, which means no more data is required since the node already has received enough data to decode the BL information.

With network coding, the SBS transmits different packets on different channels, so that the information on different channels is independent of each other since all packets are equally important. In addition, since the resource allocation (i.e., channel and power) is performed independently in each time slot, we will drop the time index t in the following discussion. The efficient delivery of BL layer information is to optimally allocate channels and power such that the basic video quality can be provided to the secondary users with the consumption of the minimum number of time slots. That is, it is the channel and power allocation problem with the objective of maximizing the total number of useful data received over all available channels at each time slot. The useful date is defined as the minimum between the remaining data required to successfully reconstruct the BL information (i.e., $R_i^{m,b}$) and the received data (i.e., $r_i^{m,b}$). Mathematically, the problem for BL transmission can be formulated as

$$\begin{aligned} \max_{\boldsymbol{g}^b,\boldsymbol{p}} \quad & A^{m,b} := \sum_{i\in N^m} \min(r_i^{m,b}, R_i^{m,b}) \\ \text{s.t.} \quad & \mathbf{1}^{\mathrm{T}}\boldsymbol{p} \le P_B \end{aligned} \tag{2}$$

where the variable vector $\boldsymbol{g}^b$ represents the gains of channels in $C^{m,B}$, and the variable vector $\boldsymbol{p}$ contains the corresponding power allocation. The reason for taking the *min* operator is due to the possible case that $r_i^{m,b}$ is larger than $R_i^{m,b}$. In this case, since the BL information can be successfully reconstructed with the number of $R_i^{m,b}$ data, the extra data larger than $R_i^{m,b}$ has no more contribution to the reconstruction of BL information due to the adoption of network coding.

Note that since we consider the multicast transmission, the variable $\boldsymbol{g}^b$ decides the number of nodes successfully receiving the multicast data over each channel. Let $g^b(l)$ be the entry corresponding to the channel c_l in the vector $\boldsymbol{g}^b$. All nodes in MG m with a gain of channel c_l higher than $\boldsymbol{g}^b(l)$ can successfully receive the data multicasted over the channel c_l. We decide $g^b(l)$ by pairing the channel c_l up with a node at which the channel c_l is available, then set $g^b(l)$ to be the channel gain of c_l at this node and set multicast rate over channel c_l to be the channel capacity of the matched node. Thus, any node with a higher channel capacity will successfully receive data with the rate of $W\log_2(1+\frac{p_l(g^b(l))^2}{N_0})$, and any node with a lower channel capacity can not successfully decode the received data. Note that there is a tradeoff between the number of nodes successfully receiving the data and multicast data rate. If we pair a channel c_l up with a node with a high channel gain, we have a large $g^b(l)$ and a high multicast data rate, but the number of nodes successfully receiving the multicast data is small. Since our objective is to maximize the aggregated data across all secondary users, this tradeoff embodied in the variable $\boldsymbol{g}^b$ has to be considered.

For simplicity, we normalize the time slot to be unit length, and thus the amount of data received at each time slot is the same as the data rate. Therefore, for a specific node n_i^m, the received data $r_i^{m,b}$ in (2) is given, based on the Shannon's formula, as follows.

$$r_i^{m,b} = \sum_{l:g_i^m(l)\ge g^b(l)} W\log_2\Big(1+\frac{p_l(g^b(l))^2}{N_0}\Big), \quad \forall i \in \mathcal{N}^m, \tag{3}$$

where W and N_0 are the channel bandwidth and power spectral density of the channel noise, respectively. The summation in (3) is over all channels where the channel gain of node n_i^m is larger than $g^b(l)$ (i.e. the node n_i^m can successfully receive data on these channels).

Since only one MG is served in each time slot, we perform a simple yet intuitive MG selection as follows:

$$m^* = \arg\max_m\{\widetilde{A}^{m,b}\}, \tag{4}$$

where $\tilde{A}^{m,b}$ is the optimal objective function of problem (2).

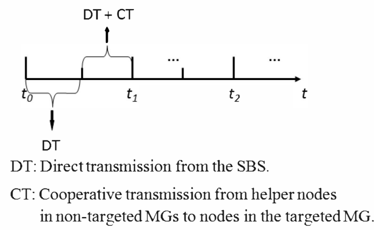

Fig. 2. The illustration of enhancement layer transmission in time domain.

B. Delivery of Enhancement Layer Information

The delivery of ELs is similar to that of BL, with the following key differences: (1) CT is enabled for efficient utilization of channel heterogeneity, and (2) superposition coding is adopted to combine the packets from different ELs into encoded packets. We first briefly introduce the CT mechanism. As shown in Figure 2, we divide each time slot into two parts with equal length. While the DT of ELs from the SBS to the targeted MG spans across both parts, the CT occurs only in the second part. Potentially a node can receive both DT and CT information using different channels. Specifically, the helper nodes from non-targeted MGs receive DT from the SBS in the first half of the time slot, and then forward their received information to the nodes in need in the targeted MG during the second half of the time slot. Besides, the use of superposition coding allows the nodes with good channel conditions to receive more data with the same set of encoded packets. For more details about superposition coding, please see [9].

For the process of CT, we define $\tilde{n}_i^m$ as the helper node that helps the n_i^m. The channel used by the helper $\tilde{n}_i^m$ to transmit data to the node n_i^m is called helper channel and denoted as $c_{\tilde{n}_i^m}$. Next we give an illustrative example with 2 ELs. Taking both DT and CT into account, the received EL data at n_i^m can be expressed as follows:

$$r_i^{m,e_q} = \sum_{\left\{\substack{c_l\in C_i^m \\ g_i^m(l)\ge g^q(l)}\right\}} x_{l,q} + x_{\tilde{n}_i^m,q}, \quad q = 1 \text{ or } 2, \tag{5}$$

where $x_{l,q}$ denotes the data of EL_q obtained from the DT via channel c_l, and $g^q(l)$ denotes the channel gains determined from the pairing process. Furthermore, the DT components via superposition coding can be expressed as:

$$x_{l,1} = W\log_2\left(1+\frac{\alpha p_l(g^1(l))^2}{(1-\alpha)p_l(g^1(l))^2+N_0}\right), \tag{6}$$

and

$$x_{l,2} = W\log_2\left(1+\frac{(1-\alpha)p_l(g^2(l))^2}{N_0}\right), \quad (7)$$

where p_l is the power allocated to c_l in DT and α the fraction controlling power allocation between the two ELs during the superposition coding [9].

The second term of right side in (5), $x_{\tilde{n}_i^m,q}$ denotes the data of EL$_q$ ($q = 1, 2$) provided by the helper node $\tilde{n}_i^m$ via helper channel $c_{\tilde{n}_i^m}$, which is given as

$$x_{\tilde{n}_i^m,1} = \min\left\{\frac{1}{2}\sum_{\substack{c_l\in C^{m,B}\cap C_{\tilde{n}_i^m}\\ g_{\tilde{n}_i^m}(l)\geq g^1(l)}} x_{l,1},\ \frac{1}{2}W\log 2\left(1+\frac{\beta P_n(g(\tilde{n}_i^m))^2}{(1-\beta)P_n(g(\tilde{n}_i^m))^2+N_0}\right)\right\}, \quad (8)$$

and

$$x_{\tilde{n}_i^m,2} = \min\left\{\frac{1}{2}\sum_{\substack{c_l\in C^{m,B}\cap C_{\tilde{n}_i^m}\\ g_{\tilde{n}_i^m}(l)\geq g^2(l)}} x_{l,2},\ \frac{1}{2}W\log 2\left(1+\frac{(1-\beta)P_n(g(\tilde{n}_i^m))^2}{N_0}\right)\right\}, \quad (9)$$

where P_n is the power of a secondary user, $g_{\tilde{n}_i^m}(l)$ is the gain of c_l perceived at $\tilde{n}_i^m$, and $C_{\tilde{n}_i^m}$ is the set of channels available at $\tilde{n}_i^m$. $g(\tilde{n}_i^m)$ denotes the gain of the helper channel $c_{\tilde{n}_i^m}$ between the helper $\tilde{n}_i^m$ and the user n_i^m. The first term in (8) and (9) represents the total amount of data received via DT from the SBS at the helper node $\tilde{n}_i^m$, and the second term represents the maximum amount of data that can be supported on helper channel $c_{\tilde{n}_i^m}$.

With the detailed breakdown of the DT and CT components given above, we now formulate the problem of EL delivery. The objective here is to maximize the aggregated weighted EL data acquired via both DT and CT with the power constraint. Let R_i^{m,e_q} denote the remaining data of EL$_q$ for n_i^m, which can be derived using the expression similar to (1). Specifically, the problem is expressed as follows:

$$\begin{aligned}\max_{\boldsymbol{g}^1,\boldsymbol{g}^2,\boldsymbol{p}} \quad & A^{m,e} := \sum_{i\in N^m}\sum_{q=1,2}\psi_i^{m,e_q}\min\left(R_i^{m,e_q}, r_i^{m,e_q}\right)\\ \text{s.t.} \quad & \mathbf{1}^{\mathrm{T}}\boldsymbol{p}\leq P_B\end{aligned} \quad (10)$$

where $\boldsymbol{g}^1$ and $\boldsymbol{g}^2$ are the variable vectors of channel gains for EL$_1$ and EL$_2$ respectively, which are determined by channel-node pairings, $\boldsymbol{p}$ is the vector of power allocation, and ψ_i^{m,e_q} is the weight that reflects the relative importance of the two ELs. Due to layer dependencies, we introduce the following weights to determine the contribution of data from different ELs. Specifically, letting Q^{m,e_q} denote the quality improvement associated with EL$_q$, we have

$$\psi_i^{m,e_1} = \begin{cases}\frac{Q^{m,e_1}}{R_i^{m,e_1}} & R_i^{m,e_1} > 0,\\ 0 & R_i^{m,e_1} = 0\end{cases} \quad (11)$$

and

$$\psi_i^{m,e_2} = \begin{cases}\frac{D^{m,e_1}-R_i^{m,e_1}}{D^{m,e_1}}\frac{Q^{m,e_2}}{R_i^{m,e_2}} & R_i^{m,e_2} > 0,\\ 0 & R_i^{m,e_2} = 0\end{cases} \quad (12)$$

where D^{m,e_1} denotes the size of EL$_1$ (in unit of bits).

After solving the problem in (10) for each MG m, we select the MG with the most significant performance improvement for service as follows

$$m^* = \arg\max_m\{\widetilde{A}^{m,e}\}\,. \quad (13)$$

V. Proposed Algorithms

Based on the discussion above, we see that the resource allocation problem involves channel-node pairing and power distribution, which are coupled and make the problem hard to solve. In fact, both the formulated problems (2) and (10) are mixed integer nonlinear programming and are therefore NP-hard. In order to design computationally tractable algorithms, we decouple the original optimization problem into two sets of subproblems. The first set of problems are to determine the channel-node pairs (for DT of BL, DT of ELs and CT of EL, respectively), while the second set are to decide the power distribution among the paired channels. The solutions to these subproblems jointly determine the multicast transmission rate, and hence the system performance. In the following subsections, we present detailed algorithms to solve the various subproblems.

A. Channel-Node Pairing for Direct Transmission

Due to network heterogeneity, channel-node pairs determine the data rates carried on the paired channels as well as the set of nodes that can benefit from such transmissions. As we discussed before, high data rate of paired channel leads to less number of nodes that can successfully receive the multicast data, and vice verse. Therefore, such a pairing process is to find the optimal tradeoff between these two factors, where optimality is defined as the aggregated data.

1) Channel-Node Pairing for DT of Base Layer: Assume that MG m is currently targeted for DT of the BL information from the SBS. We design a greedy-type algorithm to pair the channels in $C^{m,B}$ with nodes in N^m. To resolve the interconnection between the pairing process and the power distribution process, we assume that power is equally distributed across all channels in $C^{m,B}$ when computing the supported multicast rates. The pseudocode is given in Algorithm 1. At each time slot t, the channel that yields most significant rate increase is paired first (line 15) and removed from the channel pool (i.e., the set of all common channels between SBS and the targeted MG m)(line 19). This process of channel removal is continued until all the channels are paired, at which time the pool becomes empty. After this process, the resulting channel-node pairs are input into the power allocation process. Therefore, the set of channels involving in the power allocation process is determined.

2) Channel-Node Pairing for DT of Enhancement Layers: The ideas for channel-node pairing for DT of ELs are similar to those used for the DT of BL, except that the data rate is computed differently and the weighted sum of the data rate is used as the performance metric. Due to the space limit, we omit the Pseudocode in the paper.

Algorithm 1 channel-node pairing for DT of BL

Input:
  $C^{m,B}$, N^m, P_B;
  $R_i^{m,b}, \forall i \in N^m$;
  $N_l^m = \{n_i^m \in N^m | a_i^m(l) = 1\}, \forall l \in C^{m,B}$;
Initialization:
  $\Omega = C^{m,B}$, $p = P_B/|\Omega|$;
  $R_i = R_i^{m,b}, \forall i \in N^m$;
Iteraion:
while ($\Omega \neq \emptyset$) **do**
  for ($\forall l \in \Omega$) **do**
    $i^* = \arg\max_{i \in N_l^m} \sum_{\substack{j: j \in N_l^m \\ g_j^m(l) \geq g_i^m(l)}} \min\left(R_j, W\log_2\left(1+\frac{p\left(g_i^m(l)\right)^2}{N_0}\right)\right)$
    $g^b(l) = g_{i^*}^m(l)$;
    $r_l = \sum_{\substack{j: j \in N_l^m \\ g_j^m(l) \geq g^b(l)}} \min\left(R_j, W\log_2\left(1+\frac{p\left(g^b(l)\right)^2}{N_0}\right)\right)$;
  end for
  $l^* = \arg\max_{l \in \Omega}\{r_l\}$;
  for $\left(\forall i \in N_{l^*}^m, g_i^m(l^*) \geq g^b(l^*)\right)$ **do**
    $R_i = \min\left(0, R_i - W\log_2\left(1+\frac{p\left(g^b(l^*)\right)^2}{N_0}\right)\right)$;
  end for
  $\Omega = \Omega \setminus \{l^*\}$;
end while
Output: $g^b(l), \quad \forall l \in C^{m,B}$.

B. Power Allocation for Direct Transmission

In what follows, we present power allocation algorithms that maximize the aggregated data rate across all supported nodes.

1) Power Allocation for Delivery of Base Layer: With the channel-node pairs given by Algorithm 1, the set of nodes that can successfully receive data transmission over each channel are fixed. We define the binary variables $\tau_i^b(l)$ to indicate whether or not the node $n_i^m \in N^m$ can successfully receive the data transmitted by SBS over the channel $c_l \in C^{m,B}$. Specifically, we have

$$\tau_i^b(l) = \begin{cases} 1, & \text{if } c_l \in C_i^m \text{ AND } g_i^m(l) \geq g^b(l) \\ 0, & \text{if } c_l \notin C_i^m \text{ OR } g_i^m(l) < g^b(l) \end{cases}. \quad (14)$$

With this notation, we formulate the subproblem of BL delivery as follows:

$$\max_{\boldsymbol{p}} \sum_{c_l \in C^{m,B}} \sum_{i=1}^{|N^m|} \tau_i^b(l) W \log_2\left(1 + \frac{p_l g^b(l)^2}{N_0}\right) \quad \text{s.t.} \quad \mathbf{1}^{\mathrm{T}}\boldsymbol{p} \leq P_B, \quad \boldsymbol{p} \succeq \mathbf{0} \quad (15)$$

Since the problem in (15) is not convex, it is not guaranteed that we can find the global optimal solution. In order to avoid being trapped at local maximums, we employ standard gradient-based optimization strategies with multiple starting points. Specifically, for each starting point, the power allocation vector $\boldsymbol{p}$ is randomly initialized to be a feasible solution. After all starting points are tried, the vector $\boldsymbol{p}$ corresponding to the empirically optimal solution is selected, and is used to compute the carried data rate for BL delivery.

2) Power Allocation for Delivery of Enhancement Layers: Similar to the case of BL delivery, we define binary variables $\tau_i^q(l)$ for $q \in \{1, 2\}$ as follows

$$\tau_i^q(l) = \begin{cases} 1, & \text{if } c_l \in C^{m,B} \text{ AND } g_i^m(l) \geq g^q(l) \\ 0, & \text{if } c_l \notin C^{m,B} \text{ OR } g_i^m(l) < g^q(l) \end{cases}. \quad (16)$$

Correspondingly, the problem of power allocation can be formulated as:

$$\max_{\boldsymbol{p}} \sum_{c_l \in C^{m,B}} \sum_{i=1}^{|N^m|} \Big\{ \psi_i^{m,e_1} \tau_i^1(l) W \log_2\Big(1 + \frac{\alpha p_l \left(g^1(l)\right)^2}{(1-\alpha)p_l (g^1(l))^2 + N_0}\Big) + \psi_i^{m,e_2} \tau_i^2(l) W \log_2\Big(1 + \frac{(1-\alpha)p_l \left(g^2(l)\right)^2}{N_0}\Big) \Big\}$$
$$\text{s.t.} \quad \mathbf{1}^{\mathrm{T}}\boldsymbol{p} \leq P_B, \quad \boldsymbol{p} \succeq \mathbf{0} \quad (17)$$

Again, this problem is non-convex and hence we may not be able to identify the global optimal solution. However, we can take a similar approach as above to find a good solution to the problem. We employ gradient-based strategies with multiple starting points, and record the empirically optimal solution as the power allocation for the delivery of EL information.

C. Channel-Node Pairing for Cooperative Transmission

In this subsection, we describe an approach to determine the channel-node pairs for CT of ELs. Since the helper nodes in CT rely on the information received from the DT, this subsection has to be placed after the power allocation problems for DT have been addressed. Also note that for CT, we assume each helper node utilizes a single helper channel with a constant power P_n at a particular time slot. Therefore, there is no issue of power allocation for CT.

Since CT involves both helper nodes and the nodes being helped, the channel-node pairing process is intuitively more complicated than that for the direction transmission. Recall that we bind the helper node n_h, helper channel c_h, and the node being helped $\hat{n}_h$ into a tuple. The pairing process therefore aims at finding the optimal combination of these components, such that the rate improvement is maximized. Specifically, let $\bar{N}^m = N \backslash N^m$ denote the set of potential helper nodes, and let $\bar{C}^m$ denote the set of all helper channels. The algorithm we proposed traverses all the helper channels in $\bar{C}^m$, and for each of them, we determine the optimal pairing nodes including one helper node and the nodes being helped using a greedy-type approach similar to that presented in Algorithm 1. After the optimal pairing nodes for all the helper channels are recorded, the channel that yields maximum performance improvement is selected and removed from the pool of candidate channels . This iterative process continues until all the helper channels are paired. Since the pseudocode of this algorithm is similar as that of channel-node pairing for DT, we omitted it due to the space constraint.

VI. Numerical Examples

To demonstrate the effectiveness of the proposed algorithm, we simulate a cognitive radio network composed of 4 primary channels and 10 secondary users. There are 2 MGs in the network and each MG includes 5 members which are randomly selected from the 10 secondary users. Secondary base station multicasts video sequences *Foreman* and *Football* to 2 MGs, respectively. Each video sequence is encoded into 1 BL with quantization parameter (QP) of 32 and 2 ELs with QP of

TABLE I. EXPERIMENTAL PARAMETERS

Parameter	Description	Value
W	channel bandwidth	5MHz
N_0	noise power spectral density	-90dbm
P_B	power of SBS	10 Watt
P_n	power of secondary users	2 Watt
α	power division constant for DT	0.7
β	power division constant for CT	0.7

28. The two ELs are further splitted with the medium-grain scalability, where EL1 consists of the lowest 4 transform coefficients and EL2 the remaining 12 transform coefficients. The sequences are encoded at a frame rate of 30 Hz, and 32 frames of each sequence are encoded. The total duration of playback is therefore 1.06 seconds, which translates into 53 time slots with time slot duration of 0.02 second. At each time slot, the channel availability changes according to a binary random variable, while the channel gains are computed from random geographic locations of the SBS and nodes. The other main experimental parameters are listed in Table I.

In order to better demonstrate the effect of cooperative transmission, we abstract the channel heterogeneity among MGs into a single parameter Pr, which denotes the probability that a helper channel is available. Such probability is determined by various factors, including primary users' activities and the geographic locations of the secondary users. We demonstrate the effect of CT with various setting of Pr in Figures 3 and 4. Figure 3 shows the average received data across all nodes in an MG. We can observe that CT effectively increases data rate by up to 15% and hence improves overall video quality. In addition, the comparison across the set of curves reveal that the performance improvement of CT increases with the availability of helper channels.

To further demonstrate the video quality, we also show the PSNR (Peak Signal-to-Noise Ratio) of the reconstructed video at a representative node. PSNR is the most commonly used performance measure to evaluate the quality of reconstructed video. Since the layered video adopted in the simulation is composed of 1 BL and 2 ELs, PSNR is discretized into three levels according to the quality scalable layers. From Figure 4, we can observe that when achieving the same video quality, the time slots needed in proposed framework with cooperative transmission is much less than that without cooperative transmission. With CT the node achieves higher data rate, and consequently can decode BL and ELs at an earlier time than in the case when only DT is available. For instance, the transmission time needed for receiving the video quality $BL + EL_1$ is 37 time slots with Pr=1, which is 30% shorter than that without cooperative transmission. Such a performance improvement is very significant especially for real-time multimedia services.

VII. CONCLUSIONS

In this paper, we proposes a multimedia multicast transmission framework in cognitive radio networks to exploit the channel heterogeneity among multicast groups. We have formulated the BL and ELs transmissions as channel-node pairing and power allocation problems and designed a set of heuristic algorithms. Simulation shows the proposed framework can improve the average received data rate by up to 15%. With

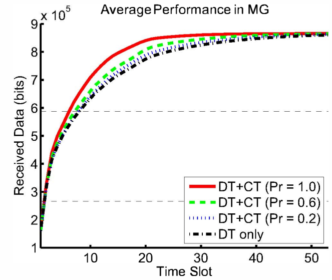

Fig. 3. The average received data.

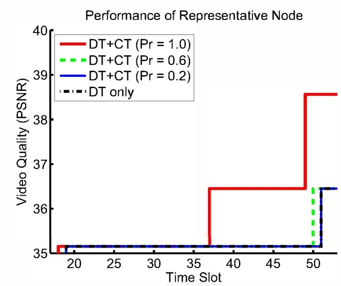

Fig. 4. PSNR of reconstructed video.

the same video quality the proposed framework can save 30% transmission time compared with that without cooperative transmission.

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