Resource Allocation with Minimum End-to-End Delay Differential Consideration in Multi-hop Cognitive Radio Networks

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Abstract. In cognitive radio networks, devices can dynamically sense, negotiate, and switch to available spectral bands so as to enhance spectrum utilization. The available spectral resource may vary with time, location, and spectral bands. This leads to many implementation difficulties, and one especially challenging one is how to fairly allocate these resources for multiple concurrent transmission flows in a multi-hop wireless environment. In this paper, we attempt to minimize the maximum end-to-end delay differential among all multi-hop flows within interference range. Flows within the same interference range may be on different routing paths with different network conditions such as hop count, network load and primary user's behavior in previous hops. Determining how to fairly allocate resources to flows within the same interference range among a disjoint set of spectral bands in terms of minimal end-to-end delay differential becomes an important issue. We consider the accumulated delays (including sensing and negotiating delay, and queuing delay) up to this hop, and the rates of channel error and primary-user interruption on different bands. We then adopt four approximation schemes to solve this problem. The simulation results show that the average end-to-end delay differential with our proposed algorithms for all flows is minimized.

Keywords: Cognitive radio networks, delay differential, negotiation, priority, resource allocation, spectral bands.

1 Introduction

Cognitive radio (CR) is the technology that allows secondary users (SUs) to use the radio spectrum unoccupied by primary users (PUs) [1] [2]. With CR, unused spectral bands in existing wireless networks can be better utilized. To avoid affecting the operation of PUs, SUs should keep sensing channels and switch to other available spectrum holes when PUs appear on the channel. The available

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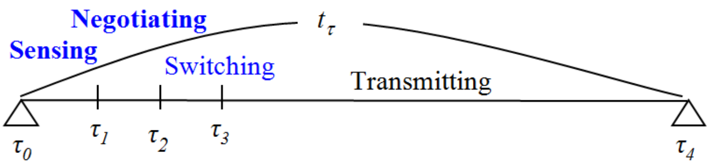

Fig. 1. A general operating cycle for a CRN

spectrum holes refer to the spectral bands such that 1) no PUs are present or currently using them, 2) SUs are free to use them, and 3) the transmission between two SUs will not affect the normal operation of PUs on neighboring links [3]. Since the presence behavior of PUs may vary with time, location, and different radio technology, the available spectral band set available for each SU may also vary. Moreover, for a certain SU node, the characteristics of the channels in the associated available spectral band set may also be different. The important factors that affect the channels include link error rate, PU interruption rate (due to its presence on the link), link length (or equivalently, transmission range and interference range), and the delay in the queue.

To send data on a channel, SUs need to search for available spectral bands to form a spectral channel. As shown in Figure 1, SUs follow an operation cycle with sensing, negotiating, switching, and transmitting [3]. In each cycle, the amount of resources used for transmission depends on: 1) sensing period ($\tau_0 - \tau_1$): the time used to sense and obtain unoccupied spectral bands; 2) negotiating period ($\tau_1 - \tau_2$): the time used to negotiate sensed free spectral bands with neighboring SUs; and 3) switching period ($\tau_2 - \tau_3$): the time used to switch to another spectral channel formed by a different subset of spectral bands. The sensing range is the area within which SUs are able to detect whether or not any PU sends signal on a spectral band. Even though a CR is able to sense in a large area (e.g., 1 km^3), the sensed free spectral bands, which are out of the transmission range (e.g., 100 m^3), may not be available for current transmissions. In addition, the time is too short to sense for longer range. Thus, we treat the effect of the sensing range as equivalent to that of the interference range. This leads to the effect that the negotiation range is equivalent to the sensing range with the same reasons, i.e., 1) out-of-range sensing result messages require longer path transmission; 2) out-of-range free spectral bands may not be available for SUs within the transmission range, and 3) out-of-range SUs which adopt the same spectral bands for transmission will not affect the SUs within the interference range. Therefore, the effects of sensing range and negotiation range in this work are limited to the interference range.

In general, the transmission range determines the interference range. A node which can reach its next hop nodes to form a set of links is initialized by the maximum transmission range, but the range of some links may be less than the maximum transmission range. The link range is determined by the required signal strength for the link nodes to communicate with each other. Accordingly, the sensing and negotiation ranges for each link are also determined.

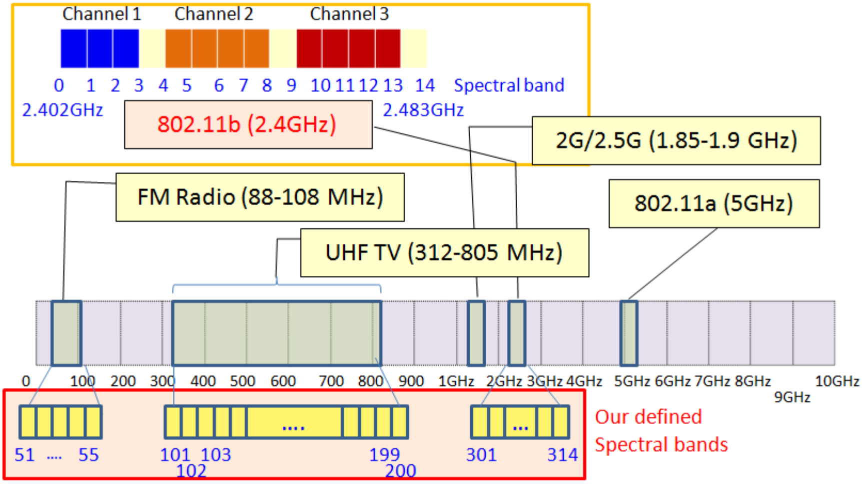

Fig. 2. The defined spectral bands marked with a serial number

The trade-off between the transmission range and the amount of available resources must be balanced. If a CR node chooses a longer link (i.e., a larger transmission range), the number of spectral bands and available duration decrease because it may need to wait for more PUs to release the spectral bands within the sensing range. In addition, the sensing range is determined by the sensing time and the capability of a CR device. The faster the sensing time, the shorter the sensing ranges. Therefore, the transmission range and the sensing range are both controlled to enlarge the amount of available spectral bands and transmission time with a reasonable sensing time.

A spectral band is the basic unit to model wireless transmission resource. The pool of spectral bands is marked with a set of numbers from 1 to M, where $|M|$ is the total number of spectral bands, as shown in Figure 2. Then, one to multiple bands are moderated as a spectral channel. For example, four spectral bands form one channel in IEEE 802.11 wireless standard [4]. When PUs in an area do not use channels 1 and 2 (which cover frequency bands $0-3$ and $4-8$, respectively), frequency bands 0 to 8 are available for use by SUs in that area. Then, each link can adopt one or more channels for transmissions.

In this paper, we will explore the resource allocation problem in multi-hop cognitive radio network with quality-of-service guarantees. We consider that each flow in the CR network has an end-to-end delay constraint. Then, we would like to design an efficient spectrum sharing mechanism among flows such that the maximum end-to-end delay for each flow is within its tolerance. We suppose that the routing path for each flow is given, and the presence behavior of PUs on a channel follows a certain distribution. The transmission time over each link on the path may be affected by many factors, including the PU presence behavior and the link condition (e.g., link error rate, link length, and wireless interference). The higher the PU interruption rate, the longer the packets must wait in the outgoing queue and the longer the packet delay. For each node, the number of flows passing through may not be identical, and the routing path (together with the accumulated delay up to this node) of each flow may also be different. Moreover, the number of hops and the link condition on the remaining path to be traversed by each flow may also be different. Our problem is then to determine an efficient resource allocation scheme to ensure the delay requirement of each flow is satisfied. We take into account the elapse time of each flow has been traversed and its remaining until the deadline in our allocation problem.

To tackle this problem, we introduce the concept of delay differential (denoted by d_ρ), which is defined as the difference between the packet delay and the maximum tolerable delay at the current hop for packet ρ. The packet delay here includes all possible delay components incurred at this hop, including the nodal delay, the queuing delay, and the transmission time. The average per-hop tolerable delay is approximated by the maximum tolerable end-to-end delay divided by the number of hops on the path that a flow traverses to reach its destination. Thus, the maximum tolerable delay at the kth hop for an n-hop path is then expressed by $D - h \times (k + 1)$, where D is the maximum end-to-end tolerable delay for this flow, and h is the per-hop tolerable delay (i.e., D/n). The smaller the delay differential, the longer the waiting time that the packet can tolerate at this hop without missing the deadline. A negative delay differential indicates that the packet may have experienced harsh path condition in previous hops and/or may have more hops to travel on the remaining path so that it should be allocated spectral bands with priority in order not to miss the deadline. A path with larger hop count tends to be more sensitive to small delay differentials. In other words, a longer path needs to be allocated resource with higher priority at each hop; otherwise, the deadline may be missed with a higher probability. This differential value is carried in each packet header, and the delay differential of each packet to the current node can be used as an indicator for scheduling. In this way, for each out-going link, the delay differential values of all flows in the interference range can be minimized.

Figure 3 shows an example of two flows with a maximum end-to-end tolerable delay of $D = 500$ unit time. Flow 1 is routed via path $\{o, a, c, e, g\}$, and Flow 2, via path $\{b, c, d, f\}$. For Flow 1, there are five nodes to traverse, and the accumulated tolerable delay at node c (i.e., via link (c, e) to node e) is $h_{1c} = 300$. For Flow 2, the accumulated tolerable delay at node c (via link (c, d) to node d) is $h_{2c} = 250$. Suppose that a packet x for Flow 1 is queued on the outgoing link (c, e) with a packet delay of 225, so its delay differential is $d_x = -75$. Similarly, for packet y of Flow 2 queued on link (c, d) with a packet delay of 275, its delay differential is $d_y = 25$. In this case, packet y is more likely to miss the deadline when it reaches the destination due to 1) having experienced more harsh path conditions in previous hops, and/or 2) having to travel more remaining hops to reach its destination. Therefore, Flow 2 should be scheduled with priority for transmission.

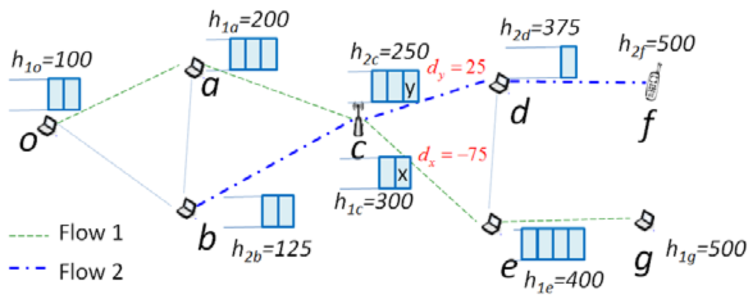

Fig. 3. An example illustrating the delay differential concept

The number of available spectral bands varies with different time and locations. The basic idea of our method is that the packet with larger delay differential has higher priority for spectral allocation, resulting in less available spectral bands for its neighbors. In other words, a transmission pair of nodes negotiating for more spectral bands can moderate higher bit-rate, which means more queued packets can be sent to the next hop in this cycle time so that the aggregated delay differential is decreased in the next hop.

The main contribution of this work is to allocate available spectral bands for CR network with minimal end-to-end delay guarantees by the following mechanisms:

– **Local resource allocation to achieve global load balancing.** We consider the effect of the sensing and negotiation range within the interference range, which is determined by the transmission range. We then introduce the concept of delay differential as the local fairness metric, and a distributed algorithm to ensure end-to-end delay fairness.
– **Four approximation schemes for proportional allocation under different CR network conditions.** The proportional resource allocation is designed according to CR network conditions, such as the queue size, delay differential, and PU interruption rate to approximate the delay differential fairness among the flows such that the relative importance of such attributes are properly requested.
– **Packet level performance evaluation to achieve flow level load balancing.** The basic unit of our model and performance evaluation is the packet. The flow transmission load balancing is achieved by packet fairness scheduling within interference range. In this way, the delay differential caused by various CR network conditions is balanced hop-by-hop for each packet to achieve end-to-end flow fairness.

The rest of the paper is organized as follows. In Section 2, the network model and problem are described. In Section 3, the proposed allocation schemes and evaluation algorithm are presented. In Section 4, the simulation results and related discussions are shown. Finally, this paper is concluded in Section 5.

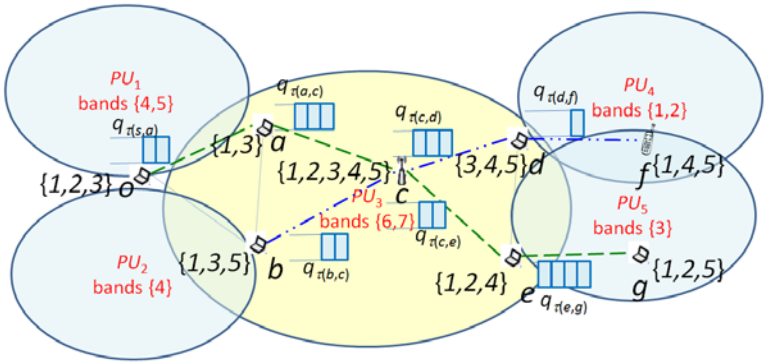

Fig. 4. The network model of our problem

2 Network Model and Problem Description

2.1 Network Architecture

The network is modeled as a connected graph $G(V, L)$, where V represents a set of nodes in the network, L is a set of links (u, v) such that nodes u and v are within the transmission range of each other. The node set V contains two subsets V_{SU} and V_{PU} for SU nodes and PU nodes, respectively. Each node $v \in V_{SU}$ is static and associated with a finite buffer for each CR and each link $(u, v) \in L$ has a capacity $c_{\tau(u,v)}$ at time τ. For each node $v \in V_{PU}$, the wireless technology employed by node v will determine its transmission range and the allocated set of spectral channels. In this work, the routing path for each flow is given so that each node has to maintain a table or cache for transmission to its next hop node. As such, the interference (negotiation) range can be obtained. The link (u, v) may not be connected if there is no available spectral band for the link. For example, Figure 4 shows an 8-node CR network with two flows over two paths $\{o, a, c, e, g\}$ and $\{b, c, d, f\}$, respectively. The transmission range of each link is based on the link length at each time slot τ. There are no available spectrum bands for link (b, c) because the set of spectral bands $\{1, 3, 5\}$ has been allocated to links (a, c) and (c, d).

2.2 Spectral Band Pool

The sensed spectral bands within a CR pool are numbered to represent a series of spectral bands. Several available spectral bands can be formed as a spectral channel. Suppose that there are $|M|$ spectral bands in a CR network. Let $M_{\tau v}$ denote the set of available spectral bands sensed and obtained by node v at time τ. Each available spectral band $m \in M_{\tau v}$, where $v \in V_{SU}$ and $\tau \in T$, can be moderated bandwidth b_m under the Signal to Noise Ratio (SNR) limitation. A spectral band m is "available" for a link (u, v) if 1) the spectral band is currently not in use by PUs located within the interference range of the link,

2) the transmission range r_m of the link using this band can cover both nodes u and v, and 3) the duration tm available for the transmission over the link is sufficiently long. Once the conditions $t^*_m = \min\{t_m\}$ and $r^*_m = \min\{r_m\}$, $\forall m \in M_{\tau v}, v \in V_{SU}, \tau \in T$, are satisfied for a subset of spectral bands, the intersection of these subsets of available spectral bands, denoted by $M_{\tau(u,v)}$, are selected for link (u, v) [3]. For example, suppose the two sets of spectral bands $M_{\tau o} = \{1, 2, 3\}$ and $M_{\tau a} = \{1, 3\}$ satisfy the transmission range and duration limitations indicated above. Then, the only common spectrum band both link nodes o and a can select for transmission at time slot is $M_{\tau(o,a)} = \{1\}$, because spectral band $\{3\}$ has been assigned to link (a, c).

2.3 Link-Based Interference Model

If a pair of nodes on link (u, v) selects a common set of available spectral bands for transmission, they have to adjust their transmission power based on the distance between nodes u and v in order to avoid interference with PUs and other SUs. With the interference consideration, the channel capacity for each transmission link is calculated based on the negotiated spectral bands, error rates, and interferences [5] [6]. Since each receiving node must reply with an ACK for a successful transmission, any sender, even those located near its receiver, cannot send or receive data on the same spectral bands at the same time. Without proper coordination, this operation may result in collisions and data retransmissions, which may degrade the performance. Therefore, the interference range should cover a two-hop distance from the sender or receiver when allocating a disjoint set of spectral bands for link (u, v). In other words, the range is equivalent to the negotiation range in which the neighboring SUs within the range should exchange and contend for resource with each other.

In contrast to the node-based interference model [7], which assumes a local resource at each intermediate node for each flow, we consider how to allocate available spectral bands within an interference range of a link in order to create simultaneous multi-flow transmissions. The model in [8] uses the link-based interference model and describes interference constraints as a conflict graph.

Consider nodes u and v for link (u, v) $(u, v \in V_{SU})$. The received power $P_r(v) = P_t(u)L(l_{(u,v)})$, where $P_t(u)$ is the sending power, and $L(l_{(u,v)})$, the degradation function of link length $l_{(u,v)}$ at node v, has to exceed a threshold so as to correctly receive a data packet from sender u. Hence, we have $SNR_{(u,v)} \geq \theta_v$, where $SNR_{(u,v)} = P_t(u)L(l_{(u,v)})/\sigma$ is the SNR of the wireless link (u, v), with σ being a constant and θ_v being the SNR threshold for a node to correctly decode a signal. The transmission range r_m of sender u $(\forall m \in M_{\tau u}, u \in V_{SU}, \tau \in T)$ is the longest distance from node v that node u's data packets can be correctly decoded and can be determined once the transmission power $P_t(u)$ of node u and θ_u are given. For a multi-hop CR network, multiple pairs of nodes may transmit data packets simultaneously. In addition to thermal noise, the transmission from node u to node v may be interfered by other concurrent transmitters. Let $K_{(u,v)}$ denote the set of concurrent transmitters within the interference range of link (u, v). The Signal to Interference Ratio (SIR) for link (u, v) defined in [9] can be expressed by (1). Namely, for node v to receive a data unit from node u correctly, the $SNR_{\tau(u,v)}$ value of link (u, v) must exceed the threshold θ_v at time τ, i.e.,

$$SIR_{\tau(u,v)} = \frac{P_t(u)L(l_{(u,v)})}{\sum\limits_{k\in K}\left[P_t(k)\left(L(l_{(k,u)}) + L(l_{(k,v)})\right)\right] + \sigma}, \forall(u, v) \in L, \tau \in T \quad (1)$$

In this model, we assume that each node $v \in V_{SU}$ has an SNR threshold θ_v, which must be satisfied in order to have successful reception of one data unit from a transmitter. The SIR threshold β_v, provided that $\theta_v > \beta_v$, is also given so as to guarantee correct signal decoding when concurrent transmissions are performed. Based on Shannon's theorem [10], the supportable bit rate of any communication link incident to this node is guaranteed to be at least $c_u = b_m log_2(1+\beta_u)$, where b_m is the bandwidth of a spectral band m. Only when the SIR of the received signal is smaller than β_u, can the supportable bit rate of this node be assumed to be zero and hence the communication is prohibited for this wireless link.

Let $P_{max}(u)$ denote the maximum transmission power of node u. Suppose that each node u can adjust its transmission power $P_t(u)$, $0 \leq P_t(u) \leq P_{max}(u)$, such that the signal power of the receiver node v is slightly higher than $\theta_v \times \sigma$. Then, the maximum supportable bit rate of a wireless link incident to node v is given by $c_{v,\max} = B_v \log_2(1+\theta_v)$, provided that there is no interference from the neighboring nodes. The maximum interference budget B_v that a node can sustain to correctly decode the signal from the transmitter is given by $B_v = (\theta_v \times \sigma/\beta_v)-\sigma$. For a certain node k, the interference caused by another concurrent transmission from node u to node v, denoted by $I_{(u,v)k}$, can be expressed by:

$$\begin{aligned} I_{(u,v)k} &= \frac{P_t(u)\times L(l_{uk})+P_t(v)\times L(l_{vk})}{B_k} \\ &= \frac{L(l_{uk})\cdot\theta_k\cdot\beta_k+L(l_{vk})\cdot\theta_k\cdot\beta_k}{L(l_{uv})\cdot(\theta_k-\beta_k)}, \forall(u, v) \in L, k \in V \end{aligned} \quad (2)$$

Let I_{mk} denote the interference indicator for the communications performed among the set of contending nodes of node k on spectral band m at time slot τ, $\forall m \in M_{\tau(u,v)}, (u, v) \in L, k \in K_{(u,v)} \in V_{SU}, \tau \in T$. Binary variable $I_{mk} = 1$ if node k interferes with the transmission from node u to node v on spectral band m at time τ; otherwise, $I_{mk} = 0$. The set of nodes which renders the interference ratio $|I_{mk}| \geq 1$ is called the set of contending nodes for node v. Transmissions from a contending node will drop the supportable bit rate of node v to zero and will prohibit node k from accessing the wireless medium.

The interference model is dependent on the signal strength of a pair of transceivers. Only one pair of nodes can select spectral band m within the interference range of the considered link. The question is how to determine the interference range. The interference range of a link is not fully dependent on the distance between two nodes. Instead, it is affected by the transmission range of the selected spectral bands. Thus, given the transmission range for each intended transceiver pair, the interference range is the transmission range when node k reaches node u or v. Therefore, it can be expressed by (3).

$$\begin{cases} \frac{\left(r_m - l_{\tau(k,u)}\right)}{N} \leq I_{mk}, \\ \forall m = n, m \in M_{\tau(u,v)}, n \in M_{\tau(k,j)}, (u,v) \in L, (k,j) \in L, \tau \in T \\ \frac{\left(r_m - l_{\tau(k,v)}\right)}{N} \leq I_{mk}, \\ \forall m = n, m \in M_{\tau(u,v)}, n \in M_{\tau(k,j)}, (u,v) \in L, (k,j) \in L, \tau \in T. \end{cases} \quad (3)$$

2.4 Problem Description

In this problem, each SU has a minimum requirement of bit-rates in term of SNR (or equivalently, bit error rate (BER)), under the minimum transmission duration (t_m) and transmission range (r_m). Our goal is to minimize the maximum delay differential d_ρ among the transmitting packet $\rho \in P$ within the interference (negotiation) area at a specific cycle time $\pi \in T$. The objective function of this min-max problem is formulated by (4).

$$\min \max_{\rho} d_\rho \quad (4)$$

$$\text{where } d_\rho = \sum_{\tau \in \pi} \sum_{u \in V_{SU}} \phi_{\tau\rho u} t_\tau - \sum_{u \in V_{SU}} \phi_{\pi\rho u} h_{su}, \forall \rho \in P, \pi \in T, s \in S. \quad (5)$$

The first term in (5), i.e., $\sum_{\tau \in \pi} \sum_{u \in V_{SU}} \phi_{\tau\rho u} t_\tau$, aggregates the transmission cycle time t_τ with a decision variable $\phi_{\tau\rho u}$ to determine whether or not a packet ρ is stored on node u at time τ, because each packet can only stay in a node for each cycle time. Each cycle time includes the total transmission delay and nodal delay from the source node to the outgoing node located within the considered interference range (i.e., negotiation range). The nodal delay includes sensing, negotiating, selecting, and switching delays to periodically execute the exchange of spectral bands for each CR. The transmission delay is calculated based on the packet delay differential, queue size and allocated spectral bands. So we can aggregate the packet delay from cycle 0 to current time π with variable $\phi_{\tau\rho u}$ to indicate the number of cycle times that packet ρ has experienced. The second term $\sum_{u \in V_{SU}} \phi_{\pi\rho u} h_{su}$ obtains the maximum tolerable delay h_{su} for a packet ρ to stay at node u at the current time π for flow s with decision variable $\phi_{\tau\rho u}$. So the difference between packets delays and current maximum tolerable delay is calculated for each packet ρ as a delay differential d_ρ.

3 Solution Approach

To minimize the maximum delay differential within the interference range of the considered link by a greedy method, the available spectral bands are allocated to these packets with maximum delay differential within the current time slot with the highest priority. The problem is how much resource should be allocated to flows such that the delay differentials among the flows are balanced. In other words, we have to determine the link to which common available spectral band is assigned to optimally utilize the resources. This problem is NP-hard. Thus, we propose some approximation schemes to find a near-optimal solution.

Each node maintains a spectrum band pool in which the conditions of each spectral band are recorded. If there are no packets to be transmitted on a link between two nodes, they will cooperatively sense available spectral bands on the neighboring links. Once a node has a packet to transmit, they will sense and negotiate with neighboring nodes for available spectral bands. In this paper, we propose four schemes to determine the proportion $x_{\tau(u,v)}$ of allocated bands. The schemes to allocate available spectral bands to minimize transmission delay differential are described as follows:

- Equivalent amount of available spectral bands (EQU): In addition to the available bands which are sensed available only for a CR, but not available for others, it contends with other nodes based on the weight of spectral bands to obtain equivalent amount of available spectral bands based on the negotiation message:

$$x_{\tau(u,v)} = \frac{1}{\sum\limits_{(i,j)\in L} (I_{(u,v)i} \cdot y_{s(i,j)})}, \forall (u,v) \in L, s \in S, \tau \in T \tag{6}$$

  where $y_{s(i,j)}$ is the indicator that link (i,j) is on the path for flow $s \in S$.
- Proportional Queue-size allocation (QS): To negotiate the available spectral bands in line with the proportion of current queue size, which is denoted by $z_{\tau(u,v)}$, i.e., the queue size of outgoing link (u,v) at time τ, divided by the summation of queue sizes within the interference range, each CR selects the available bands based on the proportion:

$$x_{\tau(u,v)} = \frac{z_{\tau(u,v)}}{\sum\limits_{(i,j)\in L} I_{(u,v)k} \cdot z_{\tau(i,j)}}, \forall (u,v) \in L, k \in V_{SU}, \tau \in T \tag{7}$$

- Weighted delay-differential (WDD): In this scheme, each CR node negotiates the proportion of available bands based on the weight of accumulated delay differential of all other nodes within the interference range:

$$x_{\tau(u,v)} = \frac{\sum\limits_{\rho\in q_{\tau(u,v)}} d_\rho}{\sum\limits_{\rho\in q_{\tau(i,j)}} d_\rho I_{(u,v)i}}, \forall (u,v) \in L, (i,j) \in L, \tau \in T \tag{8}$$

  where $q_{\tau(u,v)}$ denotes the set of packets ρ stored in the queue of the outgoing link (u,v) at time τ.
- Weighted delay-differential with the rate of interruption (WDDI): Similar to the previous three schemes to obtain the proportion of available frequency bands, the main idea of this scheme is to design the proportion based on the weight of the delay differential of all queued packets discounted by the rate of PU interruption:

$$x_{\tau(u,v)} = \frac{\sum\limits_{\rho\in q_{\tau(u,v)}} d_\rho(1-\theta_{(u,v)})}{\sum\limits_{\rho\in q_{\tau(i,j)}} d_\rho I_{(u,v)i}(1-\theta_{(i,j)})}, \forall (u,v) \in L, (i,j) \in L, \tau \in T \tag{9}$$

  where $\theta_{(u,v)}$ denotes the average PU interruption rate on link (u,v).

The allocation policies described above are based on the proportion values $x_{\tau(u,v)}$. First, each CR exchanges the available spectral bands, queue size, and allocation proportion $x_{\tau(u,v)}$ between neighboring nodes within the interference range. Therefore, each link keeps the spectral bands only available for itself. Second, the extra spectral band requirements are calculated and the remaining available spectral bands are selected. Third, the selected available spectral bands that will be used by a link are announced. If there is a subset of spectral bands which are also selected by other links, the links with lower proportion value have to try other available spectral bands. The winner will then switch to the selected bands and send its packets to the next hop.

The set of sensed available spectral bands at each time slot is allocated to each transmission link based on the above proportion. Then, the link capacity is calculated. Once the link capacity is determined, the link and nodal delays are calculated to compare the average end-to-end delay differential.

4 Evaluation Results

In this section, we describe our simulation environment used to evaluate the proposed schemes.

4.1 Simulation Environment

In all simulations, SUs and three types of PUs are deployed in an area. All the nodes are within transmission range of one another. The maximum transmission range for each node is set from 1.6 to 2.5 units for SUs. The maximum transmission ranges for the three types of PUs are set to 1.0, 1.5, and 2.0 units, respectively, and these are 30 spectral bands. There are six flows, and each flow has different demands.

We consider the issues that affect our proposed model and cause different aggregate flow and delay differentials. The arrival process and service process of PUs follow Poisson and Exponential distributions with arrival rate λ and service rate μ, respectively. We consider flows with Constant Bit Rate (CBR) and the traffic demand of each flow is set to γ_s units per unit time. Each packet is queued at a finite buffer of capacity $T = 1000$ units.

4.2 Simulation Scenarios

The average end-to-end delay differentials are evaluated under four scenarios:

– Scenario A. Maximum tolerable end-to-end delay: In this case, we are concerned with the maximum tolerable end-to-end delay that will still satisfy the delay requirement for flows. As described in the previous section, many factors (e.g., different number of hops, different remaining number of hops, and queue lengths) can cause different capacity requirements. With this value, we can determine the delay differential at each hop so that the end-to-end delay differential is controlled at each hop.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
Number of SUs	100-220	Number of PUs	120
Average rate of interruption	0.2	Traffic demand	(0,1)
Transmission power level	2.0	Maximum radio range	$1.6 - 2.5$
Link failure rate	(0,0.2)	Sensing range	3.2-5
Number of pairs	6	Number types of network	3
Arrival rate λ of a PU	1/2	Service rate μ of a PU	2 slots
Total time slot (T)	2000	Slot time	1.0
Bandwidth / spectral bands (MHz)	15, 20,25	Negotiation time per node-to-node pair	0.01
Number of spectral bands	30	Maximum tolerable end-to-end delay	500 unit time

- Scenario B. Transmission and sensing ranges: we vary the transmission range (i.e., sensing range). Increases in the transmission range limit the number of available spectral bands for SUs, but lead to increased sensing time, and more negotiations despite further distances can be reached.
- Scenario C. Number of SUs: As in a general network, the connectivity is satisfied with the least number of SUs. The effects on the network are tested for different numbers of SUs.
- Scenario D. Traffic load of SUs: The arrival rate is controlled in order to compare how traffic loads affect the delay differentials. We increase the number of packets for each flow to test the network capacity and the effect of queue size.

4.3 Simulation Results

- Scenario A: This scenario evaluates the average end-to-end delay differential for each scheme. The amount of maximum tolerable end-to-end delay varies under each condition. As shown in Figure 5, under the condition of less tolerable delay, the delay differential is higher, so we have to adjust the sensed available resource precisely. The trend of each simulation curve for each scheme is that the longer the tolerable delay, the smaller the delay differentials. Overall, the more the features of a CR network concerned in the allocation metrics (i.e., WDDI scheme), the better the performance.
- Scenario B: This case evaluates the effect of the transmitting and sensing range on the average end-to-end delay differential, as shown in Figure 6. The trade-off between selecting a larger transmission range and the routing path with less hop count is evaluated. When the transmission range is small, the performance is improved when the range increases. However, with a larger range, more time is spent in sensing and negotiations. As a result, the performance decreases as the delay differential increases when the range becomes larger. In addition, a larger interference range results in less spectral bands available for sharing. Hence, there is a critical point to set the suitable

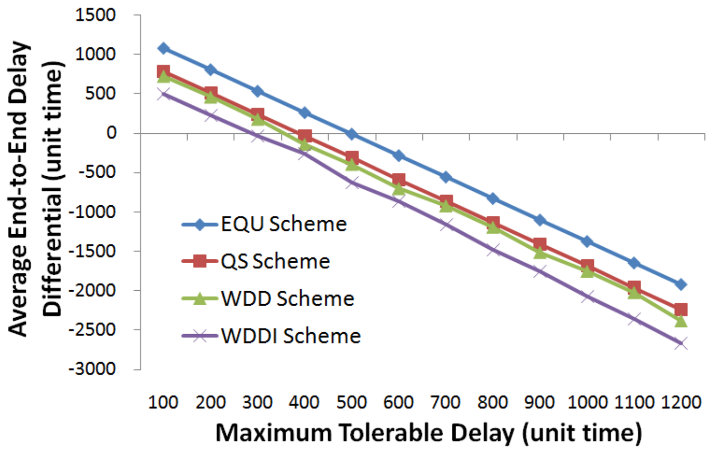

Fig. 5. The effect of the maximum tolerable delay on the average end-to-end delay differential

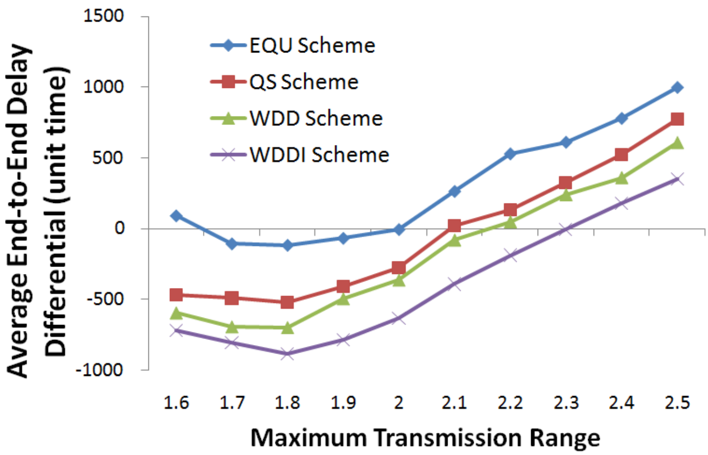

Fig. 6. The effect of transmission and sensing range on the average end-to-end delay differential

maximum transmission range for each scheme. The critical points for QS, WDD, and WDDI are smaller than that for EQU.

– Scenario C: This case evaluates the effect of the number of SUs on the average end-to-end delay differential. As shown in Figure 7, there is a trade-off between the number of negotiations and the number of cooperative sensing nodes. When the number of SUs increases with a fixed number of flows, the more the cooperative sensing nodes, the more the available frequency bands obtainable, at the expense of more negotiation overhead and increased

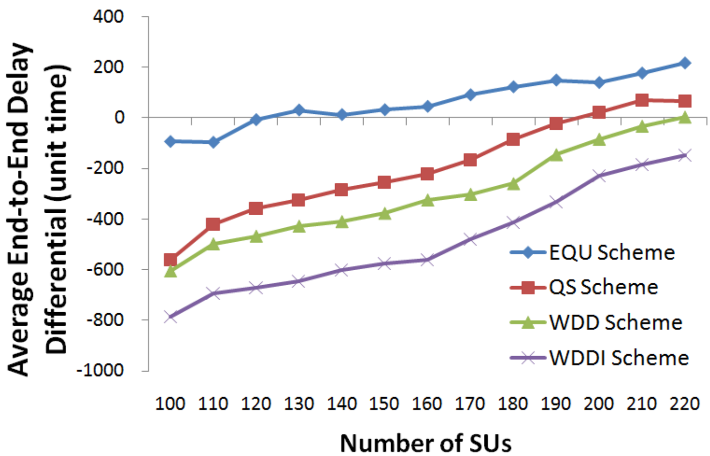

Fig. 7. The effect of the number of SUs on the average end-to-end delay differential

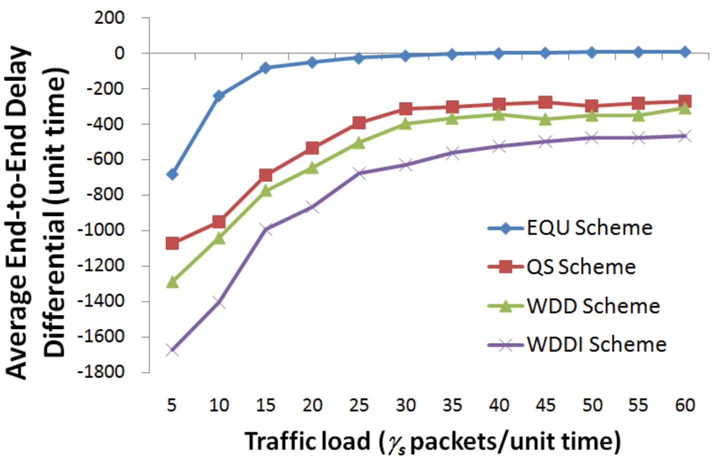

Fig. 8. The effect of traffic load on the average end-to-end delay differential

interference. Thus, with a fixed number of spectrum bands for sensing by random selection, the increased number of available bands is limited, but with longer negotiation time and more interferences, so the transmission duration is decreased. Thus, the more the duplicative sensing with larger negotiation overheads, the more the interference, which in turn causes higher average end-to-end delay differential.

– Scenario D: This case evaluates the effect of the traffic load on the average end-to-end delay differential. As shown in Figure 8, when the traffic load increases, the queue size increases, and as a result, the delay differential increases. However, the increase ratio is small when the traffic load is large. The reason is that the overdue packets will not be dropped when comparing the delay differentials among different approaches. When the capacity is limited, the amount of traffic it can handle is also limited. In other words, if the buffer is full, it blocks the transmission from the previous link. As a result, more packets will be queued at the source node, resulting in fewer packets at the receiver. Overall, the WDDI scheme outperforms the other schemes even when the traffic load is high. This is because more available spectral bands will be allocated to packets with higher delay differential, and to links with higher rates of PU interruption.

5 Conclusion

In this paper, we study the resource allocation problem for cognitive radio networks with QoS considerations. Our approach is to minimize the maximum delay differential among different flows, and to minimize the end-to-end delay, according to the sensed available spectral bands. We consider a multi-hop network with a spectral band pool and link-based interference model. Based on CR features, four allocation schemes are proposed and evaluated in terms of the average end-to-end delay differentials. Our results show that the more the resources given to packets with higher delay differentials and to links with higher rates of interruption, the better the performance. In the future, we will further consider call admission and packet dropping in our formulation.

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