The Impact of Spectrum Sensing Frequency and Packet-Loading Scheme on Multimedia Transmission over Cognitive Radio Networks

Xin-Lin Huang, *Student Member, IEEE*, Gang Wang, Fei Hu, *Member, IEEE,* and Sunil Kumar*, Senior Member, IEEE*

Abstract — Recently, multimedia transmission over cognitive radio networks (CRNs) becomes an important topic due to the CR's capability of using unoccupied spectrum for data transmission. Conventional work has focused on typical quality-of-service (QoS) factors such as radio link reliability, maximum tolerable communication delay, and spectral efficiency. However, there is no work considering the impact of CR *spectrum sensing frequency* and packet-loading scheme on multimedia QoS. Here the *spectrum sensing frequency* means how frequently a CR user detects the free spectrum. Continuous, frequent spectrum sensing could increase the MAC layer processing overhead and delay, and cause some multimedia packets to miss the receiving deadline, and thus decrease the multimedia quality at the receiver side. In this research, we will derive the math model between the *spectrum sensing frequency* and *the number of remaining packets* that need to be sent, as well as the relationship between *spectrum sensing frequency* and the *new channel availability time* during which the CRN user is allowed to use a new channel (after the current channel is re-occupied by primary users) to continue packet transmission. A smaller number of *remaining packets* and a larger value of *new channel availability time* will help to transmit multimedia packets within a delay deadline. Based on the above relationship model, we select appropriate spectrum sensing frequency under single channel case, and study the trade-offs among the number of selected channels, optimal spectrum sensing frequency and packet-loading scheme under multi-channel case. The optimal spectrum sensing frequency and packet-loading solutions for multi-channel case are obtained by using the combination of Hughes-Hartogs and Discrete Particle Swarm Optimization (DPSO) algorithms. Our experiments of JPEG2000 packet-stream and H.264 video packet-stream transmission over CRN demonstrate the validity of our spectrum sensing frequency selection and packet-loading scheme[1].

Index Terms — *Cognitive Radio Networks (CRN), Multimedia Transmission, Spectrum Sensing Frequency, Packet-Loading, Hughes-Hartogs, Discrete Particle Swarm Optimization (DPSO).*

I. INTRODUCTION

Real-time multimedia applications require stringent quality of service (QoS) performance such as enough bandwidth and strict delay constraints. Limited available bandwidth is considered to be one of the major bottlenecks for high-quality multimedia transmission over wireless links [1-3]. Recently, Cognitive Radio (CR) technology has emerged to intelligently identify and use free spectrum as long as those spectrum bands are not occupied by primary users. By opportunistically using unoccupied spectrum, CR users can use more radio bandwidth while not violating FCC regulations [4-6]. In a CRN, a secondary user's device has

[1] Manuscript received in May 2010.

Xin-Lin Huang and Gang Wang are with the Communication Research Center, Harbin Institute of Technology, Harbin 150001, P. R. China. (e-mail: xlhitcrc@163.com, gwang51@hit.edu.cn).
Fei Hu is with the department of Electrical and Computer Engineering, The University of Alabama, Tuscaloosa, AL 35487 USA (e-mail: fei@eng.ua.edu).
Sunil Kumar is with the department of Electrical and Computer Engineering, San Diego State University, San Diego, CA 92182-1309 USA (e-mail: skumar@mail.sdsu.edu).

spectrum-agile radio transceiver that can sense the available spectrum band (such an operation is called *spectrum sensing*), automatically configure the radio frequency, and switch to the selected frequency band [7-8].

Related work: In the following discussion we will summarize the existing work from two aspects that are closely related to our research:

(1) Multimedia transmission over CRN: Research on multimedia over CRN has not caused much attention so far. Optimal channels allocation and efficient packets scheduling are two important issues at the MAC layer to ensure that multimedia data to be sent within their delay bound. Recently, most of research efforts in CRNs focus on spectrum sensing and management issues. Only recently some work has been performed to investigate appropriate techniques to enable multimedia delivery in CRNs. A reliable multimedia transmission over CRNs using fountain codes is proposed in [1]. Such codes are used to deliver multimedia data to free spectrum bands, and those codes are also used to compensate for the data loss caused by the primary user's radio interference. Some schemes have been proposed in [1] to balance the performance metrics such as link reliability, spectral efficiency and coding overhead. A dynamic channel-selection scheme for delay-sensitive multimedia transmission over CRNs is proposed in [9]. It considers the visible multimedia replay effects, various data rate requirements, and delay performance of heterogeneous multimedia streams.

(2) Spectrum sensing: In CRNs, CR users are responsible for detecting the activity of primary users (PUs) and avoiding interference to PUs. However, current CR's RF front-ends can not perform spectrum sensing and data transmission simultaneously [10]. Moreover, multimedia transmission is extremely sensitive to wireless condition fluctuating [11]. Thus, sensing accuracy has been considered as the most important factor to determine the performance of multimedia transmission over CRNs. In survey [12], several typical spectrum sensing methods are discussed: energy detector-based sensing, waveform-based sensing, cyclostationarity based sensing, radio identification based sensing, matched filter based sensing. In [10, 13], they have investigated the relationship among sensing period, probability of detection and probability of false alarm based on sensing efficiency.

However, there is no work considering how CR *spectrum sensing frequency* (i.e. how frequently a CR user detects the available spectrum) impacts on multimedia transmission. This is one of the key techniques to enable multimedia services in CR links [3]. Since the CR transceiver can only do one task at a time, continuous, frequent spectrum sensing can increase the MAC (medium access control) layer processing overhead and channel access delay. Moreover, it can cause some multimedia packets to miss the transmission deadline and thus decrease the multimedia quality at a receiver side.

Transmitting multimedia content with the support of strict QoS requirements (such as delay, throughput, jitter, etc.) is a challenging topic, and the following aspects should be considered for multimedia transmission over CRNs [3,14]: (1) There are serious resource constraints in wireless networks such as spectrum bandwidth, transmission power and data rate. There also exist RF (radio frequency) interference, shadowing and multi-path fading. (2) Multimedia data may be encoded with different profiles and priorities. Loss of certain important packets may degrade the image/video quality at the receiver significantly. Delay caused by spectrum sensing and channel switching may cause image/video data to miss the time deadline. (3) Upon arrival of primary users, secondary users with multimedia traffic could be affected more seriously than the users with non-multimedia traffic due to the strict QoS requirements in multimedia applications.

Therefore, an integrated design to consider appropriate spectrum sensing, resource allocation and packet scheduling, is required to find optimal solution for multimedia transmission. Since the packets from secondary user may get lost due to the primary user's arrival, we introduce two parameters, namely, *new channel availability time* and *remaining packets*, to describe the impacts of spectrum re-occupancy by a primary user. The *new channel availability time* refers to the allowable *time* in the new channel for the continuation of packet transmission. A secondary user switches to a new channel when the channel is re-occupied again by a primary user. Therefore, the available time in the new channel could be very limited. The *remaining packets* mean the rest of packets (in a multimedia stream) waiting to be transmitted in the new channel. A longer *new channel availability time* and a smaller value of *remaining packets* can help to achieve the successful packet delivery within a maximum tolerable delay. Moreover, a smaller ratio of *remaining packets* to *new channel availability time* means a lower requirement for the quality of a new reestablished link. Those two parameters are determined by spectrum sensing frequency, the number of selected communication channels, and primary user arrival model. We will investigate the math relationship among them, and seek the optimal spectrum sensing frequency and resource allocation strategies.

The rest of this paper is organized as follows. In Section II, system models are described. In Section III, we discuss the impact of spectrum sensing frequency on multimedia transmission via strict math models. In Section IV, we provide the optimal solution to the proposed math models. In Section V, experiment results are demonstrated to show the efficiency of our algorithms in terms of supporting multimedia QoS in CRNs. In Section VI, we discuss the application of our proposed scheme to different traffic types, and conclude the paper in Section VII.

II. SYSTEM MODEL

In this section, we first introduce the concept of *spectrum pool*. It is used for searching unoccupied channels for multimedia transmissions. Later on, we will discuss the primary user arrival model and multimedia transmission structure.

A. Spectral Availability

For CR users (also called secondary users in this paper), the channel availability depends on the primary users' channel usage patterns. In order to transmit multimedia data in a CRN, secondary users should first find out the spectrum holes unoccupied by primary users. The spectrum pool concept [1, 15] could be used to describe the model of secondary users' total available spectrum holes [16]. After the available spectrum holes are detected, secondary users divide them into small channels, each of which has a bandwidth of W (Hz). Then, secondary users select a set of available channels (denoted as S) to form a RF link in a special way to ensure high performance and low interrupted ratio. For example, a good channel selection strategy can make sure that the arrival of a primary user will not cause the *complete* failure of the secondary user's radio link. In other words, the radio link can be established by multi-channel, which may not be reoccupied by primary users simultaneously.

B. Primary User Activity Model

Since the secondary users work on unlicensed channels, it should vacate the channel immediately when primary user appears. We consider each primary channel as an *ON-OFF* model [17]. An *ON/OFF* state represents the case whether or not a primary user is occupying a channel, and the channel state alternates between state *ON* (active) and state *OFF* (inactive). The secondary user can only utilize the *OFF* time slot to transmit their own packets. We assume that each primary channel changes its state independently.

For simplicity, we assume the primary user's packet arrival rate follows Poisson process in this paper. Then, primary user inter-arrival time follows the exponential distribution [1, 17].

C. Multimedia Transmission Structure

Here we assume that a multimedia data stream to be transmitted consists of a group of frames (each frame could be a picture). A frame may fit into one or multiple network packets. At the start of every picture, a secondary user's RF link is set up by selecting a set of S available channels from different licensed bands in the spectrum pool. Channel selection criterion is based on RF link quality, which is impacted by the primary user's arrival time. For instance, if a primary user quickly comes back and re-occupies that channel, the RF link will drop the current communication packets.

When the multimedia data is transmitted over CRNs, the secondary user performs spectrum sensing at the start of each picture, and senses spectrum again after transmitting f_i packets over channel i, as shown in Fig.1. After the secondary user's link is established, data is transmitted within certain delay bound. Once a channel fails due to primary user's arrival, it is considered not available during the picture transmission.

In the rest of the paper, we use f_i to indicate spectrum sensing frequency level since the time period of sending f_i packets can indirectly determine the duration of spectrum sensing. For instance, a higher value of f_i means that we have less time spent in spectrum sensing.

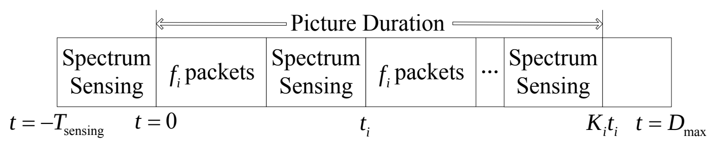


Fig. 1: Multimedia transmission structure over channel i.

D. Secondary User Activity Model

The secondary user's activity is influenced by the primary user's activity since the secondary user should vacate the frequency immediately when a primary user re-occupies the channel. We define the secondary user's activity model as shown in Fig.2. The secondary user's schedule consists of spectrum sensing time and multimedia data transmission time. Assume that a secondary user detects that channel i is available and transmits packets over it. When a primary user re-occupies channel i at time τ_i, the secondary user switches to an alternate channel j to continue packet transmission. In Fig.2, we have marked the concepts of *remaining packets and new channel availability time.* They reflect the demands on channel j to satisfy QoS requirement. Note that we may not be able to finish the transmission of all "remaining packets" within the "new channel availability time". This depends on how soon a primary user will take the channel back. In next section we will deduce the models for those two concepts.

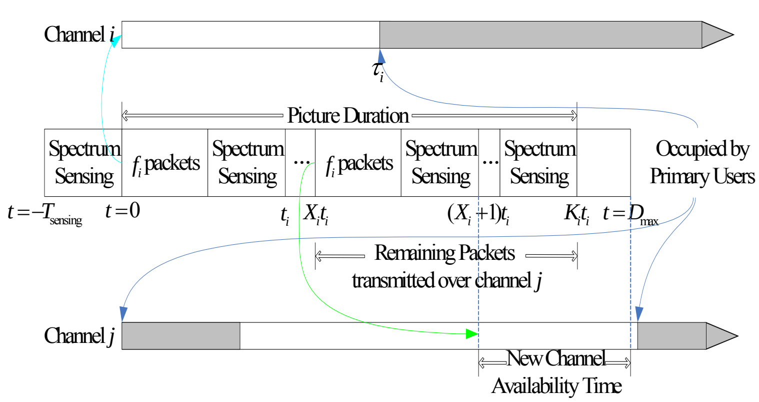


Fig. 2: Secondary user activity model.

Without loss of generality, the primary user arrival process in channel *i*, ($i = 1,2,3,\ldots,S_0$, S_0 is the number of available channels in spectrum pool), is modeled as a Poisson process with the parameter λ_i (i.e., the arrival rate). Such a model has also been assumed in many other references such as [1, 13]. Obviously, the primary user inter-arrival time τ_i will be an exponential distribute with the mean arrival time $\mu_i = 1/\lambda_i$, as shown in Fig.2. Each channel has a capacity of R_i. Here, the channel capacity is defined as total number of packets that can be transmitted during D_{max}. (This definition is the same as the one in reference [1]). It is pointed out in [3] that the key metrics in spectrum sensing are the probability of correct spectrum detection P_{CD}, probability of false alarm P_{FA}, and probability of miss detection P_{MD}. To investigate the impacts of P_{FA} in a clearer way, we assume $P_{\text{CD}} = 1$ and $P_{\text{MD}} = 0$.

III. Impact of Spectrum Sensing Frequency and Packet-Loading Scheme on QoS

In this section, we will discuss the impact of spectrum sensing frequency and packet-loading scheme on multimedia transmission performance, considering single-channel and multi-channel link, respectively. The optimal spectrum sensing frequency is solved in theory under single-channel link situation. For multi-channel case, optimal spectrum sensing frequency and packet-loading are solved by using Hughes-Hartogs and Discrete Particle Swarm Optimization (DPSO) algorithms.

A. Single Channel case

We first investigate the single-channel case, that is, each secondary user can only use single channel in each link. In section B, we will extend our discussions to multi-channel case.

We first introduce two parameters, namely, *remaining packets* and *new channel availability time,* to illustrate the impact of spectrum sensing frequency on multimedia transmissions.

From Fig.2, we can see that the sum of time consumption for f_i packets transmission and one period of spectrum sensing can be represented as follows:

$$t_i = f_i \cdot \frac{D_{\max}}{R_i} + T_{\text{sensing}} \tag{3.1}$$

where $D_{\max}$ is the maximum tolerable delay and T_{sensing} is spectrum sensing time. First, we consider that only one channel *i* is selected to transmit multimedia stream. The total number of packets that are successfully transmitted can be expressed as:

$$N_i = X_i f_i \tag{3.2}$$

where the integer (a random variable) $X_i = 0,1,2,\ldots,K_i$, and the upper bound, i.e., the maximum value of X_i, is: $K_i = \lceil N/f_i \rceil$ (here *N* is the total number of packets required to transmit on secondary user's link). Obviously, from Fig.2, we can see that K_i cannot be larger than $D_{\max}/t_i$, considering equation (3.1), we have:

$$K_i \le D_{\max} / (f_i \cdot \frac{D_{\max}}{R_i} + T_{\text{sensing}}) \tag{3.3}$$

From Fig.2, we get $K_i \ge N/f_i$. Considering (3.3), we have:

$$f_i \ge NT_{\text{sensing}} / [D_{\max}(1 - \frac{N}{R_i})] \tag{3.4}$$

Since the primary user inter-arrival time τ_i is exponentially distributed, we derive the distribution function of X_i as:

$$\begin{cases} P\{X_i \geq 0\} = 1 \\ P\{X_i \geq 1\} = (1-P_{FA})e^{-\lambda_i t_i} \\ P\{X_i \geq 2\} = (1-P_{FA})^2 e^{-\lambda_i \cdot 2t_i} \\ \vdots \\ P\{X_i \geq K_i\} = (1-P_{FA})^{K_i} e^{-\lambda_i \cdot K_i t_i} \end{cases} \tag{3.5}$$

Then, we get

$$\begin{cases} P\{X_i = 0\} = 1-(1-P_{FA})e^{-\lambda_i t_i} \\ P\{X_i = 1\} = (1-P_{FA})e^{-\lambda_i t_i} - (1-P_{FA})^2 e^{-\lambda_i \cdot 2t_i} \\ P\{X_i = 2\} = (1-P_{FA})^2 e^{-\lambda_i \cdot 2t_i} - (1-P_{FA})^3 e^{-\lambda_i \cdot 3t_i} \\ \vdots \\ P\{X_i = K_i\} = (1-P_{FA})^{K_i} e^{-\lambda_i \cdot K_i t_i} \end{cases} \tag{3.6}$$

The *remaining packets*, means the number of packets that are not transmitted yet due to a primary user's arrival. Since the secondary user must vacate a channel when a primary user is detected, the rest of packets need to be transmitted on another channel after the RF link is reestablished. Let N_{RP} represent the number of packets to be sent on another channel. A larger value of N_{RP} means that the CR transceiver needs to transmit more packets over a re-established link, and thus more delay is caused. Obviously, we get

$$N_{\mathrm{RP}} = (N - X_i f_i) \tag{3.7}$$

$$\begin{aligned} E(N_{\mathrm{RP}}) &= \sum_{n=0}^{K_i}(N-nf_i)P\{X_i = n\} \\ &= N(1-a^{K_i}) - f_i \frac{a-a^{K_i}}{1-a} + f_i(K_i-1)a^{K_i} \\ &= N - f_i \frac{a(1-a^{K_i})}{1-a} (\text{ if } K_i \text{ is a continuous variable}) \end{aligned} \tag{3.8}$$

where $a = (1-P_{FA})e^{-\lambda_i t_i}$, and $E(N_{\mathrm{RP}})$ represents the expectation value of *remaining packets* N_{RP}.

Let $\frac{d(E(N_{\mathrm{RP}}))}{df_i} = 0$, we have

$$f_i \approx \frac{-BE + \sqrt{E(BE-CD)}}{CE} \tag{3.9}$$

where

$$\begin{aligned} B &= P_{\mathrm{FA}} + \lambda_i \cdot T_{\mathrm{sensing}} - P_{\mathrm{FA}} \cdot \lambda_i \cdot T_{\mathrm{sensing}} \\ C &= (1-P_{\mathrm{FA}}) \cdot \lambda_i \cdot D_{\max} / R_i \\ D &= N \cdot P_{\mathrm{FA}} \cdot e^{-\lambda_i \cdot D_{\max} \cdot N / R_i} \\ E &= 1 - e^{-\lambda_i \cdot D_{\max} \cdot N / R_i} \end{aligned} \tag{3.10}$$

Please refer to Appendix 1 for detailed information.

In Fig.3, we set up the total number of packets that are required to transmit on the secondary user's link, as $N = 800$. And we assume that the channel capacity is $R_i = 1000$ packets, spectrum sensing time is $T_{\mathrm{sensing}} = 0.01$ seconds, and the probability of false alarm is $P_{\mathrm{FA}} = 0.01$. Fig.3 shows the relationship between *remaining packets* and *spectrum sensing frequency* for three channels with different Poisson parameters λ_i. Fig.3 also marks (with ∇) the optimal values of spectrum sensing frequency f_i that bring the lowest *remaining packets* N_{RP}. Refer back to Fig.1 we see that a smaller f_i (i.e., less packets to send, or, less time spent in data transmission) implies more time consumption in spectrum sensing. On the other hand, however, a larger f_i means that more time is spent in data transmission, which means the secondary user does not have enough time to perform spectrum sensing (i.e., detect the primary user's arrival events). For both cases the user has a larger number of packets (N_{RP}) waiting for retransmission in the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.

new channel (see Fig.2).

From Fig.3, we can conclude that a better channel (i.e., a smaller λ_i, which means a larger primary user inter-arrival time) will produce a smaller N_{RP} and thus larger optimal spectrum sensing frequency f_i.

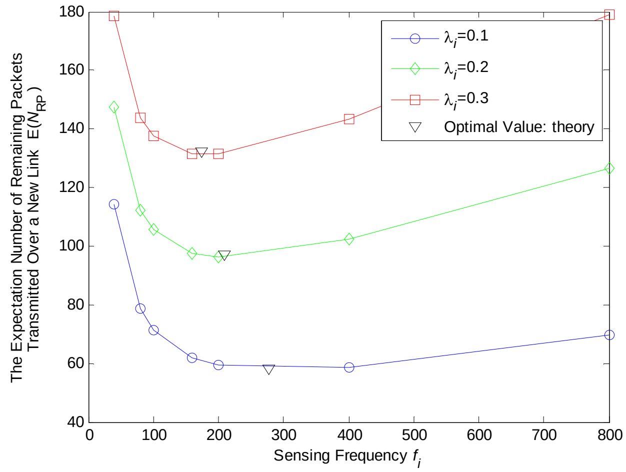


Fig. 3: The relationship between $E(N_{\mathrm{RP}})$ and f_i.

When a new link is re-established (i.e., the secondary user switches to a new channel), we not only expect *the number of remaining packets* N_{RP} to be as small as possible, but also wish the *new channel availability time* (i.e., the data transmission time available in new channel) to be as long as possible. Here, we define *new channel availability time* T_R as:

$$T_{\mathrm{R}} = D_{\max} - (X_i + 1)t_i \tag{3.11}$$

$$\begin{aligned} E(T_{\mathrm{R}}) &= \sum_{n=0}^{K_i} [D_{\max} - (n+1)\cdot(f_i \frac{D_{\max}}{R_i} + T_{\mathrm{sensing}})] P\{X_i = n\} \\ &= D_{\max} - t_i \cdot \frac{1-a^{K_i}}{1-a} \end{aligned} \tag{3.12}$$

Since the equation (3.12) has similar expression as equation (3.8) (please refer to Appendix 2), we use equation (3.9) to calculate the ***Peak (optimal) Value***. Fig.4 shows the relationship between $E(T_R)$ and f_i. The optimal value is also shown according to equation (3.9) and (3.12). The parameter setting is the same as before.

From Fig.4, we can see that *a better channel (it has smaller λ_i) has a smaller new channel availability time, since the primary user's inter-arrival time is larger, which gives the secondary user more time to transmit multimedia data*. For each channel, there also exists an optimal spectrum sensing frequency f_i that maximizes the *new channel availability time*.

It is natural to use the ratio of $E(N_{\mathrm{RP}})$ to $E(T_R)$ to reflect the QoS performance in a new re-established link. A smaller $E(N_{\mathrm{RP}})/E(T_R)$ can better support QoS requirement. In Fig.5, the relationship between $E(N_{\mathrm{RP}})/E(T_R)$ and f_i is given (the parameter setting is the same as Fig.3). From Fig.5, we can see that a better channel (with a smaller λ_i) will produce smaller $E(N_{\mathrm{RP}})/E(T_R)$ (thus better QoS).

In summary, *we can see that the peak values in theory match very well with the simulation results* (see Figs.3, 4, 5).

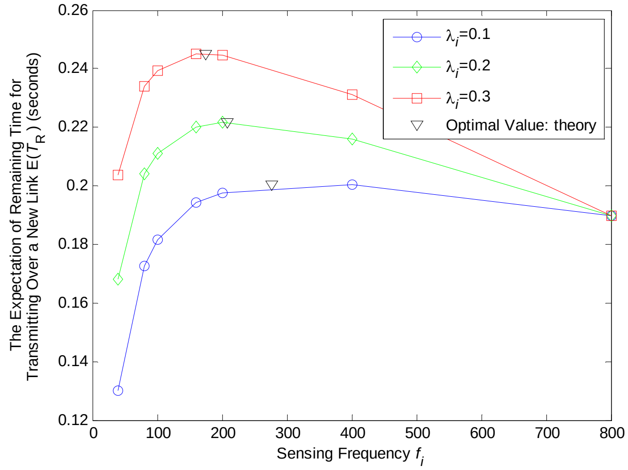


Fig. 4: The relationship between $E(T_R)$ and f_i.

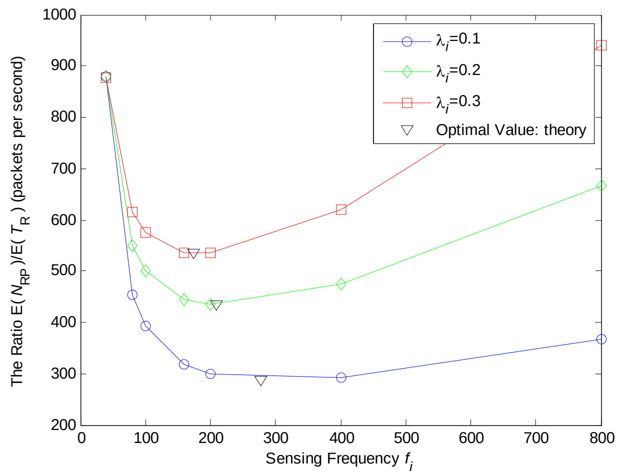


Fig. 5: The relationship between $E(N_{\mathrm{RP}})/E(T_R)$ and f_i.

B. Multi-Channel Case

Now we discuss multi-channel case, i.e., the secondary user can transmit data in multiple channels simultaneously. In CR networks, the CR transceiver can work on non-contiguous channels. In [18], a multi-band (MB) OFDM system is implemented in CR. The MB-OFDM based transceiver can detect primary user activity and transmit data over different channels simultaneously.

For a multi-channel case, a radio link could transmit data in different channels. This makes a routing path have certain diversity, which can help to achieve distributed multimedia streaming via multi-paths. Therefore, multi-channel communication can improve the network throughput.

As a multi-channel communication example, in [19] multiple streaming servers are used to provide robust delivery even if one of the communication channels fails due to network congestion. The multi-band diversity can also improve secondary users' communication reliability. For instance, if a primary user arrives in a particular channel, the secondary user could immediately vacate this band and still be able to use other channels to maintain stable data communications [1].

We assume S channels (denoted as $1,2,3,\ldots S$) are selected to transmit N multimedia packets. Channel i is licensed by primary user, with arrival rate λ_i ($i=1,2,3,\ldots S$) in that channel. We also assume N packets are loaded to S channels, and the number of packets loaded to each channel is denoted as $N_1, N_2, \ldots N_i, \ldots N_S$. For simplicity, we assume each channel has the same capacity R and spectrum sensing frequency f .

Since equation (3.8) and (3.12) obtain the peak value at approximately the same spectrum sensing frequency, we will seek for optimal spectrum sensing frequency and packet-loading scheme in theory based on equation (3.8). The optimization function is defined as:

$$E(N_{\text{RP}}) = \sum_{i=1}^{S} N_i(1-a^{K_i}) - f\frac{a-a^{K_i}}{1-a} + f(K_i-1)a^{K_i} \tag{3.13}$$

In equation (3.13), there are $S+1$ variables, $N_1, N_2, \ldots, N_S$ and f , (and $\frac{N \cdot T_{\text{sensing}}}{S \cdot D_{\max} - N \cdot D_{\max}/R} \le f \le R$). It is difficult to directly solve the optimal values of these $S+1$ variables when minimizing equation (3.13). We thus propose to use two optimization algorithms, *Hughes-Hartogs* and *Discrete Particle Swarm Optimization (DPSO)*, to efficiently find those values. For a fixed spectrum sensing frequency f , the Hughes-Hartogs algorithm can find optimal packet-loading results $N_1, N_2, \ldots, N_S$, (details later). Here *packet-loading* is similar to the concept of bit-loading in OFDM systems, which tries to find out how many bits should be allocated to each channel depending on the channel quality. After the optimal packet-loading result is obtained for a fixed spectrum sensing frequency f , we can calculate the optimization function values in equation (3.13), and use DPSO algorithm to find the optimal particle in each iteration. After several iterations, the optimal packet-loading results $N_1, N_2, \ldots, N_S$ and spectrum sensing frequency f can be obtained.

In next section, we will give the optimal solution to the selection of spectrum sensing frequency and packet-loading scheme using Hughes-Hartogs and Discrete Particle Swarm Optimization (DPSO) algorithms.

IV. Optimal Solution To Multi-Channel Case

A. Hughes-Hartogs algorithm

Hughes-Hartogs algorithm is used widely according to water-filling principle in OFDM system for optimal bit-loading [20]. Since the equation (3.8) has similar meaning as water-filling principle in OFDM [21], we can use Hughes-Hartogs algorithm to obtain the optimal packet-loading results. The water-filling principle used in our problem is shown in Fig.6. From Fig.6, we can see that a larger $f \cdot a \cdot (1-a^{K_i})/(1-a)$ will produce a smaller remaining packets $E(N_{\text{RP}})$ and vice versa (under a fixed N). Hughes-Hartogs algorithm is a greedy algorithm to seek optimal results. Here we use it to find optimal packet-loading strategy (such as how many packets should be loaded to each channel) for the multi-channel case, under a fixed spectrum sensing frequency f . The detailed steps are given below:

1) Initially, assume all channels load zero packets, that is

$$N_i = 0, i = 1, 2, \cdots, S$$

2) Calculate the increment of $E(N_{\text{RP}})_i$, denoted as $\Delta E(N_{\text{RP}})_i$, when one block (containing f packets) is loaded to the channel with channel ID i . Here $\Delta E(N_{\text{RP}})_i$ is defined as:

$$\Delta E(N_{\text{RP}})_i = \sum_{n=0}^{K_i+1} (N_i + f_i - nf_i) P\{X_i = n\} - \sum_{n=0}^{K_i} (N_i - nf_i) P\{X_i = n\}$$

3) Find out the channel ID of minimal $\Delta E(N_{\text{RP}})_i$, and calculate the *new channel availability time* based on the following relationship:

$$D_{\max} - (f \cdot \frac{D_{\max}}{R_i} + T_{\text{sensing}})(K_i + 1)$$

If $D_{\max} - (f \cdot \frac{D_{\max}}{R_i} + T_{\text{sensing}})(K_i + 1) > 0$, load one multimedia block (containing f packets) , set $K_i = K_i + 1$ for this channel and go to step 2, otherwise go to step 4.

4) Set $\Delta E(N_{\mathrm{RP}})_i = +\infty$ for the channel with minimal packets.

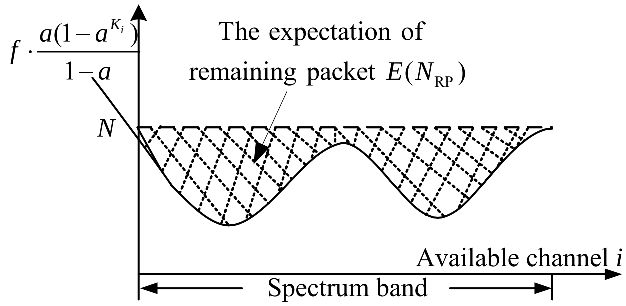


Fig. 6: The water-filling principle used in our problem.

B. Discrete Particle Swarm Optimization (DPSO) algorithm

Particle swarm optimization (PSO) is a population-based optimization method [22]. We have used it to model aircraft network routing control [23]. PSO is inspired by birds' flocking behavior in two-dimensional space. It introduces the population of particles for system optimization. Each particle has a random initialization status, and the following iterations are used to update its position and velocity:

$$v_{id}^{k+1} = v_{id}^{k} + c_1 r_1 (p_{id}^{k} - x_{id}^{k}) + c_2 r_2 (p_{bd}^{k} - x_{id}^{k}) \quad (4.1)$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \quad (4.2)$$

where $i \in \{1,2,\ldots,N_s\}$, $d \in \{1,2,\ldots,D\}$, D is the search space's dimension size, and k is the generation of evolution process. Note that we can use the optimization function of (3.13) to determine each particle's fitness value. Thus we are able to retrieve the particle's direction, position, and distance for particle update. The above two equations can ensure that each particle converges to an optimal status via an evolutionary algorithm.

In (4.1), we have used two variables, p_{id} and p_{bd}, to represent the *personal best position* (PBP) and *the global best position* (GBP), respectively. In the PBP, an individual particle has the smallest cost function (i.e., error). While in the GBP, the lowest error is achieved among all the p_{id}^{k}'s outputs. As we can see from (4.1), by tracing p_{id} and p_{bd}, PSO can successfully update each particle.

In (4.1), we have also used two pseudorandom sequences, r_1 and r_2, both of which follow uniform distribution in the range of [0, 1], to achieve the stochastic characteristics of PSO algorithm. In (4.1), the two constants, c_1 and c_2, called acceleration coefficients, are used to control how far a particle moves in a single update round. In many cases we can simply set them to a value of 2. In (4.2), x_{id}^{k} is the particle's current position. It provides the optimization solution if PSO operates in *continuous* space.

However, the above model is for *continuous* PSO update. If PSO operates in *discrete* space, we cannot use (4.1) and (4.2) to directly solve the position from velocity value. In discrete space, only 0 or 1 values are allowed for the following variables: x_{id}^{k}, p_{id}^{k}, and p_{bd}^{k}. Therefore, in discrete PSO we should use a *binary version (discrete) of PSO (DPSO)* [24-25], to update each particle, That is,

$$v_{id}^{k+1} = v_{id}^{k} + c_1 r_1 (p_{id}^{k} - x_{id}^{k}) + c_2 r_2 (p_{bd}^{k} - x_{id}^{k}) \quad (4.3)$$

$$if\ (Sig(v_{id}^{k}) > r)\ then\ x_{id}^{k+1} = 1$$

$$else\ x_{id}^{k+1} = 0 \quad (4.4)$$

where $Sig(v_{id}^{k}) = [1/1 + \exp(-v_{id}^{k})]$ is particle evolution probability, and r is a pseudorandom sequence that follows an uniform distribution in the range of [0,1].

If we represent the spectrum sensing frequency f with $\lceil \log_2 R \rceil$ bits, then we can see that a particle contains $\lceil \log_2 R \rceil$ binary numbers, i.e. $D = \lceil \log_2 R \rceil$.

Our proposed algorithm to seek for the optimal solution of spectrum sensing frequency selection based on DPSO is described below.

1) Set $k = 0$, and produce the position x_{id}^0 and velocity v_{id}^0 for each particle, where $x_{id}^0 \in \{0,1\}$, $v_{id}^0 \in [-V_{\max}, V_{\max}]$, $1 \le d \le D$.

2) For each particle, find out the optimal packet-loading results according to Section IV Part A, and determine the fitness value through the optimization function (3.13). Then we get $p_i^0 = [x_{i1}^0, x_{i2}^0, \ldots, x_{iD}^0]$, and $p_b^0 = [x_{b1}^0, x_{b2}^0, \ldots, x_{bD}^0]$, where b is the index of the fitness particle.

3) Let $k = k+1$, and change the status of v_{id}^k according to equation (4.3). If $v_{id}^k > V_{\max}$, then $v_{id}^k = V_{\max}$; If $v_{id}^k < -V_{\max}$, then $v_{id}^k = -V_{\max}$.

4) Generate a stochastic number r that follows uniform distribution in [0,1], and use (4.4) to update the status of x_{id}^k.

5) For each particle i, we use the optimization function (3.13) to determine the fitness value. If the new fitness value is less than p_i^{k-1}, set $p_i^k = [x_{i1}^k, x_{i2}^k, \ldots, x_{iD}^k]$, otherwise, set $p_i^k = p_i^{k-1}$. Similarly, if the new fitness value is less than p_b^{k-1}, we set $p_b^k = [x_{i1}^k, x_{i2}^k, \ldots, x_{iD}^k]$, else $p_b^k = p_b^{k-1}$.

6) If the number of iterations k reaches a threshold, we should stop, otherwise, go back to step (3).

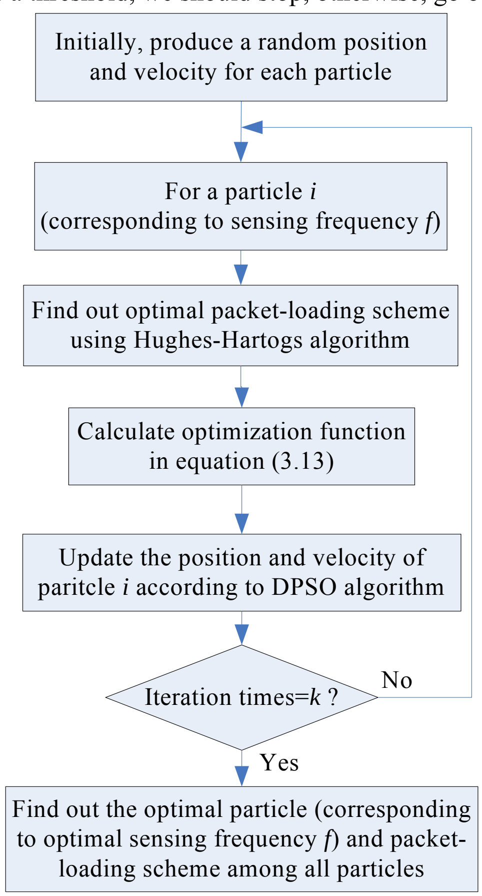


Fig. 7: Flow chart of finding out optimal solution.

Fig.7 shows the chart of joint Hughes-Hartogs and DPSO algorithms to obtain the optimal solution in multi-channel case. For each particle (corresponding to a spectrum sensing frequency *f*), we use Hughes-Hartogs algorithm to find the optimal packet-loading results over each available channel. Then, the optimization function value in equation (3.13) can be calculated. After each particle performs the above two procedures, they update the states (including the position and velocity) according to DPSO algorithm. When the iteration times reaches a threshold (i.e., the algorithm converges), the optimal/suboptimal spectrum sensing frequency and packet-loading results are then obtained.

C. Computation Complexity Analysis

Since our algorithm is a combination of Hughes-Hartogs and *DPSO* algorithms, the computation complexity depends on both algorithms. From Section IV part A, we can see that the computation complexity of Hughes-Hartogs algorithm is a linear function of the number of packets N , which determine the iteration times [20]. While the computation complexity of *DPSO* algorithm is a linear function of the number of particles N_s and the iteration times k [24]. Hence, the total computation complexity of our proposed algorithm is a linear function of $N \times N_s \times k$.

V. Experimental Results

Firstly, we conduct our experiments with JPEG2000 packet stream. The image name is "lena.bmp", with image size 512 by 512 and 8-lever pixel depth (i.e., the value of each pixel ranges from 0 to 255). Next, to illustrate the impact of the number of selected channels, optimal spectrum sensing frequency and packet-loading scheme on multimedia transmission, we use video stream "Bus" in our experiments. We implement our proposed optimal spectrum sensing frequency selection and packet-loading schemes in Matlab.

A. Theoretical Performance Study

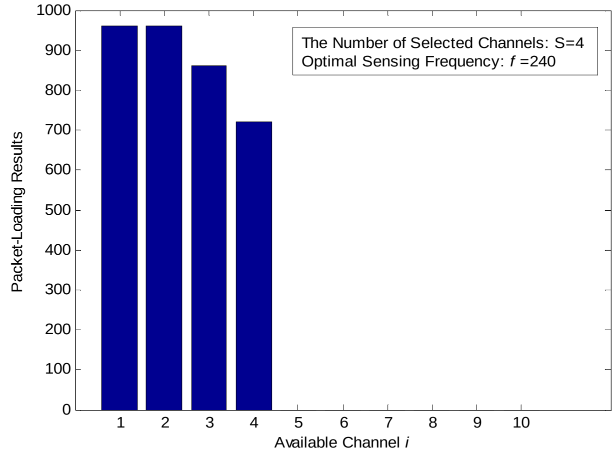
For the general case where *all channels have different primary user arrival rates,* we assume 10 channels are available in the spectrum pool with independent primary user arrival events whose rates are as follows:

$$\lambda = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]$$

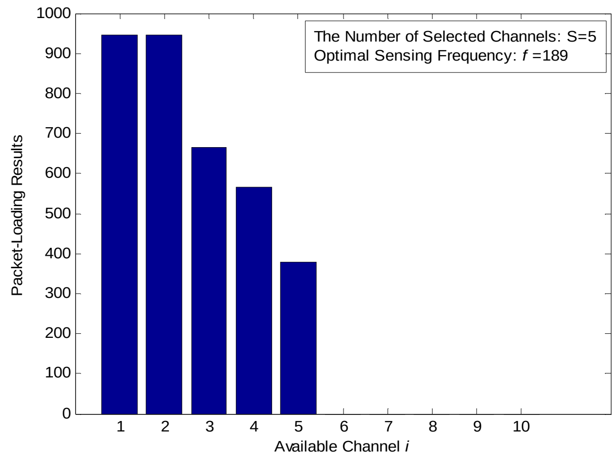
and other parameters are set up as follows: $R = 1000$ packets, $D_{\max} = 1$ second, $N = 3500$ packets, $P_{\text{FA}} = 0.01$, $T_{\text{sensing}} = 0.01$ seconds. Obviously, the quality of channel is determined by primary user arrival rate. A smaller arrival rate means a better channel quality since this means that a primary user does not arrive (and re-occupy the channel) so quickly. Thus a secondary user would have more time to finish multimedia transmission.

Fig.8 (a)~(g) show the simulation results of optimal spectrum sensing frequency and packet-loading results for different *number of selected channels (from S = 4 to S = 10*). Note that here we used Hughes-Hartogs and DPSO algorithm ($N_s = 30$ particles and $k = 10$ rounds) to obtain the *optimal spectrum sensing frequency* and *packet-loading* results.

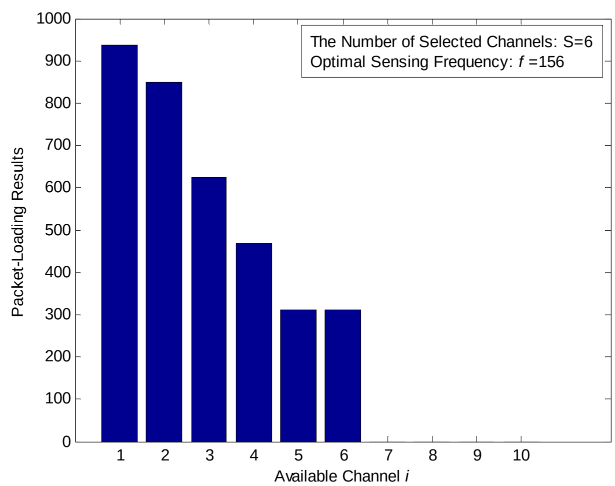
From Fig.8, we can see that a better channel will be allocated more JPEG2000 packets to transmit on; and the spectrum sensing frequency *f* will reduce as more channels participate in packet transmission, which is caused by three reasons: (1) when the number of selected channels *S* is larger, some worse channels will be selected to participate in packet transmission; (2) Meanwhile, the spectrum sensing is simultaneous for all selected channels; (3) And a worse channel need to be sensed frequently to detect primary user state, thus a smaller *f* (please refer to Section III part A). Hence, a larger number (*S*) of selected channels introduce more MAC overhead and transmission delay. However, total packets are loaded to a larger number of selected channels, and thus we have a smaller packet amount in each channel, which may bring in a higher probability of successful packets delivery and higher QoS performance.


The Number of Selected Channels: S=4
Optimal Sensing Frequency: f =240
Packet-Loading Results
Available Channel i
0
100
200
300
400
500
600
700
800
900
1000
1 2 3 4 5 6 7 8 9 10

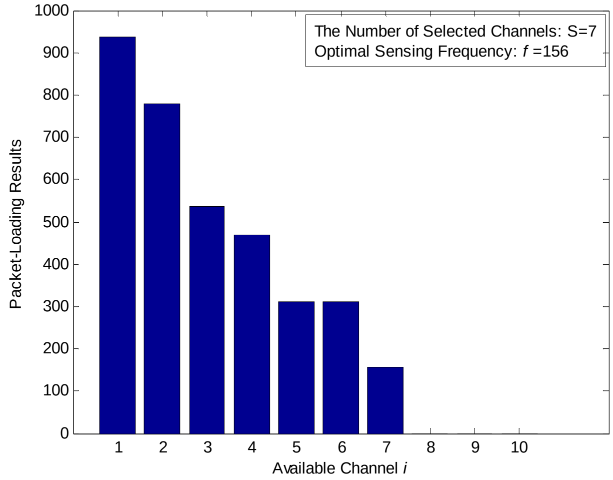
(a)


The Number of Selected Channels: S=5
Optimal Sensing Frequency: f =189
Packet-Loading Results
Available Channel i
0
100
200
300
400
500
600
700
800
900
1000
1 2 3 4 5 6 7 8 9 10

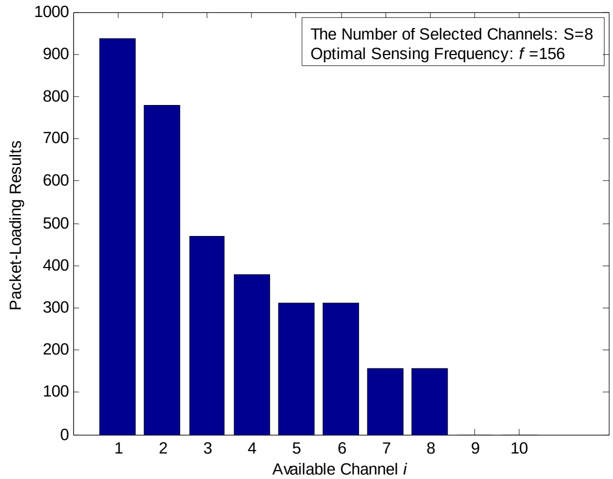
(b)


The Number of Selected Channels: S=6
Optimal Sensing Frequency: f =156
Packet-Loading Results
Available Channel i
0
100
200
300
400
500
600
700
800
900
1000
1 2 3 4 5 6 7 8 9 10

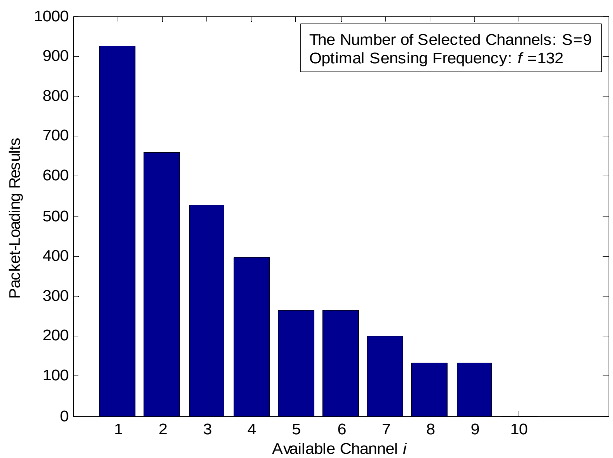
(c)


The Number of Selected Channels: S=7
Optimal Sensing Frequency: f =156
Packet-Loading Results
Available Channel i
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10

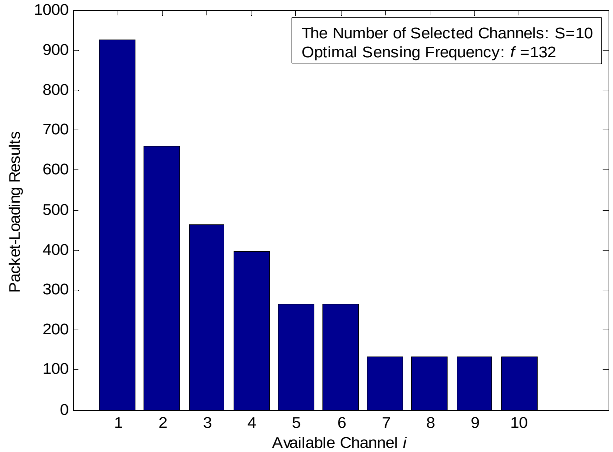
(d)


The Number of Selected Channels: S=8
Optimal Sensing Frequency: f =156
Packet-Loading Results
Available Channel i
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10

(e)


The Number of Selected Channels: S=9
Optimal Sensing Frequency: f =132
Packet-Loading Results
Available Channel i
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10

(f)



(g)

Fig. 8: Trade-offs among the number of selected channels, optimal spectrum sensing frequency and packet-loading results.

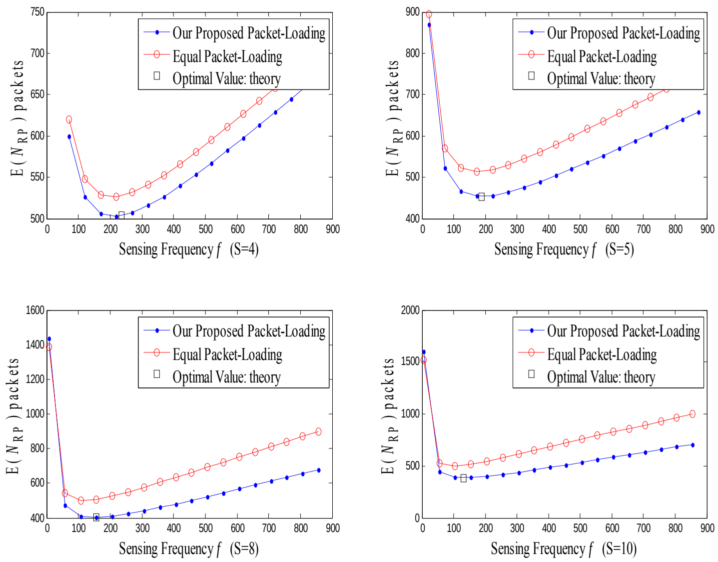


Fig. 9: $E(N_{\mathrm{RP}})$ comparison between our proposed packet-loading and equal packet-loading.

Figs.9~11 shows the performance comparison between our proposed packet-loading scheme and conventional *equal packet-loading*, which simply loads the same amount of JPEG2000 packets to each channel [1]. We can see that our proposed algorithm is better than *equal packet-loading* scheme, since our algorithm has fully utilized the *heterogeneous* feature of available channels to distribute different amount of packets in each channel. We can also see that a larger number of selected channels produce a smaller required optimal spectrum sensing frequency, which is also reflected in Fig.8.

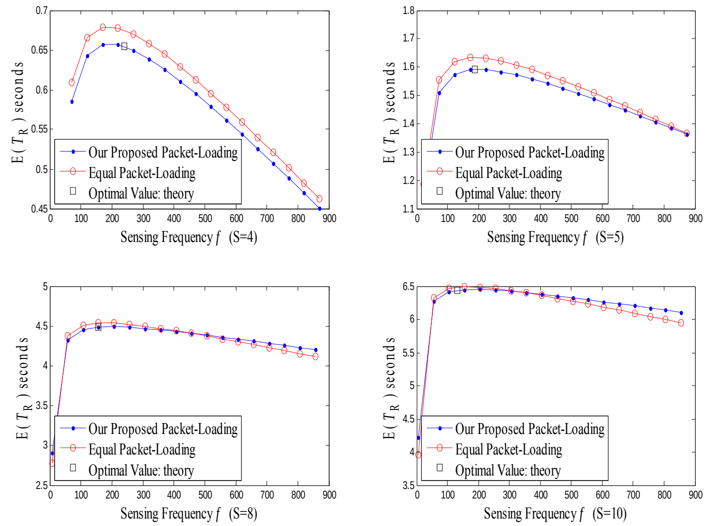


Fig. 10: $E(T_R)$ comparison between our proposed packet-loading and equal packet-loading.

From Fig.11, we can infer that our proposed algorithm has a higher successful packet delivery ratio and thus a better QoS performance. The optimal values in theory are also shown in each figure, which match very well with the simulation results.

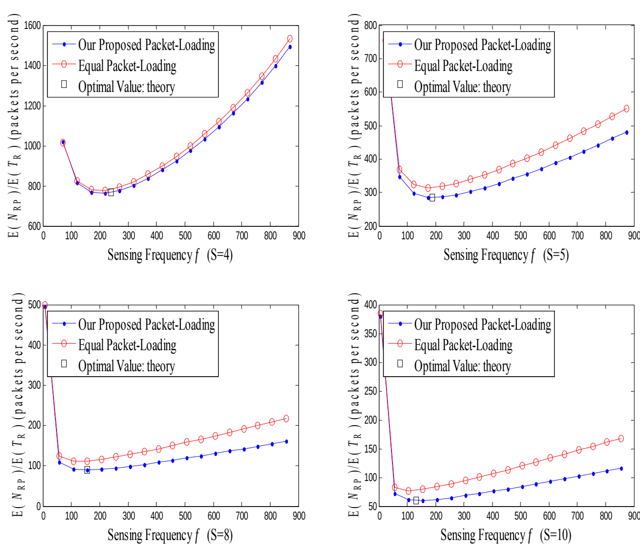


Fig. 11: $E(N_{\mathrm{RP}})/E(T_R)$ comparison between our proposed packet-loading and equal packet-loading.

B. The Impact of Spectrum Sensing Frequency and Packet-Loading Scheme on Image Transmission

To better see the performance of multimedia content transmitting in CRNs, we consider a standard picture "lena.bmp" which is to be sent. We use the compression rate of 1/16. We use JPEG2000 standard compression software "Jasper" to produce coding stream. The coding stream is divided into 816 packets. Ten channels are available in the channel pool. The primary users arrival rate changes as follows: $\lambda = [5,6,7,8,9,10,11,12,13,14]$.

Firstly, we consider single-channel case, and $R = 1000$ packets, $D_{\max} = 1$ second, $N = 816$ packets, $P_{\mathrm{FA}} = 0.01$, $T_{\mathrm{sensing}} = 0.01$ seconds. The simulation results are shown in Figs.12~14.

Fig. 12: Original compressed image (compression rate=1/16) with PSNR=34.50dB.

Fig. 13: Only one channel is selected to transmit packets, and no spectrum sensing operates during transmission. 195 packets are successfully transmitted and reconstructed (PSNR=28.79dB).

Fig. 14: One channel is selected to transmit packets before primary user arrival, and spectrum sensing (according to equation (3.9)) operates during transmission. 526 packets are successfully transmitted and reconstructed (PSNR=32.69dB).

We can see that our proposed algorithm performs better than the situation in which no spectrum sensing operates during transmission. Here we implement no-spectrum-sensing scenario by simply stopping spectrum sensing during packet transmission.

Fig.12 is the original compressed image with peak signal-to-noise ratio (PSNR) 34.50 dB. Since our proposed algorithm uses optimal spectrum sensing frequency, it can well detect primary user's activity and select a new channel for link reestablishment when primary user arrives. This can be seen from Fig.14. Our scheme performs better than no spectrum sensing case (see Fig.13) for more than 3.9 dB. The simulation results illustrate that our proposed algorithm is more suitable to cognitive radio environment, and supports a higher QoS application for secondary users, which also proves the correctness of our theory analysis in Section III Part A.

Next we consider the situation that multi-channel is used. The primary user's arrival models are set to different values as follows: $\lambda = [5,6,7,8,9,10,11,12,13,14]$, and $R = 200$ packets, $D_{\max} = 0.2$ seconds, $N = 816$ packets, $P_{\text{FA}} = 0.01$, $T_{\text{sensing}} = 0.01$ seconds. The conventional packet-loading method (such as [1]) just selects the first five channels and loads packets *equally*. For comparison, we select the first five channels (*S*=5) and load packets according to our algorithm. If one of them is occupied by primary user, we will select another channel to re-establish a new channel. We still use JPEG2000 standard compression software "Jasper" to produce coding stream. The *DPSO* algorithm uses $N_s = 30$ particles and $k = 10$ rounds.

Fig. 15: Only five channels are selected to transmit packets and no spectrum sensing operates during transmission. 142 packets are successfully transmitted and reconstructed (PSNR=27.36dB).

Fig. 16: Five channels are selected to transmit packets before primary user arrival. Optimal spectrum sensing frequency and packet-loading schemes are done with our proposed algorithm (Hughes-Hartogs and DPSO algorithms). 383 packets are successfully transmitted and reconstructed (PSNR=31.43dB).

The simulation results are shown in Fig.15 and Fig.16. Our algorithm (see Fig.16) performs better than Fig.15 case for over 4.07 dB, and provides better QoS performance for secondary users' multimedia transmission, which also proves that our theory analysis is correct (in Section III Part B).

Note that Fig.13 and Fig.15 are for the equal loading scheme. Because the maximum tolerable delay $D_{\max}$ is reduced from 1 second to 0.2 seconds, Fig. 15 has less number of packets sent and thus has poorer performance than Fig. 13. Similarly, Fig. 16 has less number of packets sent and poorer performance than Fig. 14.

Our above simulation results illustrate the importance of selecting optimal spectrum sensing frequency and packet-loading scheme to image transmission in CRNs. The image transmission is one of the major cases in multimedia applications; however, it is different from video transmission. In image transmission (especially using JPEG2000 compression) system, one packets loss may make the following packets unrecoverable due to error propagation in decoder; however, in video transmission (especially H.264 compression) system, some packets loss will not impact the decoding of the following video stream. In the following simulation, we will use video transmission with our proposed algorithm and equal-packet loading algorithm, respectively.

C. Trade-offs Among the Number of Selected Channels, Optimal Spectrum Sensing Frequency and Packet-loading Scheme, and Their Impacts on Multimedia Transmission

To further show the trade-offs among the number of selected channels *S*, optimal spectrum sensing frequency *f* and packet-loading results $[N_1, N_2, \ldots, N_S]$ and their impacts on multimedia transmission, we use video packets stream in our experiments. We also consider the situation that multi-channel is used in video transmission. The primary user's arrival models are set as follows: $\lambda = [1,2,3,4,5,6,7,8,9,10]$, and $R = 1000$ packets, $P_{\text{FA}} = 0.01$, $T_{\text{sensing}} = 0.01$ seconds. The *DPSO* algorithm uses $N_s = 30$ particles and $k = 10$ rounds. The video streaming application is "Bus" (CIF 352×288 format, 150 frames and transmission delay deadline $D_{\max} = 0.5$ seconds), which is coded by H.264/AVC JM 12.2 software [26] and produces $N = 3417$ packets with three priorities (they contain 1050, 1221 and 1146 packets, respectively).

The conventional packet-loading method (such as [1]) just allocates the total packets equally to each selected channel. For comparison, we select different number of channels *S* for packets transmission and load packets according to our proposed algorithm and conventional equal packet-loading scheme, respectively.

The simulation results are shown in Table 1. From Table 1, we can see that: (1) A better channel could be allocated more packets; (2) When the number of selected channels *S* increases, the spectrum sensing frequency *f* and the number of video packets allocated to each channel are reduced.

Furthermore, the conventional equal packet loading algorithm has a lower packet loss rate (PLR) when the selected channels *S* increases. Since no spectrum sensing occurs during packet transmission, larger number of selected channels will have less packets allocated on each channel and thus we have a high probability of successfully packet delivery [1] (i.e., low packet loss rate); However, the reconstructed video quality (we use average Y-PSNR value in our simulation) is not improved sharply when more channels are used. This situation is considered as low spectral efficiency in [1]. However, our proposed spectrum sensing and packet-loading scheme have a lower video quality when more channels are used. This is because our packet-loading scheme allocates different number of packets to different channels based on channels' conditions, and spectrum sensing operation can detect the primary user activities and switch channels when necessary. *Hence, our method is greedy and can ultimately utilize the available channel resource step by step, which indicates a higher spectral efficiency.* When the number of selected channels *S* is increased to S_0 (S_0=10 in our simulation), our proposed algorithm performs worse, since spectrum sensing is operated frequently and no alternative channels can be used when any channel is re-occupied by primary user (the secondary user activity model is based on channel switching when the primary user is detected, please refer to Fig.2).

Table 1: The impact of the number of selected channels, optimal spectrum sensing frequency and packet-loading results on multimedia transmission.

Number of selected channels (S)	Our proposed algorithm with optimal spectrum sensing frequency and packet-loading schemes				The equal packet-loading algorithm, without spectrum sensing during packet transmission		
	Optimal Sensing frequency (f)	Packet-loading scheme $[N_1, N_2, \ldots, N_S]$	PLR (%)	Average Y-PSNR (dB)	Packet-loading scheme $[N_1, N_2, \ldots, N_S]$	PLR	Average Y-PSNR (dB)
S =4	180	[900,900,900,717]	21.91	20.12	[855,854,854,854]	36.72	18.03
S =5	146	[876,876,730,497,438]	24.52	19.26	[684,684,683,683,683]	35.59	18.08
S =6	121	[847,847,605,484,363,271]	28.16	19.08	[570,570,570,569,569,569]	35.08	18.12
S =7	105	[840,840,525,420,315,267,210]	30.37	18.99	[489,488,488,488,488,488,488]	34.17	18.16
S =8	105	[840,735,525,372,315,210,210,210]	32.35	18.91	[428,427,427,427,427,427,427,427]	33.91	18.17
S =9	105	[840,735,525,315,315,210,210,162,105]	35.48	18.09	[380,380,380,380,380,380,379,379,379]	33.27	18.33
S =10	91	[819,728,455,364,273,182,182,182,141,91]	37.03	18.02	[342,342,342,342,342,342,342,341,341,341]	33.08	18.35

Table 2: The impact of transmission delay deadline $D_{\max}$ on multimedia transmission over CRNs with our proposed algorithm and the equal packet-loading algorithm respectively.

Number of selected channels (S)	$D_{\max} = 0.35$ seconds, $R = 700$ packets				$D_{\max} = 0.40$ seconds, $R = 800$ packets				$D_{\max} = 0.45$ seconds, $R = 900$ packets			
	Our proposed algorithm		The equal packet-loading algorithm		Our proposed algorithm		The equal packet-loading algorithm		Our proposed algorithm		The equal packet-loading algorithm	
	PLR (%)	Average Y-PSNR (dB)	PLR (%)	Average Y-PSNR (dB)	PLR (%)	Average Y-PSNR (dB)	PLR (%)	Average Y-PSNR (dB)	PLR (%)	Average Y-PSNR (dB)	PLR (%)	Average Y-PSNR (dB)
S =4	43.56	16.80	44.38	16.76	30.41	18.99	39.42	17.84	30.36	18.99	36.93	18.02
S =5	35.03	18.12	36.00	18.07	34.99	18.12	36.00	18.07	28.97	19.00	35.94	18.07
S =6	40.83	17.67	35.13	18.11	35.33	18.10	35.13	18.11	31.75	18.96	35.12	18.11
S =7	40.80	17.66	34.37	18.15	36.27	18.06	34.19	18.15	33.19	18.33	34.18	18.15
S =8	40.79	17.66	33.99	18.16	37.44	17.99	33.98	18.16	34.32	18.15	33.83	18.18

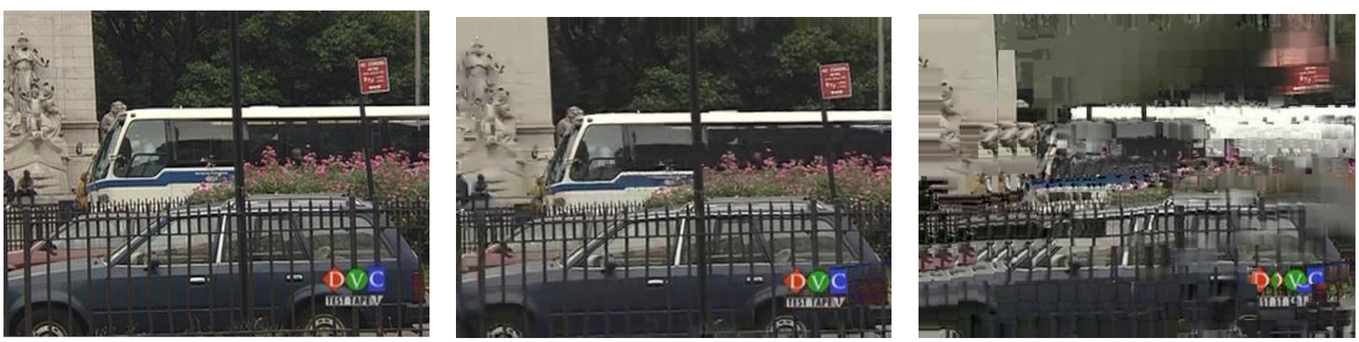

(a) (b) (c)

Fig.17 The quality of reconstructed video frame: (a) original video frame No.18; (b) reconstructed frame using our proposed algorithm; (c) reconstructed frame using the equal-packet loading algorithm without spectrum sensing during packet transmission.


(a) (b) (c)

Fig.18 The quality of reconstructed video frame: (a) original video frame No.140; (b) reconstructed frame using our proposed algorithm; (c) reconstructed frame using the equal-packet loading algorithm without spectrum sensing during packet transmission.

For comparison, Fig.17 and Fig.18 show the reconstructed video frames of two algorithms, where $S = 4$ channels are selected to transmit video packets (The first case in Table 1). We can see that our proposed method performs better than the algorithm that uses equal packet loading, and provide a higher QoS to secondary users.

Since multimedia transmission is not only sensitive to available spectrum band, but also to transmission delay deadline, we study the impact of transmission delay deadline on multimedia transmission over CRNs. For comparison, we fix the optimal spectrum sensing frequency and packet-loading scheme in Table 1, and set the transmission delay deadline $D_{\max}$ as {0.35, 0.40, 0.45} seconds, respectively. The simulation results are shown in Table 2. From Table 2, we can see that:

(1) Under the same number of selected channels, a larger $D_{\max}$ will produce a higher average Y-PSNR, and our proposed algorithm provides sharply improved performance since more spectrum resource can be used (when the allocated spectrum bands is small, i.e., S=4 and 5);

(2) We can use more spectrum bands (more channels) to overcome the stringent transmission delay deadline $D_{\max}$, and the disadvantage of smaller $D_{\max}$ is reduced when lots of channels are selected;

(3) Our proposed algorithm is better than the algorithm that uses equal-packet loading (it does not have spectrum sensing operation during packet transmission) under different $D_{\max}$, when the number of selected channels S is small.

VI. Application to Different Traffic Types

By selecting the optimal spectrum sensing frequency and packet-loading scheme, our proposed algorithm exploits the channel characteristics to deliver more packets within a maximum tolerable delay. We have focused on image and video transmissions in our theoretical analysis and simulation results. However, our proposed spectrum sensing frequency and packet-loading scheme can also be useful to other types of traffic. We discuss three popular traffic types and their applications which can be supported in CRN by our proposed algorithm.

(1) *Video traffic*: Video applications include remote video monitoring, video-on-demand, and Internet Protocol Television (IPTV). Since these applications have strict QoS requirements (i.e., delay and throughput), we need to carefully select the spectrum sensing frequency and packet-loading scheme to support high quality video service. In this paper, we have explicitly provided the system model, algorithm and experimental results for video transmission. Specifically, we derived the optimal spectrum sensing frequency for single-channel case (in Section III Part A), and optimal spectrum sensing frequency and packet-loading scheme for multi-channel case (in Section III Part B and Section IV). Simulation results show that the reconstructed video quality is better than the conventional equal packet loading scheme.

(2) *Audio traffic:* Audio applications include voice over IP (VoIP), music-on-demand (i.e., iTunes), and other sound/speech-oriented services. In general, audio traffic requires lower bit rate than video traffic. However, audio applications also have strict delay requirements like video. Our proposed scheme can be directly applied to audio traffic.

(3) *Data/Text traffic*: Typical data/text applications include many non-real time services, such as document transmission (i.e., File Transfer Protocol (FTP)), email, and database update. Different from video and audio services, these applications usually do not have stringent delay requirements. We can therefore set the maximum tolerable delay to a larger value (i.e., $D_{\max} = \infty$) in the optimization function (in equation (3.13)). Then, our proposed algorithm can derive the optimal spectrum sensing frequency and packet-loading scheme to maximize the throughput performance for data/text traffic.

VII. CONCLUSIONS AND FUTURE WORK

Since the CR transceiver can only do one task at a time, continuous sensing may increase the MAC overhead and delay, and cause some multimedia packets to miss the transmission deadline, and thus the multimedia quality decreases at a receiver side. Meanwhile, because the channels features are different from each other, the packet-loading must adapt to the heterogeneous channels and improve the quality of service (QoS). In this paper, we have introduced two QoS parameters to measure the performance of multimedia transmission in cognitive radios, i.e., *new channel availability time* and *remaining packets*, and have derived the relationship between spectrum sensing frequency, packet-loading and the above two parameters. Then, we used this relationship to select optimal spectrum sensing frequency and packet-loading scheme through two algorithms (Hughes-Hartogs and Discrete Particle Swarm Optimization (DPSO) algorithms), considering a Poisson-based model to describe primary user traffic. Simulation results showed that our algorithm could well utilize the *heterogeneous* channels and perform a better QoS under the situations with single channel and multi-channel links.

Future investigations in this area include video transmission from multiple secondary users simultaneously, and multi-hop multimedia transmission in CRNs. A multimedia-oriented routing protocol should be designed considering spectrum sensing frequency and packet-loading scheme along the path from source to destination to support the QoS for secondary users.

ACKNOWLEDGEMENT

The authors sincerely thank all anonymous reviewers for their valuable comments on this work. The authors also thank Seethal Paluri for her help in video simulation. Part of this research work was done when the first author was in Dr. Fei Hu' s research lab in the University of Alabama.

APPENDIX

1. *Proof:* $\frac{d(E(N_{\mathrm{RP}}))}{df_i} = 0 \Rightarrow f_i \approx \frac{-BE + \sqrt{E(BE - CD)}}{CE}$.

We consider K_i as a continuous variable, and $K_i = N / f_i$. Then,

$$E(N_{\mathrm{RP}}) = N(1 - a^{K_i}) - f_i \frac{a - a^{K_i}}{1 - a} + f_i (K_i - 1) a^{K_i}$$

$$= N - f_i \frac{a(1 - a^{K_i})}{1 - a}$$

$$\frac{a}{1-a} = \frac{(1 - P_{\mathrm{FA}}) \cdot e^{-\lambda_i (f_i \cdot \frac{D_{\max}}{R_i} + T_{\mathrm{sensing}})}}{1 - (1 - P_{\mathrm{FA}}) \cdot e^{-\lambda_i (f_i \cdot \frac{D_{\max}}{R_i} + T_{\mathrm{sensing}})}}$$

$$= \frac{(1 - P_{\mathrm{FA}}) \cdot [1 - \lambda_i (f_i \cdot \frac{D_{\max}}{R_i} + T_{\mathrm{sensing}})]}{1 - (1 - P_{\mathrm{FA}}) \cdot [1 - \lambda_i (f_i \cdot \frac{D_{\max}}{R_i} + T_{\mathrm{sensing}})]}$$

$$= \frac{1 - (P_{\mathrm{FA}} + \lambda_i \cdot T_{\mathrm{sensing}} - P_{\mathrm{FA}} \cdot \lambda_i \cdot T_{\mathrm{sensing}}) - (1 - P_{\mathrm{FA}}) \cdot \lambda_i \cdot \frac{D_{\max}}{R_i} \cdot f_i}{P_{\mathrm{FA}} + \lambda_i \cdot T_{\mathrm{sensing}} - P_{\mathrm{FA}} \cdot \lambda_i \cdot T_{\mathrm{sensing}} + (1 - P_{\mathrm{FA}}) \cdot \lambda_i \cdot \frac{D_{\max}}{R_i} \cdot f_i}$$

$$= \frac{1 - B - C \cdot f_i}{B + C \cdot f_i}$$

$$
\begin{aligned}
f_i\cdot(1-a^{K_i}) &= f_i - f_i\cdot\{(1-P_{\mathrm{FA}})\cdot e^{-\lambda_i\cdot(f_i\cdot\frac{D_{\max}}{R_i}+T_{\mathrm{sensing}})}\}^{K_i}\\
&= f_i - f_i\cdot(1-P_{\mathrm{FA}})^{K_i}\cdot e^{-\lambda_i\cdot\frac{D_{\max}}{R_i}\cdot f_i\cdot K_i}\cdot e^{-\lambda_i\cdot T_{\mathrm{sensing}}\cdot K_i}\\
&\approx f_i - f_i\cdot(1-\frac{N}{f_i}\cdot P_{\mathrm{FA}})\cdot e^{-\lambda_i\cdot\frac{D_{\max}}{R_i}\cdot N}\\
&= (1-e^{-\lambda_i\cdot\frac{D_{\max}}{R_i}\cdot N})\cdot f_i + N\cdot P_{\mathrm{FA}}\cdot e^{-\lambda_i\cdot\frac{D_{\max}}{R_i}\cdot N}\\
&= E\cdot f_i + D
\end{aligned}
$$

Let $\frac{d(E(N_{\mathrm{RP}}))}{df_i}=0$, then

$$
C^2E\cdot f_i^2 + 2BCE\cdot f_i + CD - B(1-B)E = 0
$$

$$
f_i = \frac{-BE+\sqrt{E(BE-CD)}}{CE}
$$

2. ***Proof:*** equation (3.8) and equation (3.12) have the similar characteristics.

Since $t_i = f_i\cdot\frac{D_{\max}}{R_i}+T_{\mathrm{sensing}}$, equation (3.8) can be further rewritten as:

$$
\begin{aligned}
E(N_{\mathrm{RP}}) &= N - f_i\frac{a(1-a^{K_i})}{1-a}\\
&= N - \frac{R_i}{D_{\max}}\cdot(t_i - T_{\mathrm{sensing}})\cdot(a+a^2+\cdots+a^{K_i})\\
&\approx N - \frac{R_i}{D_{\max}}\cdot t_i\cdot(a+a^2+\cdots+a^{K_i})
\end{aligned}
$$

and equation (3.12) can be rewritten as:

$$
\begin{aligned}
E(T_{\mathrm{R}}) &= D_{\max} - t_i\cdot\frac{1-a^{K_i}}{1-a}\\
&= D_{\max} - t_i\cdot(1+a+a^2+\cdots+a^{K_i-1})\\
&= D_{\max} - t_i\cdot(1-a^{K_i}) - t_i\cdot(a+a^2+\cdots+a^{K_i})\\
&\approx D_{\max} - t_i\cdot(a+a^2+\cdots+a^{K_i})
\end{aligned}
$$

We assume $t_i >> T_{\mathrm{sensing}}$ (packets transmission time t_i larger than spectrum sensing time T_{sensing} in each period) and $D_{\max} >> t_i$ (total multimedia transmission time $D_{\max}$ larger than each time slot t_i). Hence, we can conclude that equation (3.8) and equation (3.12) have similar characteristics.

REFERENCES

[1] Harikeshwar Kushwaha, Yiping Xing, Rajarathnam Chandramouli, and Harry Heffes. "Reliable Multimedia Transmission Over Cognitive Radio Networks Using Fountain Codes," *Proceeding of The IEEE,* vol. 96, no. 1, pp. 155-165, 2008.

[2] R.-T. Sheu and J.-L.C. Wu. "Performance Analysis of Rate Control With Scaling QoS Parameters for Multimedia Transmissions," *Proc. of IEE conference in Communications,* vol. 150, no. 5, pp. 361-366, 2003.

[3] Norazizah M. Aripin, Rozeha A. Rashid, Norulhusna Ahmad, Aida E.M Hamzah, Norsheila Fisal, and Sharifah K. Syed –Yusof. "Cross Layer Design of Multimedia Transmission Over Cognitive Radio UWB Multiband OFDM System," *Int'l Graduate Conference in Engineering & Science (IGCES), Johor Bharu,* pp. 1-10, 2008.

[4] Andrew Michael James. "A Link-quality-aware Graph Model for Cognitive Radio Network Routing Topology Management," *Thesis, Rochester Institute of Technology*, pp. 1-4, 2007.

[5] Hicham Khalife, Satyajeet Ahuja, Naceur Malouch, Marwan Krunz. "Probabilistic Path Selection in Opportunistic Cognitive Radio Networks," *Proc. of IEEE Globecom conference,* pp. 1-5, 2008.

[6] Miao Pan, Rongsheng Huang, and Yuguang Fang. "Cost Design for Opportunistic Multi-Hop Routing in Cognitive Radio Networks," *Proc. of IEEE MILCOM conferenc*e, pp. 1-7, 2008.

[7] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, and Shantidev Mohanty. "Next Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: a Survey," *Computer Networks*, vol. 50, no. 13, pp. 2127-2159, 2006.

[8] Guomei Zhu, Ian F. Akyildiz, and Gengsheng Kuo. "STOD: A Spectrum-Tree Based On-Demand Routing Protocol for Multi-hop Cognitive Radio Networks," *Proc. of IEEE Globecom conference,* pp. 1-5, 2008.

[9] Hsien-Po Shiang and Mihaela van der Schaar. "Queuing-Based Dynamic Channel Selection for Heterogeneous Multimedia Applications Over Cognitive Radio Networks," *IEEE Transactions on Multimedia*, vol. 10, no. 5, pp. 896-909, 2008.

[10] Won-Yeol Lee and Ian. F. Akyildiz. "Optimal Spectrum Sensing Framework for Cognitive Radio Networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 10, pp. 3845-3857, 2008.

[11] Wei Wang, Michael Hempel, Dongming Peng, Honggang Wang, Hamid Sharif, and Hsiao-Hwa Chen. "On Energy Efficient Encryption for Video Streaming in Wireless Sensor Networks," *IEEE Transactions on Multimedia*, vol. 12, no. 5, pp. 417-426, 2010.

[12] Tevfik Yücek and Hüseyin Arslan. "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications," *IEEE Communications Survey & Tutorials*, vol. 11, no. 1, pp. 116-130, 2009.

[13] Ying-Chang Liang, Yong-Hong Zeng, Edward C. Y. Peh, and Anh Tuan Hoang. "Sensing-Throughput Tradeoff for Cognitive Radio Networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 4, pp. 1326-1337, 2008.

[14] Norazizah Mohd Aripin, Norsheila Fisal, and Rozeha A. Rashid. "Performance Evaluation of Video Transmission Over Ultiwideband WPAN," *Proc. of 2009 Third Asia International Conference on Modeling & Simulation*, pp. 676-680.

[15] Harikeshwar Kushwaha and R. Chandramouli. "Secondary Spectrum Access With LT Codes for Delay-Constrained Applications," *Proc. of IEEE Consum. Commun. Netwok*, 2007.

[16] Danijela Čabrić, Shridhar Mubaraq Mishra, Daniel Willkomm, Robert Brodersen, and Adam Wolisz. "A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum," *Proc. of 14th IST Mobile Wireless Commun.*, 2005.

[17] Hang Su and Xi Zhang. "Opportunistic MAC Protocols for Cognitive Radio Based Wireless Networks," *Proc. of CISS 41st Annual Conference on Information Sciences and Systems*, pp. 363-368, 2007.

[18] Timo A. Weiss and Friedrich K. Jondral. "Spectrum Pooling: An Innovative Strategy for The Enhancement of Spectrum Efficiency," *IEEE Communications Magazine*, vol. 42, pp. 8-14, 2004.

[19] John Apostolopoulos, Tina Wong, Wai-Tian Tan, and Susie Wee. "On Multiple Description Streaming With Content Delivery Networks," *Proc. of IEEE INFOCOM conference*, vol. 3, pp. 1736-1745, 2002.

[20] Xin-Lin Huang, Gang Wang, Yong-Kui Ma, Cheng-Wen Zhang and Hao Jiang, "An Efficient Bit Loading Algorithm for OFDM System," *Journal of Harbin Institute of Technology*, vol. 42, no. 9, pp. 1379-1382, 2010.

[21] Dirk Hughes Hartogs and Morgan Hill, "Ensemble Modem Structure for Imperfect Transmission Media," U. S. Patent Number: 4833706(May 1989).

[22] James Kennedy and Russell Eberhart. "Particle Swarm Optimization," *Proc. of IEEE Neural Networks Conference*, vol. 1995, no. 4, pp. 1942-1948, 1995.

[23] Xin-Lin Huang, Gang Wang, Fei Hu, and Sunil Kumar, "Stability-Capacity-Oriented Routing for High Mobility, Multi-Hop Cognitive Radio Networks," *IEEE Transactions on Vehicular Technology*, submitted in August 2010.

[24] Zhijin Zhao, Shiyu Xu, Shilian Zheng, and Yangxiao Niu. "Cognitive Radio Decision Engine Based on Binary Particle Swarm Optimization," *Acta Physica Sinica*, vol. 58, no. 7, pp. 5118-5125, 2009.

[25] Yan Liu and Xue-Ping Gu. "Skeleton-Network Reconfiguration Based on Topological Characteristics of Scale-Free Networks and Discrete Particle Swarm Optimization," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 1267-1274, 2007.

[26] Please refer to: http://iphome.hhi.de/suehring/tml/.

Authors' Biographies:

Xin-Lin Huang is working for Ph.D. degree in communication engineering at Communication Research Center, Harbin Institute of Technology, Harbin, P. R. China. His research focuses on joint source-channel coding, OFDM technology and Cognitive Radio Networks. He was a recipient of Chinese Government Award for Outstanding Ph.D. Students in 2010. He is a student member of IEEE and paper reviewer for "IEEE Communications Letters", "Wireless Personal Communications", and "International Journal of Communication Systems".

Gang Wang, as professor, he is now with the Communication Research Center, Harbin Institute of Technology, Harbin, P. R. China. His general interests include joint source-channel coding, ISDN, and wireless communications. He has published over 50 research papers and four books in these fields. He was a recipient of "National Grade II Prize of Science and Technology Progress" and "National Grade III Prize of Science and Technology Progress".

Fei Hu is an associate professor in the Department of Electrical and Computer Engineering at the University of Alabama, Tuscaloosa, AL, U.S.A. His research interests are wireless networks, wireless security and their applications in Bio-Medicine. His research has been supported by NSF, Cisco, Sprint, and other sources. He obtained his first Ph.D. degree at Shanghai Tongji University, China in 1999, and second Ph.D. degree at Clarkson University, U.S.A. in 2002, all in the field of Electrical and Computer Engineering. He has published over 100 journal/conference papers and book (chapters). He is also the editor for over five international journals.

Sunil Kumar is an Associate Professor and Thomas G. Pine Faculty Fellow in the Electrical and Computer Engineering department at San Diego State University, San Diego, California, U.S.A. From August 2002 to July 2006, he was an Assistant Professor in Electrical and Computer Engineering at Clarkson University, Potsdam, NY. He received M.E. and Ph.D. in Electrical and Electronics Engineering from Birla Institute of Technology and Science, Pilani (India) in 1992 and 1997, respectively. His research interests include QoS-aware Cross-layer Protocols for Multimedia Traffic in Wireless Networks, and Robust Multimedia Compression techniques. He has published more than 95 research articles in international journals and conferences, including two book/book chapters. His research has been supported by U.S. National Science Foundation (NSF), U.S. Air Force, DOE, Cisco and Sprint.