Resource Control for Cognitive Multi-hop Network in Traffic Cross Environment

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***Abstract*—In this paper, we have proposed secondary user (SU) resource assignment algorithm for a multi-hop cognitive radio network to improve end-to-end latency. In the multi-hop networks for spectrum sharing, a traffic-cross, in which multiple flows are crossed each other, degrades the throughput due to appearing high traffic and shortage resource area. However each SU has to protect the flow of primary users (PU). To overcome this problem, we have set the PU acceptable received power which is decided by the acknowledgment (ACK) power from PU receiver to each SU user. From this information, we analyzed the performance of the proposed algorithm to minimize the end-to-end delay of SU multi-hop flow considering PU acceptable interference power by optimizing SU transmit power, where Lagrangian duality based technique has been utilized to solve the optimization problem and effective allocate the power for each SU users.**

***Keywords*-Cognitive Radio; Multi-hop Network; Lagrangian duality optimization; Resource Allocation;**

I. Introduction

With recent development of wireless communication services, the requirement of frequency bandwidth increases. However, in a current regulation policy, frequency band is assigned to licensed users for exclusive use. This policy causes the shortage of spectrum resource due to the inflexible spectrum usage. In a fixed frequency allocation policy, unused license bands remain because of their unutilized spectrum resource in the spatial and time domain. To overcome this problem, Cognitive Radio (CR) technology has been proposed[1][2]. CR can adaptively change the communication parameters of a transmitter and a receiver according to the recognized surrounding environment of wireless communication.

The concept of CR networks based on spectrum sharing can be categorized into two ways. The first one is the Overlay technique. Spectrum overlay allows unlicensed secondary users (SUs) to utilize unused spectrum simultaneously with primary users (PUs) if the interference from the SU to PUs can be avoided[3]. The other spectrum sharing technique is Underlay scheme. In the underlay technique, simultaneous primary and secondary transmissions are allowed under the interference constraint. In this scheme, SU, which is unlicensed user, has to control the amount of interference to the primary users under sufficiency of tolerable limits. Due to the interference constraints associated with underlay systems, the underlay technique is useful for short range communications[4].

On the other hand, Multi-Hop (MH) networks are known as a way to realize flexible communications in CR network[5]. MH networks are the communication scheme, which can expand the service area by using multi-hop wireless communications, and establishes the communication by using distributed nodes such as cellular phone, laptop PC and some other devices, by relaying packets from the source node toward their destination node. They also exhibit great robustness due to their distributed nature, node redundancy, and the lack of single links of failure[6]. From these advantages, MH network is utilized for many applications such as smart grid, intelligent transport system, disaster communication network and so on.

According to the development of wireless mesh network, it is important point of view for cognitive radio multi-hop (CRMH) networks to share the spectrum with such PU systems. Spectrum sharing for CRMH networks has been studied actively in particular solving optimization algorithm[7]-[11]. The main focus for optimizing of each SU characteristics in CRMH networks are categorized into routing, channel assignment and SU transmit power control (TPC)[12]. Also, for more flexible communications for CRMH networks, orthogonal frequency division multiple access based technique using optimizing problem is introduced in [13]-[17]. However, these existing methods does not consider the interference power limitation in the system.

In general, in order to avoid the interference toward the primary user (PU) and to decide the transmission power of each nodes, it is better to control SU nodes by using a central spectrum resource controller. However, since a multi-hop CR network is a kind of ad-hoc network, SU cannot use the central controller to share the information about transmit power, interference to PUs and so on. To overcome this problem, a common control channel shared by all SU nodes has been proposed[18]. By using the shared control

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channel, each node can obtain the information of each link such as signal to noise ratio (SNR), the received power of acknowledgment (ACK) signal from PUs, locations of each node and so on. Then, each node can control the transmit power with satisfaction of demand[19][20].

In this paper, we utilize spectrum underlay sharing method for PU multi-hop flow coexistence. Each PU link utilizes different channel and has the acceptable interference power limitation. Each SU flow underlays the PU channel and uses frequency reuse method for end-to-end communications. In order to obtain necessary information from PU, we assume that a PU receiver sends ACK signal to PU transmitter and SU can detect this signal to set the interference margin. From this information, SU can estimate the interference level and then operate transmission power control (TPC). Then, an efficient resource assignment algorithm is proposed to minimize the total end-to-end delay in the SU multi-hop flow under PU interference limits. A Lagrangian duality based optimization is introduced to solve the algorithm efficiently which converges to optimal SU transmit power by considering signal to interference plus noise ratio (SINR) of each link. Different from the existing methods, the interference power limitation is included by using Lagrangian multipliers.

The rest of this paper is organized as follows. System model is introduced in Section II. Proposed algorithm and optimization problem modeling are shown in Section III. Computer simulation results with this proposed method are shown in Section IV. Finally, a conclusion is given in Section V.

II. SYSTEM MODEL

In this paper, we assume frequency division multi-hop wireless system, and we discuss the situation for frequency channel statement. In this system, co-channel interference to each link should be considered to calculate SINR if links transmit the packet on the same channel. We assume that a node can only transmit to or receive from single other node. In this section, we explain a system model and assumption for this paper by using equations.

A. Traffic Cross Model

We consider a traffic cross environment shown in Fig.1, where SU multi-hop flow crosses PU multi-hop flow each other. In this system, we have to consider co-channel interference between each link if these links use the same channel m. We assume that PU can select the channel for data transmission from $m \in M$ channels. Then, SU also select their channel from M channels. If both PU and SU transmit the packet on the channel m, we consider interference. We also assume that both PU and SU multi-hop links assign the channel by frequency reuse method. In this method, channel m is assigned to links repeatedly from a source node to a destination node.

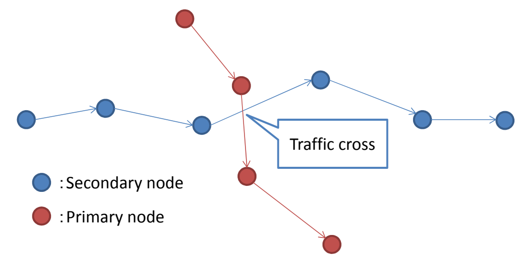

Figure 1. Traffic cross environment.

B. Channel Model

For all the links in our system model, the link channel gain between the transmitter node i and the receiver node j can be given by,

$$g_{ij}^{(m)} = \mu(d_{ij}/d_0)^{-\gamma}, \tag{1}$$

where, $g_{ij}^{(m)}$ is the channel gain from node i to node j on channel (m), and for all links, the channel gains are independent identical distribution (i.i.d). Equation (1) denotes the distance dependent path loss effect, where, d_0 is a reference distance, d_{ij} is the distance from nodes i to j, and μ depends on the antenna characteristics and the average channel attenuation, and can be calculated from,

$$\mu = G_A(\lambda/4\pi d_0)^2, \tag{2}$$

where, G_A is the antenna gain, λ is the wave length. In this paper, the antenna gain G_A is defined as 1. Then the received power P_{r_j} from the transmitter node i to the receiver node j is defined as,

$$P_{r_j} = p_i g_{ij}^{(m)}. \tag{3}$$

We assume that SU uses underlay method for their data transmission. In this system, SINR of SU j on the channel m can be expressed as,

$$\begin{aligned} SINR_{ij} &= \frac{P_{r_j}}{I_{j,total}^{(m)} + N_0} \\ &= \frac{p_i g_{ij}^{(m)}}{\sum_{\forall k \setminus \{i,j\}} I_{kj}^{(m)} + N_0}, \end{aligned} \tag{4}$$

where, k is the transmitter node including both PU and SU, $I_{kj}^{(m)}$ is the interference from the neighbor transmitter node k on the channel m, and N_0 is the Gaussian noise power on the channel m.

III. PROPOSED METHOD

In this section, we explain the proposed algorithm to minimize the end-to-end delay of our research. The flow chart of this algorithm is shown in fig.2. As shown in fig.2, at first, each SU controls their transmission power by the highest PU ACK power. After deciding first transmission power, SU establishes the route from a source node to a destination node according to their transmission power using the control channel. Once established the route from the source node to the destination node, we set the frequency for data transmission based on frequency reuse method. After established the route and set the data channel for each link. Then, to achieve the optimal solution for this system, power allocation based on a minimizing problem is operated. We explain more detail as below.

A. First TPC

For all SU transmitter, to protect the PU transmission, they need to control their transmission power. In this operation, SU nodes detect ACK signal from their neighboring PU,

$$p_{PU_k-j} = g_{PU_k-j} p_{PU(ACK)_k}, \tag{5}$$

where, P_{PU_k-j} and g_{PU_k-j} are the received power and the channel gain from PU node k to SU transmitter node j, and $p_{PU(ACK)_k}$ is the transmission power from PU node k, respectively. Then, SUs keep the highest ACK power from neighboring PU nodes,

$$P_{r_{(ACK)-j}} = \max\left[\boldsymbol{p_{PU_1-j}}, \boldsymbol{p_{PU_2-j}}, \cdots, \boldsymbol{p_{PU_K-j}}\right]. \tag{6}$$

Once SUs control their transmission power, we consider acceptable received power to PUs to protect their transmission and quality. Then we set the interference power limit at PU_k as Γ_{PU_k}. Then, all the SU node should keep following limitation,

$$g_{i2PU_k} p_i \leq \Gamma_{PU_k} \tag{7}$$

$$p_i \leq P_{max}, \tag{8}$$

where, g_{i2PU_k} is the channel gain from SU transmitter node i to PU receiver node k.

From this information, SU controls the transmission power by equation (9)

$$p_i = P_{max} - \left(P_{r_{(ACK)-j}} - \Gamma_{PU_k}\right). \tag{9}$$

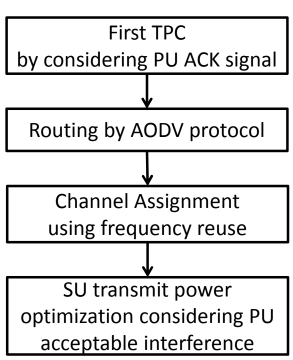

Figure 2. Proposed algorithm.

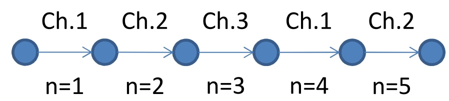

Figure 3. Frequency reuse method.

Then, we establish the route considering this transmission power.

B. Routing and Channel Assignment

After deciding SU transmission power for all the SU transmitter node, for end-to-end data transmission from a source to a destination node, we set the route and data channel.

To establish the route from the source node to the destination node in multi-hop network, Ad-hoc On-Demand Distance Vector (AODV) routing protocol is popular way to realize it. We assume that node i can transmit the data to node j if the received SNR of node j is large enough and defined as following equation,

$$SNR_{ij} \geq SNR_{req} \tag{10}$$

where, SNR_{ij} is signal to noise ratio (SNR) between node i to j, calculated by $\frac{p_i g_{ij}}{N_0}$, SNR_{req} is the required SNR which is constant in this system.

We also consider the channel assignment for all the hops in multi-hop network. In this paper, we consider the channel reuse method which assigns the M data channels to each hop. For example, as shown in fig.3, we consider a 5 hop multi-hop network whose available channels are 3. Channel $m = 1$ is assigned to link number $n = 1, 4$, channel $m = 2$ is assigned to $n = 2, 5$, and channel $m = 3$ is assigned to $n = 3$. If the links use the same channel to each other, co-channel interference is happened.

C. Power control and end-to-end delay optimization

The constrained problem can be given as,

$$\min_{p_i} \quad D_{e2e} = \sum_{n=1}^{N} \frac{1}{R_n} \tag{11}$$

$$s.t.$$

$$I_{PU}^{(m)} = \sum_{\forall i \in SU} g_{i2PU_k}^{(m)} p_i \leq \Gamma_{PU_k}^{(m)} \tag{12}$$

$$p_i \leq P_{max}, \tag{13}$$

where, D_{e2e} is the end-to-end delay of SU flow, N is the number of hops in the SU multi-hop flow, $I_{PU}^{(m)}$ is the amount of interference to PU from SU flow on channel m, $g_{i2PU}^{(m)}$ is the interference channel gain from SU transmitter i, and $\Gamma_{PU_k}^{(m)}$ is the interference power limit at PU_k on channel m.

R_n is the data rate of SU link n on channel m, which is given by,

$$R_n = B log_2(1 + p_i \beta_{ij}), \tag{14}$$

where,

$$\beta_{ij} = \frac{g_{ij}^{(m)}}{\sum_{\forall p \setminus \{i,j\}} I_{pj}^{(m)} + N_0} \quad (15)$$

is the ratio of carrier gain to interference and noise. B is the bandwidth of channel m.

The Lagrangian function associated with the above optimization problem can be written as,

$$\begin{aligned} L(p_i, \psi, \phi_i) &= \sum_{n=1}^{N} \frac{1}{R_n} \\ &+ \psi \left(\sum_{\forall i \in SU} g_{i2PU_k}^{(m)} p_i - \Gamma_{PU_k}^{(m)} \right) \\ &+ \sum_{n=1}^{N} \phi_i (p_i - P_{max}), \end{aligned} \quad (16)$$

where, $\psi \geq 0$,$\phi_i \geq 0$are non-negative Lagrangian multipliers.

The Karush-Kuhn-Tucker (KKT) conditions [21] of Lagrangian function are derived as following,

$$\psi^* \left(\sum_{\forall i \in SU} g_{i2PU_k}^{(m)} p_i - \Gamma_{PU_k}^{(m)} \right) = 0 \quad (17)$$

$$\phi_i^* (p_i - P_{max}) = 0 \quad (18)$$

$$\frac{\partial L}{\partial p_i} = \frac{-\beta_{ij} ln(2)}{(1 + \beta_{ij} p_i) B \{ log(1 + \beta_{ij} p_i) \}^2} + \psi g_{i2PU_k}^{(m)} + \phi_i = 0, \quad (19)$$

where, ψ^*, ϕ^* are the optimal solutions. Then, from (19), we can obtain the transmit power allocation for SU transmitter i on channel m is calculated as,

$$p_i^* = \frac{-1 + exp \left\{ 2W \left(\frac{1}{2} \sqrt{\frac{\beta_{ij}}{(g_{i2PU_k}^{(m)} \psi + \phi_i) B}} \sqrt{ln(2)} \right) \right\}}{\beta_{ij}}, \quad (20)$$

where, $W(x)$ is the Lambert W function which is the inverse function of

$$f(W) = We^W. \quad (21)$$

Moreover, to solve the optimal solution, Lagrangian multiplier ψ,ϕ_i should be updated as the following iteration, which are based on the sub-gradient search method, then we can achieve the optimal value.

$$\psi^{x+1} = \left(\psi^x - \epsilon \left(\sum_{\forall i \in SU} g_{i2PU_k}^{(m)} p_i - \Gamma_{PU_k}^{(m)} \right) \right)^+ \quad (22)$$

$$\phi_i^{x+1} = \left(\phi_i^x - \epsilon \left(p_i - P_{max} \right) \right)^+, \quad (23)$$

where, $(\cdot)^+ = max\{0, \cdot\}$, $0 \leq \epsilon \leq 1$ is a sub-gradient search step size, and ψ^x, ϕ_i^x is the Lagrangian multiplier at iteration x respectively.

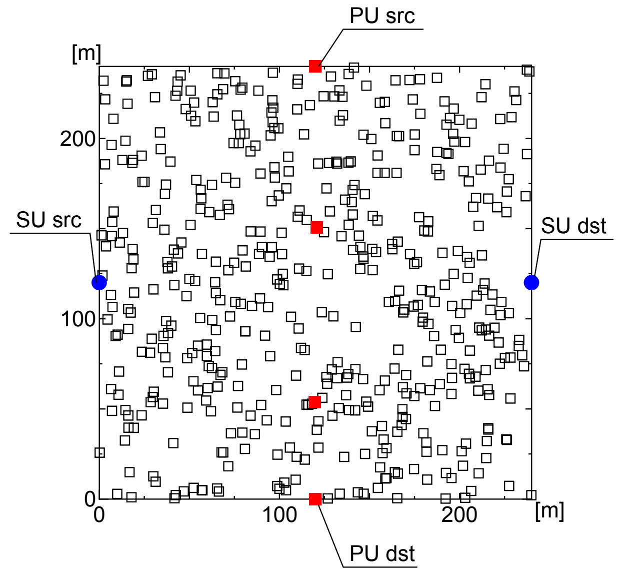

Figure 4. Simulation environment.

Table I
SIMULATION PARAMETER

Simulation area	240[m] × 240[m]
Number of nodes	500
Frequency	2.45[GHz]
Number of channel : M	3
Bandwidth of channel : B	20[MHz]
Max transmit power:P_{max}	25[dBm]
PU transmit power:P_PU	25[dBm]
Sensing level	-85.0[dBm]
AWGN	-95.0[dBm]
Pass loss index : γ	3.0
Reference distance : d_0	1.0[m]
Routing SNR	20[dB]
PU acceptable interference power : $\Gamma_{PU_k}^{(m)}$	-80[dBm]

IV. SIMULATION RESULT

In this section, we present the simulation result for our analysis which considered acceptable interference to PU. We assume $N = 500$ nodes in 240[m] × 240[m] area. We consider that SU the data flow from the source node to the destination node and 3 hop PU multi-hop network as shown in Fig.4. We assume that the sensing level for each SU is -85.0[dBm]. We also assume that each node can perfectly sense the PU's signal and detect the SINR for each link.

The route of both PU flow and SU flow are established by using the AODV routing protocol by exchanging the Route REQuest (RREQ) and Route REPly (RREP) packets through the common control channel. After the route is established, the node assigns the channel by using frequency reuse method. The simulation parameters are explained in Table I. In this section, we evaluate the end-to-end delay of SU flow, the amount of interference to PU, and throughput

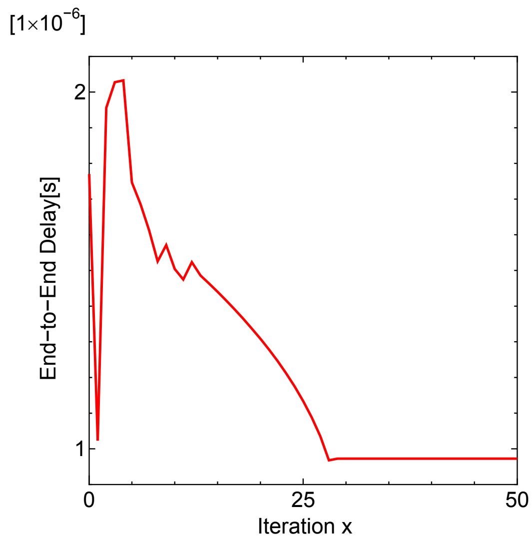

Figure 5. SU end-to-end delay.

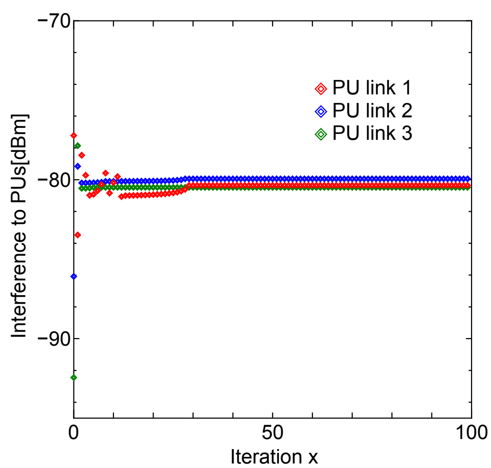

Figure 6. Interference to PU.

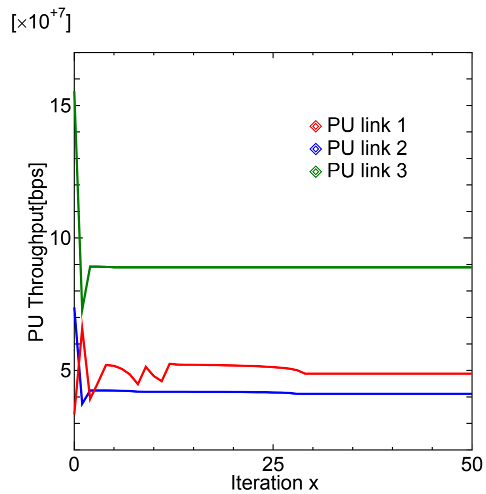

Figure 7. PU throughput.

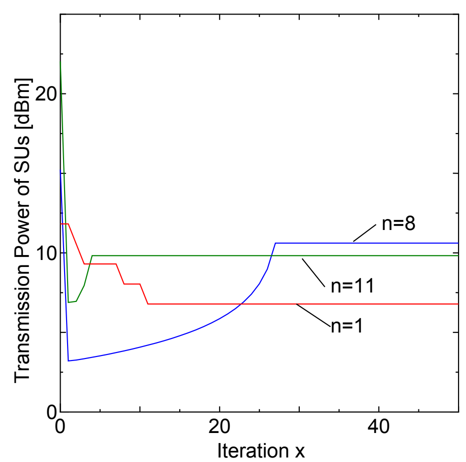

Figure 8. SU transmit power.

of each link both PU and SU multi-hop flow by increasing the iteration x.

Figure 5 shows the performance of end-to-end delay of SU flow. From Fig.5, we can see end-to-end delay converged smallest value by increasing iteration number x of the algorithm for SU transmit power. Moreover, we can see the end-to-end delay converges at iteration $x = 28$. In this graph, when the number of iteration is smaller, end-to-end delay is temporary higher than initial value. This is because each SU transmitter control their transmit power higher and causes interference between links.

Figure 6 shows the amount of interference to each PU link by increasing iteration number x of the algorithm for SU transmit power. In this paper, we set the acceptable interference to PU $\Gamma_{PU_k}^{(m)} = -80.0$[dBm]. From Fig.6, the amount of PU interference to each PU link is achieved required value at last. From this graph, we can see the effectiveness of the proposed SU TPC to protect the PU transmission.

Figure 7 shows the PU throughput by increasing the iteration x. From Fig.7, we can see PU throughput converges by increasing iteration x. In this paper, we assume PU routing SNR = 20[dB], $\Gamma_{PU_k}^{(m)} = -80.0$[dBm] and the AWGN = -95.0[dB]. From this relations, we can calculate the lower bound for PU throughput as,

$$C_{LB} = B * log_2 \left(1.0 + \frac{P_r^{routing}}{\Gamma_{PU_k}^{(m)} + N_0} \right) \quad (24)$$

$$= 40.47[Mbps] \quad (25)$$

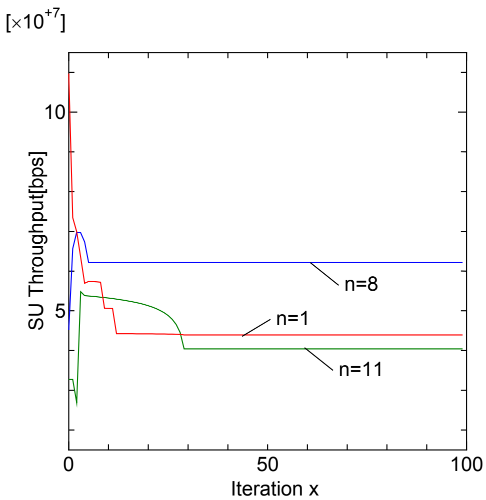

Figure 9. SU throughput.

where, $P_r^{routing}$ is the required received power that satisfies routing SNR. From this equation, the throughput of each PU link achieved the C_{LB}. Therefore, we can see that all the PU links satisfy the quality of link by SU TPC considering acceptable interference power.

Figure 8 shows the SU transmit power by increasing the iteration x. In this simulation, the number of hops for SU flow was 15, then we show the link 1,8, and 11, for example. We can see each SU changes their transmit power as increasing x and converges to optimal value from Fig.8.

Figure 9 shows the SU throughput by increasing the iteration x. For example, we show the situation about the link 1, 8 and 11. From Fig.9, these links converge their throughput as increasing x value of the algorithm for SU transmit power. Also, each link satisfies the equation (24).

V. CONCLUSION

In this paper, we have analyzed the end-to-end delay of SU multi-hop flow by considering PU acceptable interference power limitation, where Lagrangian duality based optimization technique and subgradient method are utilized to solve the SU optimal transmit power. We considered SINR model which interference occurs between links caused by co-channel interference in multi-hop flow if each link utilized same channel. We have simulated that the performance of end-to-end delay converged to optimal value, and interference to each PU link was converged to acceptable interference power by increasing iteration number x of the algorithm for SU transmit power.

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