In this paper, we propose a secondary user (SU) resource assignment algorithm for a multi-hop (MH) cognitive radio network to improve the end-to-end throughput. In the MH networks used for spectrum sharing, each SU needs to improve the throughput by taking the primary user (PU) into account. For overcoming this problem, we estimate the PU acceptable received power, which is determined by the acknowledgment packet (ACK) power from the PU receiver. With this estimation, we propose an SU optimal transmit power control algorithm to not only maximize the end-to-end throughput of the SU MH flow but also maintain the considered PU acceptable interference power. In this study, a distributed joint allocation algorithm has been used to solve the optimization problem and to effectively allocate the power of each SU.

**key words:** cognitive radio, multi-hop network, resource allocation, joint allocation

1. Introduction

Recently, the development of wireless communication systems for diverse applications has caused an extremely increasing data traffic. For accommodating this huge traffic, many frequency bands are necessary. However, a frequency band is allocated to a licensed user for exclusive use. This policy causes shortage of the spectrum resource, and it is an obstacle to introduce a new system for future use. Instead, in the case of dynamic frequency allocation, the frequency bands are reused both in the time domain and in the space domain. As a result, newly vacant frequency bands are discovered. For overcoming this problem, the cognitive radio (CR) technology has been used, which is attracting much attention [1], [2]. The CR nodes can adaptively change their communication parameters according to the recognized surrounding environment of wireless communication.

The concept of CR-network-based spectrum sharing can be categorized into two schemes. The first scheme is the overlay technique. Spectrum overlay sharing allows unlicensed secondary users (SUs) to share the unused spectrum with the primary users (PUs) if the interference from the SUs to the PUs can be avoided [3]. The second scheme is the underlay scheme. In the underlay scheme, the PU can simultaneously access the channel, which is frequency band, because the signal power of the SU is small enough to be an acceptable interference to the PU. The underlay technique is useful for short-range communications [4], considering the interference constraints associated with the underlay systems.

Multi-hop (MH) wireless communication networks are a suitable means to realize flexible communication in the CR networks [5]. The MH networks are the communication networks, which can expand the service area by using MH wireless communications and can establish the communication by using distributed nodes such as cellular phones, laptop PCs, and some other devices, by relaying the packets from the source node toward the destination node. The MH networks also exhibit a great robustness owing to their distributed nature and node redundancy as well as for overcoming single-link failure [6]. With these advantages, the MH networks are used for many applications such as smart grids, intelligent transport systems, and disaster communication networks.

With the development of wireless mesh networks, as mentioned earlier, it is important for cognitive radio multi-hop (CRMH) networks to share the spectrum with the PU system. Spectrum sharing through the CRMH networks has been actively studied in particular for solving the optimization algorithm [7]–[11]. The main focus in optimizing each of the SU characteristics in the CRMH networks is on routing, channel assignment, and SU transmission power control (TPC) [12]. In addition, for more flexible communication through CRMH networks, an orthogonal frequency-division multiple access (OFDMA)-based technique considering the optimizing problem was introduced in [13]–[17]. However, these existing methods do not consider the interference power limitation in the system.

In this paper, we propose an SU frequency sharing scheme that can be applied to both the PU ad-hoc network and the SU MH wireless network. For predicting the interference power of the PUs, we assume that each SU can detect the acknowledgment packet (ACK) signal from the PU receiver. From this interference prediction for the PU, each SU determines the channel that is effective for data transmission and is available for the SU to control the transmit power for suppressing the harmful interference to the PU. This concept is called spectrum underlay sharing. Further, an efficient resource assignment algorithm is proposed to maximize the end-to-end throughput in the SU MH flow by taking the interference power of each PU into account. For
solving the bottle-neck link problem in MH wireless communication, we propose a frequency assignment scheme on the basis of the link priority and channel priority. Further, each SU controls the transmission power. We realize end-to-end throughput maximization and protection of the PU activity by considering the signal-to-interference-plus-noise-ratio (SINR).

The rest of this paper is organized as follows. A system model is introduced in Sect. 2. The proposed algorithm and optimization problem modeling are described in Sect. 3. The computer simulation results of the proposed method are described in Sect. 4. Finally, the conclusion is presented in Sect. 5.

2. System Model

In this paper, we assume a frequency-division MH wireless system. In this section, we discuss the condition for frequency channel allocation. In the frequency-division MH wireless system, the co-channel interference to each link should be considered to calculate the SINR if the links use the same channel for data transmission. We assume that a node can only transmit the signal to or receive the signal from the other node. In the following section, we explain a system model and the assumption made for the theoretical analysis of the considered system.

2.1 Channel Model

As illustrated in Fig. 1, we assume an MH network system constructed with a source node, destination node, and relay node. For all the links in our system model, the link channel gain between the transmitter node \(i\) and the receiver node \(j\) can be expressed as

\[
g_{ij} = \mu(d_{ij}/d_0)^{-\gamma},
\]

where \(g_{ij}\) is the average channel gain from node \(i\) to node \(j\). In this paper, we assume that the frequency band is selected within 2.4–2.5 [GHz] by considering wireless LAN on ISM band. The frequency band is divided into 3 channels and each channel has 20 [MHz] bandwidth. Since the difference of the frequency in each channel is small, we assume the channel loss of each channel is the same in this paper. Equation (1) also includes the propagation loss effect, where \(d_0\) is the reference distance, \(d_{ij}\) is the distance from node \(i\) to node \(j\), \(\gamma\) is the propagation loss index, and \(\mu\) depends on the antenna characteristics and average channel attenuation and can be calculated from

\[
\mu = G_A(\lambda/4\pi d_0)^2,
\]

where \(G_A\) is the antenna gain, and \(\lambda\) is the wavelength [6]. In this study, the antenna gain \(G_A\) is defined as 1. Then, \(\mu\) is a constant in this paper. Further, the received power \(P_{rj}\) from the transmitter node \(i\) to the receiver node \(j\) is defined as

\[
P_{rj} = p_i \cdot g_{ij},
\]

where \(p_i\) is the transmission power of node \(i\). Also, the receiver node \(j\) estimates average channel gain by sending pilot signals repeatedly. As an example to this problem, a pilot signal is utilized to estimate the channel gain as shown in the reference [18]. At first the transmitter node \(i\) sends the pilot signal to receiver node \(j\), and then the receiver node \(j\) can estimate the channel gain \(g_{ij}\). Also the receiver node \(j\) detects the interference power from other adjacent node. Here, we assume that each SU can estimate the interference power in the frequency sharing environment by sensing the interference plus noise power before transmitting the data. Also, we assume that each node shares the information of noise floor to estimate SNR. From these information, receiver node \(j\) can estimate SNR and SINR. We assume that the SU uses the underlay method for data transmission. In this system, the SINR of SU \(j\) can be expressed as

\[
\text{SINR}^{(m)}_{ij} = \frac{P_{rj}}{\sum_{k \neq j} I_{kj}^{(m)} + N_0} = \frac{P_{rj}}{\sum_{k \neq j} I_{kj}^{(m)} + N_0},
\]

where \(k\) is the transmitter node including both the PU and the SU, \(I_{kj}^{(m)}\) is the interference from the neighbor transmitter node \(k\) over channel \(m\), and \(N_0\) is the Gaussian noise power over . Moreover, the interference generation sources are different in each channel. Therefore, we define that the SINR, which has the dimension of interference, depends on \(m\).

2.2 Routing Scheme

In the MH wireless communication system, each SU node needs to set the route for end-to-end data transmission from the source node to the destination node. For establishing the route from the source node to the destination node in the MH network, the ad-hoc on-demand distance vector (AODV) routing protocol is widely used. In the AODV routing protocol, to establish the route, both the source and relay nodes forward the route REQuest (RREQ) packet to the next node until the RREQ packet reaches the destination node. Further, after the destination node receives the RREQ packet, it transmits back the route REPLY (RREP) packet to the path, thereby establishing the route. We assume that node \(i\) can transmit the data to node \(j\) if the received SNR of node \(j\) is large enough, as defined in the following equation:
where $SNR_{ij}$ is the average signal-to-noise ratio (SNR) between nodes $i$ and $j$ and is calculated as $\frac{P_{inj}}{N_0}$, and $SNR_{req}$ is the required SNR, which is predefined in this system.

### 2.3 End-to-End Throughput

When the end-to-end route from the source node to the destination node is established, the throughputs of all the links in the MH flow are different because the links are constructed with several regenerative relaying channels with different channel gains in series. In general, the capacity of the link $ij$ is expressed as

$$R_{ij} = B \cdot \log_2 \left(1 + SINR_{ij}^{(m)} \right),$$

where $B$ and $SINR_{ij}^{(m)}$ are the bandwidth of the data channel and SINR of link $ij$ which is established over the channel $m$, respectively.

In the MH wireless network, the end-to-end throughput, $R_{2e}$, is determined by the smallest single-hop capacity,

$$R_{2e} = \min_{i \in F} R_{ij},$$

where $F$ is the set of links in a flow. From this characteristic, the best end-to-end throughput of the MH wireless network can be obtained by considering the following equation:

$$R_{12} = R_{23} = \cdots = R_{ij} = \cdots = R_{(N-1)N},$$

where $N$ is the number of nodes in an end-to-end flow.

### 3. Proposed Method

In this section, we explain the proposed algorithm to maximize the end-to-end throughput. The optimization problem in the CRMH network has been studied along with the routing techniques, channel assignment scheme, and TPC scheme, called joint allocation optimization. In this paper, we focus on the joint optimization scheme by taking the channel assignment and TPC into account to maximize the end-to-end throughput. In the proposed channel assignment scheme, we set the priority to each link to determine the bottle-neck link that decreases the end-to-end throughput. We propose a link priority and a channel priority to improve the throughput of the link that has the smallest capacity in the SU MH flow. Further, the proposed TPC algorithm to maximize the end-to-end throughput controls the transmission power of each SU node, which is explained in more detail as follows.

#### 3.1 Priority Based Channel Assignment Scheme

In this section, we explain in detail the proposed channel assignment scheme. The problem, in particular, for the MH wireless communication systems is a bottle-neck link problem, which decreases the end-to-end throughput because of the smallest single-hop capacity of the MH links. As shown in Eq. (7), the end-to-end throughput is determined as the throughput of the bottle-neck link. For overcoming this problem, we propose two priorities. The first priority is based on the total link capacity. The second priority is based on the channel gain of each channel of the link by considering the SINR. The former and the latter are the link priority and the channel priority, respectively.

#### 3.1.1 Link Priority

The end-to-end throughput is determined as the single-hop throughput of the bottle-neck link in the MH wireless network. From this characteristic, we need to consider the improvement of the bottle-neck link. In this paper, we set the highest priority to assign the resources for the smallest capacity link to recover the bottle-neck link. The flowchart for determining the link priority is shown in Fig. 2.

First, we calculate the average SINR over channel $m$ in the dB domain of each hop by using Eq. (4).

From this equation, the total link capacity where the link can make maximum use of the resources can be written as

$$C_{ij}^{(total)} = \sum_{m=1}^{M} B \cdot \log_2 \left(1 + SINR_{ij}^{(m)} \right),$$

where $M$ is the number of available channels.

The constructed routing table includes the link quality estimated by the exchange of the RREQ and RREP messages. We assume that the QoS parameters such as bandwidth, average SINR and the information of occupied channel of each link are shared by these messages for all the links.

![Fig. 2 Determination of link priority.](image-url)
in a flow such like a QoS-aware routing [19], [20]. Thus, the total link capacity defined by Eq. (9) is estimated. Further, for achieving the required data rate for data transmission, all the available channels are combined. In this study, we assume that each node shares the total link capacity by using the RREQ packet and the link priority is determined by the destination node. Further, the destination node transmits the RREP packet back to the path with the routing table and the information of link priority. In this case, we set the highest priority to the link that has the smallest total link capacity in the flow. Therefore, we define the link priority as follows:

\[ \text{1stPri}_{\text{(link)}} = \arg \min_{ij \in F} C_{ij}^{\text{(total)}}, \] (10)

where \( F \) is the set of links in the SU MH flow.

An example of the total link capacity of each link is shown in Fig. 3. As shown in Fig. 3, the total link capacity of each link is different, and we can observe that link 2 has the minimum total link capacity in the flow. Therefore, we set the highest priority for link 2.

From Eq. (10), the data channel is assigned to the first priority link. When the data channel is assigned, to determine channel that can be efficiently used, we set the channel priority as described in Sect. 3.1.2. Using Eq. (10), the data channel is assigned from the idle channels in the descending order according to the priority. The link priority is updated by eliminating the set of assigned link nodes.

3.1.2 Channel Priority

When each SU node assigns the data channel to its link, we need to consider the PU protection to avoid the interference to the PU receivers and improve the quality of data transmission for SU MH flow by assigning the data channel with the highest channel gain. Further, we propose to set the channel priority on the basis of the SINR over channel \( m \). The flowchart for determining the channel priority is shown in Fig. 4. Each SU collects the SINR information of each channel on the link from \( M \) channels. Further, we set the highest priority to the channel with the largest SINR on the link, which is calculated as

\[ m_{\text{1stPri}} = \arg \max_{m \in M} \text{SINR}_{ij}^{(m)} \] (11)

The channel priority and the channel assignment information of adjacent link are updated by eliminating the set of assigned channels on the link. Further, the information of the assigned channels is shared with the neighbor links.

3.2 TPC Algorithm

In the underlay scheme for spectrum sharing, each SU controls its transmission power to protect simultaneous access by the PU. For controlling the transmission power, each SU estimates the received ACK power from the ACK signal between the PU receiver and the transmitter. This is because that each SU node has to protect the PU communication. It means SU needs to protect not only the opportunity of PU transmission but also the quality of received signal at the PU receiver. Therefore, we make use of the ACK signal from the PU receiver node for estimating the interference level in this paper. The received ACK power from the adjacent PU node over channel \( m \) is expressed as

\[ P_{PU_{k-i}} = g_{PU_{k-i}} \cdot P_{PU_{k}}, \] (12)

where \( P_{PU_{k-i}} \), \( g_{PU_{k-i}} \) and \( P_{PU_{k}} \) are the received ACK power from PU node \( k \) to SU node \( j \), channel gain from PU node \( k \) to SU node \( j \), and transmit power of PU node \( k \), respectively.

In this paper, we assume that the transmission power of PU node \( k \) is fixed considering to WLAN circumstance in my simulation. From this information, the largest received ACK power is estimated from the ACK signals of all the PUs, and, thus, the power of the \( j \)th SU and \( m \)th channel is defined as follows:

\[ P_{(j, \text{ACK})}^{(m)} = \max_k P_{(j, \text{ACK})}^{(m)} \] (13)

Each SU node can predict the channel gain from SU node \( i \) to neighbor PUs \( g_{PU_{k-i}}^{(m)} \) by considering the information of the maintained ACK power to protect PU activity. We assume that each SU shares the predicted aggregation interference power by considering Eq. (13) when it assigns the data channel. We assume that this information is shared when the data
channel is assigned. For calculating the predicted aggregation interference power, the channel statement is updated as:

\[ a_{ij}^{(m)} = \begin{cases} 1 & \text{channel } m \text{ is used on link } ij \\ 0 & \text{otherwise} \end{cases} \]  

(14)

Further, the aggregation interference by the SU MH network to the neighbor PUs is expressed as

\[ I_{\text{sum}}^{(m)} = \sum_{ij \in F} a_{ij}^{(m)} \cdot g_{ij} \cdot P_{ij}, \quad \Gamma_{\text{PU}} \leq \Gamma_{\text{PU}}, \]  

(15)

where \( g_{ij} \) are the channel gain from SU node \( i \) to PU node \( k \), transmission power of SU node \( i \), and pu acceptable interference power, respectively. If this aggregation interference power exceeds the PU interference constraint, each SU controls its transmission power as

\[ p_i = p_i - (I_{\text{sum}}^{(m)} - \Gamma_{\text{PU}}) \frac{g_{ij}}{\sum_{s \in F} a_{ij}^{(m)} g_{ij}}. \]  

(16)

As mentioned above, we explain the equation for TPC. Further, we explain the constraint problem in this paper as follows:

\[ \max_{p_i} R_{2e} = \max_{p_i} \{ \min R_{ij} \} \]  

(17)

s.t. \( I_{\text{sum}}^{(m)} = \sum_{ij \in F} a_{ij}^{(m)} g_{ij} \cdot P_{ij}, P_{ij} \leq \Gamma_{\text{PU}}, \)  

(18)

\[ p_i \leq P_{\text{max}}, \]  

(19)

where \( R_{2e}, I_{\text{sum}}^{(m)}, g_{ij} \) and \( P_{\text{max}} \) are the end-to-end throughput of the SU MH network, predicted aggregation interference power of the PU over channel \( m \), channel gain from SU node \( i \) to PU node \( k \), and acceptable interference power of each PU, respectively. The objective function of the optimization problem is to obtain the transmission power that maximizes the end-to-end throughput \( R_{2e} \). \( R_{ij} \) denotes the throughput of link \( ij \), which is expressed as

\[ R_{ij} = B \cdot \log_2 \left( 1 + \frac{p_{ij} \cdot g_{ij}}{\sum_{k \in \{i,j\}} I_{\text{sum}}^{(m)}(k) + N_0} \right), \]  

(20)

\[ R_{ij} = B \cdot \log_2 \left( 1 + \frac{p_{ij} \cdot g_{ij}}{\sum_{k \in \{i,j\}} I_{\text{sum}}^{(m)}(k) + N_0} \right), \]  

(21)

where \( B \) and \( g_{ij} \) are the bandwidth of the link and channel gain from transmitter node \( i \) to receiver node \( j \), respectively.

Each SU node iteratively controls its transmission power distributed link by link. Further, we assume that each SU transmitter node can receive the information of the throughput of the neighbor link by overhearing the signal transmitted to the next node. From this information, the target capacity that the link should attain to satisfy the controlled transmission power is determined as

\[ R_{ij}^{(\text{target})}(x + 1) = \min R_{\text{NeighborLink}}(x), \]  

(22)

where \( R_{\text{NeighborLink}}(x) \) is the throughput of its own link and the neighbor link at iteration \( x \).

Using Eqs. (16) and (22), transmission power \( p_{ij}^{(x+1)} \) of each SU transmitter at iteration \( x + 1 \) is expressed as

\[ p_{ij}^{(x+1)} = \min_{p_i} \left\{ \frac{(2R_{\text{NeighborLink}}(x+1)/B - 1)(I_{\text{sum}}^{(m)} - \Gamma_{\text{PU}})}{g_{ij}} \right\}. \]  

(23)

Here, \( x \) is the iteration number of the TPC algorithm. With Eq. (23), each SU transmitter node \( i \) controls its transmission power and optimizes the end-to-end throughput according to the channel \( m \).

4. Simulation Result

In this section, we present the simulation results of our proposed distributed joint allocation algorithm, which considers the acceptable interference to the PU. We assume \( N = 500 \) nodes in a \( 500 \times 500 \) area. We consider four PU links in this area and a PU receiver is set within the range of this area, which satisfies SINR = 20[dB] from each PU transmitter node in an ad-hoc wireless network. The frequency band is selected within 2.4–2.5 [GHz] by considering wireless LAN on ISM band. We assume that the number of available channels \( M \), which has 20 [MHz] bandwidth each other, and the sensing level for each SU is \( -85.0 \) [dBm]. Since the difference of the frequency in each channel is small, we assume the channel loss of each channel is the same in this paper. In addition, we assume that each node can accurately sense the PU signal and estimate the SINR for each link.

The route for the SU MH flow is established by using the AODV routing protocol according to the result of the exchange of the RREQ and RREP packets through the common control channel. After the route is established, the node assigns the channel by using the proposed channel assignment scheme. The simulation parameters are summarized in Table 1. In this section, we evaluate the end-to-end throughput of the SU MH network, amount of interference to the PU, and throughput of each SU link by increasing iteration \( x \).

For the sake of comparison, we consider the water filling (WF) algorithm, which is based on centralized control, and the existing distributed TPC algorithm with the PU interference constraints [21]. The existing distributed TPC algorithm sets the target capacity, as in Eq. (22), as

\[ R_{ij}^{(\text{target})}(x + 1) = \frac{1}{K} \sum_{\text{NeighborLink}} R_{\text{NeighborLink}}(x), \]  

(24)

where \( K \) is the total number of the links including its own link and the neighbor link. As shown in Eq. (24), each link shares the information of its throughput with the neighbor links, and the average throughput of those links is set as the
Table 1  Simulation parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation area</td>
<td>500 [m] × 500 [m]</td>
</tr>
<tr>
<td>Number of PU links</td>
<td>4</td>
</tr>
<tr>
<td>Number of SU nodes</td>
<td>500</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.45 [GHz]</td>
</tr>
<tr>
<td>Number of channel : $M$</td>
<td>3</td>
</tr>
<tr>
<td>Bandwidth of channel : $B$</td>
<td>20 [MHz]</td>
</tr>
<tr>
<td>Initial transmit power : $P_i^{(n+1)}$</td>
<td>20 [dBm]</td>
</tr>
<tr>
<td>Max. transmit power : $P_{\text{max}}$</td>
<td>25 [dBm]</td>
</tr>
<tr>
<td>PU transmit power : $P_PU$</td>
<td>25 [dBm]</td>
</tr>
<tr>
<td>Sensing level</td>
<td>$-85.0$ [dBm]</td>
</tr>
<tr>
<td>AWGN</td>
<td>$-95.0$ [dBm]</td>
</tr>
<tr>
<td>Propagation loss index : $\gamma$</td>
<td>3.0</td>
</tr>
<tr>
<td>Reference distance : $d_0$</td>
<td>1.0 [m]</td>
</tr>
<tr>
<td>Routing SNR</td>
<td>20 (dB)</td>
</tr>
<tr>
<td>PU acceptable interference power : $\Gamma_m^{(n)}$</td>
<td>$-80$ [dBm]</td>
</tr>
<tr>
<td>Fading</td>
<td>Rayleigh fading</td>
</tr>
</tbody>
</table>

Fig. 5  SU End-to-End throughput (compared with algorithm w/o proposed channel assignment scheme).

Figure 5 shows the effect of the proposed distributed algorithm comparing to the algorithm without the proposed channel assignment scheme. We can see that the SU end-to-end throughput of the proposed algorithm is superior. This is because, in the proposed channel assignment scheme, each SU link can select the data channel effectively by considering the bottleneck link that has small amount of spectrum resources. Also, Fig. 6 shows the effect of the proposed distributed algorithm comparing to the algorithm without the proposed TPC algorithm. From this figure, the proposed algorithm can suppress their transmission power and keep the PU interference limitation, which is set as $-80.0$ [dBm] in this paper. This is because, each SU shares the received power of ACK signal from PUs for each channel $m$ and makes their transmission power maximum with protecting PUs in the proposed TPC algorithm. From these figures, the proposed distributed algorithm can obtain not only higher SU end-to-end throughput but also keeping the interference power to PUs to the limitation level. By combining these ways, each channel on SU multi-hop link can be assigned effectively to make their link throughput higher as shown in Fig. 5 and maximize the throughput with protecting PUs as shown in Fig. 6.

Figures 7–9 show the SU throughput of each link by increasing iteration $x$ of the algorithm for the SU transmission power. Figures 7, 8, and 9 show the throughput convergence of each SU link of the proposed algorithm, that of the WF algorithm based on the centralized control, and that of the conventional distributed TPC algorithm, respectively. As shown in Figs. 7–9, the throughputs of the proposed algorithm and WF algorithm are converged, and these algorithms are more efficient when compared with the conventional distributed algorithm. This is because the conventional distributed algorithm devotes the capacities of both the own link and neighbor ones to be flat. Moreover, the proposed distributed algorithm converges slower than the WF algorithm.
algorithm based on the centralized control. This is because, in the proposed distributed algorithm, each SU sequentially processes their algorithm by using information from only adjacent nodes and then converges to maximum end-to-end throughput which almost equals to centralized control.

Figure 10 shows the aggregated interference power to the PU in each algorithm. As shown in this figure, a graph is illustrated by using the cumulative distribution function (CDF) to show the characteristic of the received interference power of the PU. As shown in Fig. 10, the proposed distributed algorithm and WF algorithm based on the centralized control are satisfied with the PU acceptable interference power limitation \( \Gamma_{\text{PU}}^{(m)} = -80.0 \text{[dBm]} \). We can observe the advantage of the proposed method by predicting the PU interference power. The existing distributed algorithm can only share the information of the neighbor link, and it degrades the performance. In the existing distributed algorithm, each SU transmitter protects the neighbor PUs. However, when the aggregated interference power is considered, the amount of the interference power exceeds the threshold.

Figure 11 shows the SU end-to-end throughput of each algorithm by using the CDF. As shown in Fig. 11, the proposed algorithm is similar to the WF algorithm based on the centralized control. In addition, we can observe that the existing distributed algorithm achieves a higher throughput of approximately 155 [Mbps]. We can explain that this is because of the effect of the lack of PU interference constraints, as shown in Fig. 10. After reaching 155 [Mbps], the end-to-end throughput decreases because of the system whose target capacity is only considered about the average throughput of their own and the neighbor links that cannot attain the higher throughput.

Figure 12 shows the SU end-to-end throughput of the proposed algorithm and the centralized control algorithm with changing PU occupancy ratio. As shown in Fig. 12,
the proposed algorithm is closed to centralized algorithm in each PU occupancy ratio.

5. Conclusion

In this paper, we have proposed an algorithm to improve the end-to-end throughput of the SU MH flow with the joint channel assignment scheme and TPC algorithm by taking into account the PU acceptable interference power limitation. We have determined the SU end-to-end throughput under the interference constraints by using the CDF. As a result, the proposed joint resource allocation improves the end-to-end throughput and interference constraint to the PUs when compared with the existing distributed algorithm. Moreover, the proposed method achieves nearly end-to-end throughput and PU interference constraints with the centralized WF algorithm.

The future work of this research is to consider the mobility of each node. In this paper, our target is actually the static condition by using WLAN system. In order to expand this system mode, the mobility is one of the candidates for consideration. However, it is too complicated for discussing in the same paper. Therefore, in this paper, we focus only on WLAN system, which is one of the spectrum sharing system in a future for effectively utilizing the limited 2.4 GHz band and 5 GHz band and it can be used expanding to mesh networks. The consideration of mobility will be remained to our future works.

References


Shuta Kako received B.E. and M.E. degree in The University of Electro-Communications, Japan, in 2011 and 2013. His research topic is resource allocation in cognitive multi-hop wireless communication networks. He is a member of IEICE and IEEE.

Osamu Takyu received the B.E. degree in Electrical Engineering from Tokyo University of Science, Chiba, Japan, in 2002 and the M.E. and Ph.D. degrees in Open and Environmental Systems from Keio University, Yokohama, Japan in 2003 and 2006, respectively. From 2003 to 2007, he was a research associate in the Department of Information and Computer Science, Keio University. From 2004 to 2005, he was visiting scholar in the School of Electrical and Information Engineering, University of Sydney. From 2007 to 2011, he was an assistant professor in the Department of Electrical Engineering, Tokyo University of Science. He was an assistant professor from 2011 to 2013 and has been an associate professor from 2013 in the Department of Electrical & Electronic Engineering, Shinshu University. Dr. Osamu TAKYU is a recipient of the Young Researcher’s award of IEICE 2010 and 2010 Active Research Award in Radio Communication Systems from IEICE technical committee on RCS. His current research interests are in wireless communication systems and distributed wireless communication technology. He is a member of IEEE.

Takeo Fujii was born in Tokyo, Japan, in 1974. He received the B.E., M.E. and Ph.D. degrees in electrical engineering from Keio University, Yokohama, Japan, in 1997, 1999 and 2002 respectively. From 2000 to 2002, he was a research associate in the Department of Information and Computer Science, Keio University. From 2002 to 2006, he was an assistant professor in the Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology. Since 2006, he has been an associate professor in Advanced Wireless Communication Research Center, The University of Electro-Communications. His current research interests are in cognitive radio and ad-hoc wireless networks. He received Best Paper Award in IEEE VTC 1999-Fall, 2001 Active Research Award in Radio Communication Systems from IEICE technical committee of RCS, 2001 Ericsson Young Scientist Award, Young Researcher’s Award from the IEICE in 2004, The Young Researcher Study Encouragement Award from IEICE technical committee of AN in 2009, and Best Paper Award in CCNC 2013. He is a member of IEICE and IEEE.