Distributed Spectrum Sharing for Video Streaming in Cognitive Radio Ad Hoc Networks

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Abstract. A distributed joint routing and spectrum sharing algorithm for video streaming applications over cognitive radio ad hoc networks is proposed in this article. The proposed cross-layer control scheme dynamically allocates routes, spectrum and power to maximize the network throughput under the constraints posed by delay-sensitive video applications. The algorithm evaluates the expected delay of competing flows in single-hop and two-hop networks considering the time-varying spectrum condition and occupancy, traffic characteristics, and the condition of queues at intermediate nodes. Simulation results show that the proposed algorithm significantly reduces the packet loss rate and improves the average peak signal-to-noise ratio (PSNR) of the received video streams.

Key words: Cross-layer design, spectrum sharing, video streaming, cognitive radio

1 Introduction

Cognitive [1] radio [1] [2] is a promising technology to increase the utilization efficiency of the existing radio spectrum. In a cognitive radio network, users access the existing wireless spectrum opportunistically, without interfering with existing users. A key challenge in cognitive radio networks is the design of efficient *spectrum sharing* algorithms, which enable wireless devices to opportunistically access portions of the spectrum as they become available. Consequently, techniques for dynamic spectrum access have received significant attention in the last few years, e.g., [3] [4] [5] [6].

Most recent work in this area, however, has focused on infrastructure-based single-hop cognitive radio networks. Conversely, in cognitive radio networks with multi-hop communication requirements (i.e., cognitive radio ad hoc networks [7]), the dynamic nature of the radio spectrum calls for the development of novel spectrum-aware routing algorithms. Spectrum occupancy is in fact location-dependent, and therefore the available spectrum bands may be different at each relay node in a multi-hop path.

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The availability of cognitive and frequency agile devices thus motivates research on new algorithms and models to study cross-layer interactions that involve spectrum management-related functionalities, routing, and the characteristics of application-layer traffic. Recent work has started investigating cross-layer optimizations for cognitive radio networks. In [8], Hou et al. formulated a cross-layer optimization problem for a network with cognitive radios, whose objective is to minimize the required network-wide radio spectrum resource needed to support traffic for a given set of user sessions. The problem is formulated as a mixed integer non-linear problem (MINLP), and a sequential fixing (SF) algorithm is developed where the integer variables are determined iteratively via a sequence of linear programs, which provides a near-optimal solution to the original problem. However, the proposed solution is centralized, while distributed solutions are needed in ad hoc networks without centralized control, which makes joint routing and distributed spectrum allocation still a largely open problem.

In addition to this, no previous work has to the best of our knowledge investigated the interdependencies between routing, dynamic spectrum allocation, and the application-level characteristics of the traffic to be transmitted. For this reason, in this paper we concentrate on delay-sensitive applications such as real-time video streaming, where the final user needs to receive the transmitted information within a certain delay bound. This directly impacts the design of optimized communication protocols, since maximizing the network throughput, which is a reasonable objective for elastic traffic, does not necessarily lead to improved Quality of Service (QoS) in terms of video distortion with video traffic [9].

Some recent paper have investigated joint routing and dynamic channel selection [10] [11] [12] for delay-sensitive applications. However, these papers do not consider the complex issue of power control, which is jointly addressed in our work. In addition, the algorithms in these work are based on the so-called protocol model [13] in which two links either interfere destructively or do not interfere at all. Although simple, this model fails to capture the cumulative effect of interference. Conversely, our work assumes a richer interference model, which provides a comprehensive representation of radio interference. For example, it accounts for the fact that advanced transmission techniques such as code-division multiple access (CDMA) [3] [14] [15] allow concurrent co-located communications so that a message from node i to node j can be correctly received even if there is a concurrent transmission close to j.

Based on the above considerations, we propose a new cross-layer control scheme that jointly addresses the routing, dynamic spectrum assignment, scheduling and power allocation functionalities under the delay constrained imposed by stream packetized video content over cognitive radio ad hoc networks. The objective of the proposed algorithm is to allocate resources efficiently, distributively, and in a cross-layer fashion. We focus on real-time and computationally efficient spectrum allocation and routing algorithms. Our algorithm is practically and distributively implementable and provides performance guarantees. Our preliminary results show how a cross-layer solution that addresses routing and spectrum allocation jointly, and with additional delay constraints, outperforms approaches where routes are selected independently of the spectrum assignment, with moderate computational complexity.

The remainder of this paper is organized as follows. In Section 2, we introduce the system model. In Section 3, we state the problem and propose a distributed solution in detail. Section 4 presents simulation results. Finally, Section 5 concludes this paper.

2 System Model

Let the multi-hop wireless network be modeled by a directed *connectivity* graph $\mathcal{G}(\mathcal{V}, \mathcal{L})$, where $\mathcal{V} = \{v_1, ..., v_N\}$ is a finite set of wireless nodes, with $N = |\mathcal{V}|$, and $(i, j) \in \mathcal{L}$ represent a unidirectional wireless link from node v_i to node v_j (referred to also as node i and node j, respectively, for simplicity). We assume $\mathcal{G}$ is link symmetric, i.e., if $(i, j) \in \mathcal{L}$, then $(j, i) \in \mathcal{L}$. We assume that every node in the spectrum agile network is equipped with a reconfigurable transceiver and a scanner. The transceiver can tune to a set of contiguous frequency bands $[f, f + \Delta f_i]$, where Δf_i represents the bandwidth. There are F minibands for data communication in the network, denoted by the set $\mathcal{F} = \{1, 2, ..., F\}$. The bandwidth of each miniband is w. A *common control channel* (CCC) is used by all network nodes for spectrum access negotiation, and is assumed to be time slotted. Each node that has packets to send contends for spectrum access on the control channel f_{cc}, where $f_{cc} \notin \mathcal{F}$. All nodes in the network exchange local information on the common control channel.

Let the traffic demands consist of a set $\mathcal{S} = 1, 2, \cdots, S$, where $S = |\mathcal{S}|$, of unicast sessions. Each session $s \in \mathcal{S}$ is characterized by a fixed source-destination node pair. We indicate the arrival rate of session s at source node i as λ_i^s, and with $\mathbf{\Lambda}$ the vector of arrival rates. Each node maintains a separate queue for each session s for which it is either a source or an intermediate relay. At time slot t, define $Q_i^s(t)$ as the number of queued packets of session s waiting for transmission at node i.

At the application layer, the video stream is encapsulated in a sequence of video packets. We classify the video packets into unequal importance levels according to the dependencies introduced by the encoding algorithm, such as MPEG [16], H.264/AVC [17], H.264/SVC [18]. There are three basic common types of coded frames: (1) intra-coded frames (I-frames), where the frames are coded independently of all other frames; (2) predictively coded (P-frames), where the frame is coded based on a previously coded frame; and (3) bi-directionally predicted frames (B-frames), where the frame is coded using both previous and future coded frames. Each frame must be delivered and decoded by its playout time, therefore the sequence of frames has an associated sequence of deliver/decode deadlines. Any data that is lost in transmission cannot be used at the receiver. Furthermore, any data that is received after a playout deadline is useless. Specifically, any data that arrives after its decoding and display deadline is too late to be displayed. Therefore, each frame should be delivered and decoded by its playout deadline.

2.1 Prioritized Queuing

Each node maintains a separate queue for each session s for which it is either a source or an intermediate relay. Assume that for session s, there are T deadlines $\{t_1, t_2, ..., t_T\}$.

Packets with a common decoding deadline are organized into one group. Groups are put in the increasing order of their deadlines. Hence, after reorganization, we have T groups in the queue for s. Each group may contain video packets with different importance levels.

Define $Q_i^{s,P}$ as the prioritized queue value of session s waiting for transmission at node i. The prioritized queue value is calculated as follows:

$$Q_i^{s,P} = \sum_{g=1}^{T} (N_I^g \cdot W_I + N_P^g \cdot W_P) \tag{1}$$

where N_I^g and N_P^g are the number of queued I packets and P packets from group g. The values W_I and W_P represent weights that indicate quality effects of the packets, with $W_I > W_P$.

Let Q_i^s denote the actual queue size of session s at node i

$$Q_i^s = \sum_{g=1}^{T} (N_I^g + N_P^g) \tag{2}$$

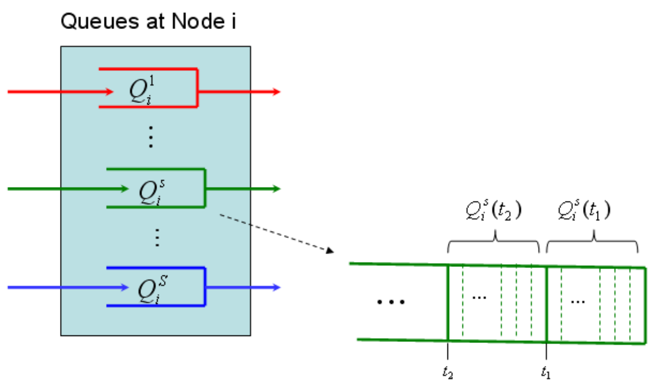
which is updated as follows:

$$Q_i^s(t+1) = Q_i^s(t) + \sum_{k \in \mathcal{V}, k \neq i} r_{ki}^s(t) - \sum_{l \in \mathcal{V}, l \neq i} r_{il}^s(t) + \lambda_i^s(t), \tag{3}$$

where r_{ij} is the transmission rate on link (i, j).

Figure 1 illustrates the queues at a node.

Fig. 1. Illustration of the prioritized queuing model.



3 Distributed Spectrum Sharing and Medium Access Control for Video Streaming

In this section, we present the distributed joint routing, spectrum sharing and medium access control scheme for secondary users in multihop cognitive radio networks. We first introduce the *spectrum sharing principle* in Section 3.1, i.e., the interference conditions under which multiple cognitive radio nodes can transmit simultaneously on the shared wireless medium. Then, we introduce the notion of *spectrum utility* in Section 3.2, i.e., the criterion based on which opportunities to transmit are assigned to different nodes competing for channel access. Opportunities to transmit and routes are selected with the objective of maximizing the *spectrum utility*. In Section 3.3 we discuss how power and channel are dynamically selected to maximize the link capacity, while in Section 3.4 we discuss how end-to-end delays can be estimated in a two-hop network to prioritize packet transmission and to make sure that packets that are expected to be received after predefined playout deadline can be dropped. Based on these considerations, in Section 3.5 we discuss a distributed cross-layer control scheme that allows secondary users to jointly control the routing, spectrum and power allocation functionalities to maximize the global spectrum utility under the delay constraints imposed by video streaming applications.

Our solution is inspired by the throughput optimality of the dynamic back-pressure algorithm [19] [20][21]. Given the system described in Section 2, the optimal routing and scheduling can be obtained by solving

$$\mathbf{R} = \arg\max_{\mathbf{R}} \sum_{i \in \mathcal{V}} \sum_{j \in \mathcal{V}, j \neq i} r_{ij} \left(Q_i^{s^*_{ij}} - Q_j^{s^*_{ij}} \right) \tag{4}$$

where

$$s^*_{ij} = \arg\max_{s} \left\{ Q_i^s - Q_j^s \right\}. \tag{5}$$

In (4) r_{ij} is the transmission rate on link (i, j). r_{ij} depends on the capacity of link (i, j) which is defined in 3.2 and can be optimized by our dynamic spectrum allocation algorithm as discussed in 3.3.

However, exact solution to (4) can be found by centralized algorithms only and, under realistic interference models, is likely to be NP-complete and difficult to achieve in a distributed system. In addition, the algorithm does not consider the characteristics of the traffic, which should not be ignored for multimedia communication. These provide the motivation of our distributed algorithm to coordinate the spectrum sharing among different users.

We concentrate on finding a solution that performs the functions of routing and spectrum assignment jointly for video streaming. Our goal is to design a cross-layer control scheme to maximize the sum of weighted differential backlogs in a distributed way, which should be easy to implement and yield high throughput.

In addition to optimize the utilization of spectrum resources on the multi-hop path, in 3.5 we show how our cross-layer scheme gives priority to the most “important” and “urgent” traffic by using the *Prioritized Queuing Model* as introduced in 2.1.

3.1 Spectrum Sharing Principle

In this section, we discuss the interference con- ditions under which multiple cognitive radio nodes can transmit simultaneously on the shared wireless medium. To share spectrum, all transmitters within the network need to

1. Satisfy minimum bit error rate (BER) requirements at the receiver;
2. Avoid interfering with ongoing communications.

The BER depends on the signal-to-interference-plus-noise power ratio (SINR) at the receiver. We indicate a mini-band by simply referring to its central frequency. Let $SINR^{th}(BER^*)$ represent the minimum SINR that guarantees a target bit error rate BER^*, and $P_i(f)$ represent the transmit power of i on f. The first constraint can be expressed by

$$\frac{P_i(f) \cdot L_{ij}(f) \cdot G}{N_j(f) + \sum_{k \in \mathcal{S}_j, k \neq i} P_k(f) L_{kj}(f)} \geq SINR^{th}(BER^*), \tag{6}$$

We can also indicate interference at node $l \in \mathcal{S}_i, l \neq j$ as $NI_l(f) + \Delta I_{il}(f)$, where $NI_l(f)$ represents noise plus interference at l before i's transmission, and $\Delta I_{il}(f)$ represents the additional interference caused at l by i's transmission, i.e., $P_i(f)L_{ik}(f)$.

The second constraint represents the fact that communications for a node $l \in \mathcal{S}_i$'s are not impaired by i's transmission. This can be expressed as

$$\frac{P_l^R(f)}{NI_l(f) + \Delta I_{il}(f)} \geq SINR^{th}(BER^*), l \in \mathcal{S}_i, l \neq j, \tag{7}$$

where $P_l^R(f)$ represents the signal power being received at receiver l. Since this has to be true for every node in the neighborhood of i, the constraint can be written as

$$P_i(f) \leq \min_{l \in \mathcal{S}_i} \frac{\Delta I_l^{max}}{L_{il}(f)} \triangleq P_i^{max}(f). \tag{8}$$

where $\Delta I_k^{max}(f) = \frac{P_l^R(f)}{SINR^{th}(BER^*)} - NI_l(f)$.

The constraint in (6) states that the SINR at receiver j needs to be above a certain threshold, which means the power received at receiver j on frequency f needs be sufficiently high to allow receiver j to successfully decode the signal given its current noise and interferences. The constraint in (8) states that the interference generated by i's transmission on each frequency should not exceed the threshold value that represents the maximum interference that can be tolerated by the most vulnerable of i's neighbors $l \in \mathcal{S}_i, l \neq j$. Hence, i's transmit power needs to be bounded on each frequency. Constraint in (6) represents a lower bound and constraint in (8) represents an upper bound on the transmit power for each frequency.

3.2 Spectrum Utility

Here, we introduce the notion of *spectrum utility*. Spectrum is selected and opportunities to transmit are assigned with the objective of maximizing the *spectrum utility*.

The control channel is time slotted. At each time slot for which node i is backlogged and not already transmitting, node i will evaluate the spectrum utility for link (i, j), defined as

$$U_{ij}^{s} = c_{ij} \cdot \left(Q_i^{s^*,P} - Q_j^{s^*}\right), \tag{9}$$

$$c_{ij}(f, P_i(f)) = \sum_{f \in [f_i, f_{i+\Delta f_i}]} w \cdot log_2 \left[1 + \frac{P_i(f) L_{ij}(f) G}{N_j(f) + I_j(f)}\right], \tag{10}$$

$$s_{ij}^{*} = \arg\max_{s} \left\{Q_i^{s,P} - Q_j^{s}\right\}, \tag{11}$$

where c_{ij} represents the achievable capacity for link (i, j) given the current spectrum condition. Note that this spectrum utility is defined for link (i, j). In (10), G is the processing gain, e.g., length of the spreading code, $L_{ij}(f)$ is the transmission losses from i to j. $P_i(f)$ represents the transmit power of i on frequency f. $I_j(f)$ represents interference at j. Finally, $N_j(f)$ is the receiver noise on frequency f.

Let $Q_i^{s,P} - Q_j^{s}$ represent the *prioritized* differential backlog of session s, and let s_{ij}^{*} represent the session that maximizes the differential backlog over all sessions $s \in S$. Data of session $s{*}_{ij}$ is selected to be routed from node i to node j. The route for each group of packets is found dynamically according to the maximum prioritized differential backlog policy. The differential backlog algorithm stabilizes the system by making use of backpressure [19], where data finds its way to the destination by moving in the direction of least resistance while being pushed by newly arriving data. Our proposed algorithm thus uses modified backpressure to find an optimal routing. Note that, by using $Q_i^{s,P}$ instead of Q_i^{s}, sessions that have more "important" packets backlogged, i.e., packets from I-frame, have higher value of $Q_i^{s,P}$ and thus have higher probability to be transmitted. We emphasize that our proposed *prioritized* differential backlog gives priority to the most "important" data. In such a way, traffic characteristics are considered in routing and scheduling as discussed in the following subsections.

3.3 Dynamic Spectrum Allocation

In this section, we discuss how power and channel are dynamically selected to maximize the link capacity. In spectrum agile networks local spectrum resources may change from time to time, hence link capacity is time-varying and can be maximized through spectrum allocation. Maximizing the capacity of link (i, j) means selecting a spectrum band and the corresponding transmit power on each mini-band to maximize the Shannon capacity without interfering with ongoing communications.

$$\begin{aligned} Given: &\; BER^{*}, P_k(\,\forall k \in \mathcal{S}_i),\; L_{ij},\;\; \forall (i,j) \in \mathcal{E} \\ Find: &\; [f_i, f_{i+\Delta f_i}, P_i(f)] \\ Maximize: &\; c_{ij} \\ Subject\,to: & \end{aligned} \tag{12}$$

$$P_i^{min}(f) \le P_i(f) \le P_i^{max}(f), \; \forall\, f \in [f_i, f_{i+\Delta f_i}]; \tag{13}$$

$$\sum_{f \in [f_i, f_{i+\Delta f_i}]} P_i(f) \le P_i^{Bgt}. \tag{14}$$

where $P_i^{max}(f)$ is defined in (8) and $P_i^{min}(f)$ is the value of $P_i(f)$ for which equality in (6) holds. In (14), P_i^{Bgt} represents the instantaneous power available at the cognitive radio.

The objective of the problem above is to select spectrum and power with maximal capacity, given spectrum condition and hardware limitations of the cognitive radio. Note that constraint (13) imposes the spectrum sharing principle, and constraint (14) indicates the hardware restrictions. We have developed an iterative gradient-descent based algorithm to solve the above problem, which is discussed in detail in [22].

3.4 Delay Estimation

Expected delays are important for video applications due to their delay-sensitivity nature. For video applications, any data that is received after a playout deadline is useless since it is too late to be displayed. Therefore, evaluating the expected delay of the data is important to avoid transmitting useless data. In our proposed scheme, any packet that exceeds a predetermined playout deadline will be dropped before scheduling.

In this section, we show how to calculate expected delays for single-hop and two-hop routing networks.

Consider group g scheduled for transmission on link (i, j), the average delay X_{ij}^g consists of the average transmission delay $E[D_{ij}^{g,TX}]$ and average queuing delay $E[D_i^{g,Q}]$ experienced by the node i

$$X_{ij}^g = E[D_{ij}^{g,TX}] + E[D_i^{g,Q}]. \tag{15}$$

Given physical transmission rate r_{ij}, the expected transmission time for groups containing packets with equal packet size L may be computed as

$$E[D_{ij}^{g,TX}] = \frac{(N_I^g + N_P^g) \cdot L}{r_{ij}} + E[D_{ij}^{g,O}] \tag{16}$$

where $E[D_{ij}^{g,O}]$, defined in (17), is the delay caused by overhead of the MAC protocol, including expected backoff delay, acknowledgement time and duration of empty slots. Note that here we do not employ retransmission in our MAC protocol.

$$E[D_{ij}^{g,O}] = E[BC_{ij}] + T_{hs} \tag{17}$$

where $T_h s$ is handshake time which consists of DIFS, SIFS, and control packets (RTS/CTS/DTS) transmission time.

At each packet transmission, the backoff time is uniformly chosen in the range $(0, 2^{CW-1})$. The value CW decreases when U_{ij}^s increases. The backoff time counter decreases when the control channel is sensed idle, frozen when a transmission is detected on the control channel, and reactivated when the control channel is sensed idle again for more than a DIFS. The transmission is triggered when the backoff counter reaches zero. With this mechanism, heavily backlogged queues (i.e., containing more important packets) with more spectrum resources are given higher probability of transmission.

Since the groups wait in the queue and are transmitted based on their deadlines, we have

$$E[D_i^{g,Q}] = \sum_{n=1}^{N_g} X^n \tag{18}$$

where N_g is the number of groups already in queue, and their deadlines are earlier.

Consider a two-hop transmission, i.e., from source node i to destination node k with relay node j. We may estimate the end-to-end delay for group g as

$$D_{ik}^g = X_{ij}^g + X_{jk}^g. \tag{19}$$

We assume that information about link (i, j) and queue size at j is known, which means X_{ij}^g can be estimated. Note that above delay is estimated at node i, where information about link (j, k) may not be available. We assume that j has a record of the average transmission rates for different receivers based on past record of transmissions, i.e., $E[r_{jk}]$ So X_{jk}^g may be computed as

$$X_{jk}^g = \frac{(N_I^g + N_P^g) \cdot L}{E[r_{jk}]} + E[D_{jk}^{g,O}] \tag{20}$$

where $E[D_{jk}^{g,O}]$ depends on $E[U_{jk}^s]$. Since k is the destination, we may estimate U_{jk}^s as

$$E[U_{jk}^s] = E[r_{jk}] \cdot Q_j^{s,P}. \tag{21}$$

3.5 Proposed Cross-Layer Control Scheme

We now present the proposed cross-layer control scheme, which dynamically utilizes available spectrum for video streaming in multihop wireless networks.

Every backlogged node, once it senses an idle common control channel, performs the following algorithm:

1. Find the set of feasible next hops $\mathcal{N}^s = \{n_1^s, n_2^s, ..., n_k^s\}$ for the backlogged session s. Feasible next hops are the neighbors with positive advance towards the destination of s and can relay the packets to the destination before their deadlines. Node n has *positive advance* with respect to i iff n is closer to the destination than i.
2. For each link (i, j), where $j \in \mathcal{N}^s$, find $[f_i, f_i + \Delta f_i]$ such that

$$[f_i, f_{i+\Delta f_i}, P_i(f)] = \arg\max c_{ij} \tag{22}$$

3. Select s^* with next hop j^*, which has maximum U_{ij}^s.

$$[s^*, j^*] = \arg\max \left\{ U_{ij}^{s_{ij}^*} \right\} \tag{23}$$

Estimate the delay for the first waiting group, if the delay cannot satisfy the playout delay, drop this group and schedule the next group. Note that U_{ij}^{s} defined in (9) depends on both the capacity and the differential backlog of link (i, j). Hence, routing is performed in such a way that heavily backlogged queues with more spectrum resource have higher probability of transmitting.

4. Once spectrum allocation, session and next hop are determined, the probability of accessing the medium is calculated based on the value of U_{ij}^{s}. Nodes with higher U_{ij}^{s} will get a higher probability of accessing the medium and transmit. This probability is implemented through the contention window at MAC layer. The transmitting node generates a backoff counter chosen uniformly from the range $[0, 2^{CW-1}]$, where CW is the contention window, whose value decreases when U_{ij}^{s} increases. With this mechanism, heavily backlogged queues with more spectrum resources are given higher probability of transmission.

As discussed in Section 2.1, packets with a common decoding deadline are organized into a common group. The algorithm first estimates the delay for the first waiting group. If the delay cannot satisfy the playout deadline, it drops this group of packets and schedules the next group.

To efficiently manage available spectrum resources in a decentralized manner, information exchange among users is necessary and important. As discussed earlier, we assume that each node is equipped with two transceivers, one of which is a reconfigurable transceiver that can dynamically adjust its waveform and bandwidth for data transmission. The other is a conventional transceiver employed on the common control channel. Scanner-equipped cognitive radios can detect neighboring transmissions by sensing the data channel. Environment learning can be achieved by combining scanning results and information from control packets exchanged on the control channel that contain info about transmissions and power used on different minibands. A medium access control protocol on the common control channel arbitrates channel access, as described in detail in [22] .

4 Performance Evaluation

In this section, we analyze the performance of the proposed scheme in a multi-hop cognitive radio network, and compare it to the performance of other schemes. We concentrate on video streaming applications with predefined delay constraints and evaluate delay, reliability, and perceived video distortion with real video traces.

We consider one typical Common Intermediate Format (CIF) video sequence (Highway) under the simulation conditions reported in Table 1.

Figure 2 shows the data rate delivered by $1\,\mathrm{MHz}$ of spectrum as a function of the SINR. This represents a stepwise approximation of (10), which can model, among others, different modulation schemes available for different $SINR$ values.

We compare the performance of our proposed scheme with two alternative schemes. In particular, we consider Routing with Fixed Allocation (RFA) as the solution where routing is based on differential backlog with pre-defined channel and transmit power, and to Routing with Dynamic Allocation (RDA) as the solution where routing is based

Table 1. PARAMETERS FOR VIDEO SIMULATION

Area	3000m x 3000m	Video Sequence	"Highway"
Number of Nodes	9	playout Deadline	500 ms
Data Channel Bandwidth	54-57 MHz	Frames/sec	30
Bandwidth per Mini-band	500 KHz	Packet Size	500 bytes
Bandwidth of Control Channel	2 MHz	Number of Active Sessions	2

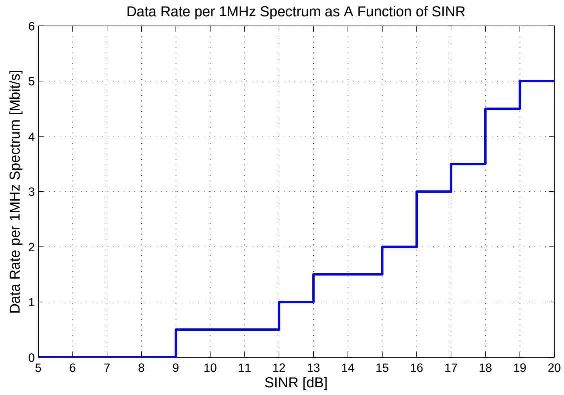


Fig. 2. Data Rate per 1MHz Spectrum as A Function of SINR.

on shortest path with dynamic channel selection and transmit power allocation without considering differential backlog.

Table 2 shows the average delay and the percentage of packets that are either lost, or exceed the playout deadline (*late* packets). The results show that the video streams of RFA and RDA have more late packets, which decreases the received video quality.

Table 2. COMPARISONS FOR VIDEO STREAMING APPLICATIONS

	ROSA-PQM			RDA			RFA		
	Late Packet Rate	Average Delay (ms)	Average PSNR (dB)	Late Packet Rate	Average Delay (ms)	Average PSNR (dB)	Late Packet Rate	Average Delay (ms)	Average PSNR (dB)
Session1	0.01%	6.76	39.07	2.09%	194.82	28.66	29.30%	438.11	26.87
Session2	0.01%	15.39	39.07	7.53%	271.87	30.70	48.28%	898.43	22.79

To verify this claim, we evaluated the distortion of the received video stream, by interfacing our simulator with a video quality assessment tool that we developed in Matlab. We define distortion in terms of the average peak signal-to-noise ratio (PSNR) of the received video. Since we are interested in the amount of distortion introduced by the video transmission, we use the difference between the PSNR actually obtained from the video transmission scheme and the best possible PSNR obtainable from the technology (i.e. no packets are lost and the highest possible rate MPEG encoder is used to encode the video frames). PSNR is defined as

$$PSNR = 10 \cdot \log_{10} \left(\frac{MAX_I^2}{MSE} \right), \quad (24)$$

where MAX_I is the maximum possible pixel value for each frame. MSE is the mean squared error, which is defined as

$$MSE = \frac{1}{mn} \sum_{i=1}^{m-1} \sum_{j=1}^{n-1} \| I(i,j) - K(i,j) \|^2 \quad (25)$$

for any two $m \, \mathrm{x} \, n$ images I and K where one of the images can be considered to be a noisy approximation of the other. To extend this to video distortion rather than image distortion, we take the PSNR measurement for each frame and average over all of the frames in the video. For any frames that are dropped or unable to be decoded at the receiver, the previous frame in the received video is measured against the current frame in the "good" video (i.e. the video before it was transmitted) and this value is used in the average. Our proposed scheme is shown to outperform the other two algorithms of approximately $10 \, dB$, which has a considerable impact on the perceived visual quality.

5 Conclusions

We discussed a distributed spectrum sharing algorithm for video streaming in cognitive radio ad hoc networks, focusing on multimedia applications with varying traffic characteristics and delay deadlines. The proposed cross-layer control scheme dynamically allocates routes, spectrum and power to maximize the network throughput under the constraints posed by delay-sensitive video applications. The algorithm evaluates the expected delay of competing flows in single-hop and two-hop networks considering the time-varying spectrum condition and occupancy, trafc characteristics, and the condition of queues at intermediate nodes. Through discrete-event simulation, our proposed scheme was shown to outperform simpler solutions for video streaming services in terms of video distortion.

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