Interoperator channel management for dynamic spectrum allocation between different radio systems

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Abstract: For the efficient use of frequency resources, dynamic spectrum allocation (DSA) between different radio systems is promising. In DSA, our approach is to allow different mobile network operators to use the same shared channel without the inter base station (BS) interference. However, this approach is computationally very expensive. Therefore, we formulate this reuse channel allocation as a 0-1 mixed-integer linear programming problem and propose an algorithm to improve the satisfaction of each BS and the time and frequency continuities, which can be used to solve the problem in practical time. Our evaluation demonstrates that our proposed algorithm can improve the satisfaction with the time and frequency continuities simultaneously.

Keywords: dynamic spectrum allocation, spectrum management system, channel allocation algorithm, 5G

Classification: Wireless Communication Technologies

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1 Introduction

For the efficient use of limited frequency resources, dynamic spectrum allocation (DSA) between mobile network systems and different existing radio systems is promising. In DSA, mobile networks are allocated and utilize unused sharable channels (USCs) that are detected based on a time, area, and frequency that are not in use by existing radio systems. Concrete spectrum management systems such as the citizens broad radio service (CBRS) [1] in the USA and licensed shared access (LSA) [2] in Europe for the social implementation of DSA among different radio systems have been examined. In Japan, the government is also considering the possibility of DSA in the 2.3 GHz, 26 GHz and 38 GHz bands [3].

Recently, to improve the spectrum efficiency, DSA methods designed according to the mobile network operator (MNO) demand have been proposed [4, 5]. However, these existing methods allocate USCs on an MNO-by-MNO basis; thus, even if an MNO is not using their allocation channel in some area, other MNOs cannot use the channel allocated to that MNO, resulting in a spatial waste of spectrum resources. In addition, to reduce the number of channel switch operations and improve the utility of shared channel, the demand-based DSA requires time and frequency continuities of channel mapping in the frequency and time directions for the same BS. The existing methods [4, 5] do not address these channel continuities.

This paper’s approach is to improve the spectrum efficiency with the these channel continuities simultaneously by allowing different MNOs to use the same shared channel when the inter base station (BS) interference is below a noise level. However, this channel reuse between BSs with these channel continuities has not been implemented due to the difficulty in calculating the allocation in practical time to meet the BS demand from the myriad combinations of mutual interference between BSs and channel mapping. In this paper, we formulate this reuse channel allocation as a 0-1 mixed-integer programming (MIP) and propose an algorithm to improve the satisfaction of each BS and the time and frequency continuities simultaneously, which can be used to solve the problem in practical time.

2 System model

We show the system model of DSA between different radio systems in Fig. 1(a). This model consists of three systems: the incumbents, the mobile networks and the spectrum management system. Incumbents are nonmobile radio systems, such as satellite systems and fixed wireless access, have been assigned a licensed band and have priority to use the spectrum. The spectrum management system detects the incumbent’s position and the USC by the usage registration information from the incumbents or the sensing data of an incumbent and dynamically allocates the USC to BSs of MNOs at a predetermined timeslot according to their demand. Our proposed channel allocation algorithm is one of the functions of the spectrum management
system. Here, the transmission power of the BS is assumed to be pre-calculated as a value that does not interfere with the incumbents in reference to the CBRS system [1].

Next, we show the proposed allocation procedure in Fig. 1(b). In Fig. 1(b), USC $B$ consisting of multiple allocation units $b$ and the demand spectrum bandwidth $f d_{n,t}$ of BS index $n \in N$ at timeslot $t \in T$ are input into the proposed allocation algorithm, which then outputs the allocation channel $x_{n,f,t}$ of BS $n$ at timeslot $t$ in channel index $f \in F$. Here, $x_{n,f,t}$ is a binary variable defined as

$$x_{n,f,t} = \begin{cases} 1 & \text{channel } f \text{ is allocated to BS } n \text{ at } t \\ 0 & \text{otherwise} \end{cases}. \quad (1)$$

Fig. 1. System model and proposed allocation procedure.

3 Design optimization problem

To judge whether the same channel can be used at the same time between BSs of different MNOs, we determine whether interference occurs depending on the operational status $BS_{n,p}$ of each BS, which is defined by:

$$BS_{n,p} = \begin{cases} 1 & \text{BS } n \text{ is up and running} \\ 0 & \text{BS } n \text{ is down} \end{cases}. \quad (2)$$

Here, $p \in P$ is an index indicating the combination set $BSset_p$ of the operational status $BS_{n,p}$, and $BSset_p$ is as follows:

$$BSset_p = \{BS_{1,p}, BS_{2,p}, \ldots, BS_{N,p}\}. \quad (3)$$

Let the interference between two BSs from BS $a \in N$ to BS $b \in N$ be $I_{a,b}$ ($a \neq b$). Then, the amount of interference $IF_n$ to $BS_{n,p}$ in the combination set $BSset_p$ can be expressed as the following as an aggregation of the interference from the set $n' \in N'$ of other BSs:

$$IF_n = \sum_{n' \in N'} I_{n',n}BS_{n',p}. \quad (4)$$
Let $P_{th}$ be the allowable interference power of BS; then, $\text{BSset}_p$, including a BS with $IF_n > P_{th}$, is determined to be the combination set $\text{BSset}_q$ with interference influence.

Next, we express the problem formulation to determine the allocation channel $x_{n,f,t}$. In this paper, our objective is to maximize three indices simultaneously: the satisfaction of each BS and the channel frequency continuity (FC) and channel time continuity (TC) of the same BS. Satisfaction at $t$ is expressed as a ratio of the allocation spectrum bandwidth to the demand spectrum bandwidth $f_{d_{n,t}}$ using the channel allocation $x_{n,f,t}$ as follows:

$$\text{Satisfaction} = \min \left(1, \frac{\sum_{f \in F} x_{n,f,t}}{f_{d_{n,t}}}\right). \quad (5)$$

FC along the frequency axis and TC along the time axis are binary variables defined as

$$FC = x_{n,f,t}x_{n,f+1,t} = \begin{cases} 1 & \text{frequency continuity in the same BS} \\ 0 & \text{otherwise} \end{cases}, \quad (6)$$

$$TC = x_{n,f,t}x_{n,f,t+1} = \begin{cases} 1 & \text{time continuity in the same BS} \\ 0 & \text{otherwise} \end{cases}. \quad (7)$$

These formulas are 1 only when the same BS $n$ is assigned to adjacent frequency or time channels. To improve these three indices, we express the problem of determining the channel allocation $x_{n,f,t}$ of the USC to the BSs as the following optimization problem:

$$\max_{x_{n,f,t}} \alpha_1 \sum_{n \in N} \sum_{t \in T} \left( \frac{\sum_{f \in F} x_{n,f,t}}{f_{d_{n,t}}} \right) + \alpha_2 \sum_{n \in N} \sum_{t \in T} \sum_{f \in F} (x_{n,f,t}x_{n,f+1,t}) + \alpha_3 \sum_{n \in N} \sum_{f \in F} \sum_{t \in T} (x_{n,f,t}x_{n,f,t+1}) \quad (8a)$$

s.t.  

$$f_{d_{n,t}} \geq \sum_{f \in F} x_{n,f,t}, \quad (\forall n,t) \quad (8b)$$

$$\sum_{n \in N} B_{n,q^{'}} x_{n,f,t} \leq \sum_{n \in N} B_{n,q} - 1, \quad (\forall q^{'}, f, t) \quad (8c)$$

$$x_{n,f,t} \in \{0, 1\} \quad (\forall n, f, t) \quad (8d)$$

Here, $\tau$ is the time slot window for solving the optimization problem. In objective function (8a), the first term counts the satisfaction, the second term counts the FC, and the third term counts the TC, where $\alpha_1$, $\alpha_2$, and $\alpha_3$ are the weights of each index. Constraint (8b) prohibits allocation in excess of demand to prevent overallocation to a particular BS. Constraint (8c) expresses that one or more BSs must be down in the interference combination set $\text{BSset}_{q^{'}}$ to prevent interference between BSs. The optimization problem (8), which is a second-order mixed-integer nonlinear programming, can be transformed into the following mixed-integer linear programming (MILP) by using the auxiliary variables $x_{n,f,t}x_{n,f+1,t} = y_{n,f,t}$ and $x_{n,f,t}x_{n,f,t+1} = z_{n,f,t}$.

$$\max_{x_{n,f,t}} \alpha_1 \sum_{n \in N} \sum_{t \in T} \left( \frac{\sum_{f \in F} x_{n,f,t}}{f_{d_{n,t}}} \right) + \alpha_2 \sum_{n \in N} \sum_{t \in T} \sum_{f \in F} (y_{n,f,t}) + \alpha_3 \sum_{n \in N} \sum_{f \in F} \sum_{t \in T} (z_{n,f,t}) \quad (9a)$$

s.t.  

$$f_{d_{n,t}} \geq \sum_{f \in F} y_{n,f,t}, \quad (\forall n,t) \quad (9b)$$

$$\sum_{n \in N} B_{n,q^{'}} x_{n,f,t} \leq \sum_{n \in N} B_{n,q} - 1, \quad (\forall q^{'}, f, t) \quad (9c)$$
4 Proposed algorithm

Although optimization problem (9) is NP-hard, a general-purpose solver [8] that provides effective approximate solutions to practical scale problems has been developed. However, as the numbers of BSs and USCs and the size of the decision variable $x_{n,f,t}$ increase, an increasingly larger number of computing resources are required in (9). Therefore, we propose the following Algorithm 1 to solve optimization problem (9) in practical time by reducing the size of the decision variables $x_{n,f,t}$ and the number of constraints (9c) of the optimization problem.

**Algorithm 1: Proposed channel allocation algorithm**

Input: $f_d(n,t), B, BSset_p, \alpha_1, \alpha_2, \alpha_3$

1: for $p = 0, P$ do
2:    Calculate $IF_n (\forall n)$ by (4)
3:    if $(IF_n > P_{th})$ then
4:        $BSset_q \leftarrow BSset_p$
5:    end for
6:    for $q = 1, Q$ do
7:        if $(BSset_{-q} \cdot BSset_{-q} \geq BSset_q \cdot BSset_{-q} + 1)$ then
8:            $BSset_{q_1} = BSset_q$
9:        end for
10:   Set $t = 0, \tau = 0$
11:  Solve problem (9). Denote the solution by $x_{n,f,0}$
12:  Add constraints $x_{n,f,0} = \{0, 1\}$
13:  for $t = 1, T - \delta + 2$ do
14:      Set $\tau$ ($\tau \in T, t-1 \leq \tau \leq t+\delta-2$)
15:      Solve problem (9). Denote the solution by $x_{n,f,t} (t \in \tau)$
16:      Add constraints $x_{n,f,t} = \{0, 1\}$ ($t \in \tau$
17:      $t = t + \delta - 1$
18:  end for

Output: $x_{n,f,t} (t \in T)$

Steps (1)–(5) show the extraction of the interfering combination set $BSset_q$ from the operating status combination set $BSset_p$. In steps (6)–(9), to reduce the number of $BSset_q$ values entered into constraint (9c), we determine the inclusion relation by calculating the inner product between $BSset_q$ and output the combination set $BSset_{q_1}$ that has no inclusion relation. Here, $-q$ denotes all combination sets except $q$. For example, if $BSset_{q_1} = \{0,0,1,1\}$ and $BSset_{q_2} = \{0,1,1,1\}$, then $BSset_{q_1}$ is included in $BSset_{q_2}$, and therefore, only $BSset_{q_1}$ is entered into constraint (9c), while $BSset_{q_2}$ is removed.

In steps (10)–(18), to reduce the size of decision variable $x_{n,f,t}$, we divide the
optimization time window into small portions and solve the optimization problem while repeatedly shifting the time window. The allocation channel $x_{n,f,0}$ at $t = 0$ is determined by solving problem (9) in steps (10)–(12). In steps (13)–(18), we repeatedly solve optimization problem (9) with the most recent channel allocation results added as a constraint until the range mapping of $t \in T$ is completed. Here, $\tau$

| Parameters and Assumptions | Value |
|----------------------------|-------|
| Center frequency $f_c$ | 3.6 GHz |
| U/C: $f_c$ | 150 MHz |
| Allocation unit $s$ | 10 MHz |
| Time slot $t$ | 5 minutes |
| BS location | Random (10 km x 10 km two-dimensional space and 160 sector BS location) |
| Transmit power of BS $P_{tx}$ | 20 dBm |
| Antenna pattern | Omni |
| Pathloss $L_{mm}$ | UMA model (loss of site ratio was set to 50%) |
| Allowable interference $P_{int}$ | 110 dBm/MHz |
| User dimension | 288 (24 users) |
| Weight $a_1$, $a_2$, and $a_3$ | (homogeneously selected) |
| Optimization time window $h$ | Dynamically selected |
| Demand spectrum bandwidth $f_{DL}$ | London Internet eXchange Point (min/10m PAL) |
| Standard deviation caused by base traffic | 10 MHz |
| The average demand spectrum ratio of the MNs to MNOs | 39.24:23.10 (The ratio of MNOs to MNs shared in Japan) |
| MIP solver | Gurobi 9.0.1 |

(a) Parameters and assumptions

Fig. 2. Comparison of the average satisfaction, time continuity, frequency continuity and computational time between the proposed method and existing methods.
is the optimization range of timeslot $t$, and $\delta$ is the time window size used in solving problem (9).

5 Evaluation

Common parameters and assumptions used for the system-level evaluation are given in Fig. 2(a). To compare with our algorithm, we used the existing channel allocation method presented in [4], which allocates the USCs for the average demand by the MNO, not by the BS, starting with the least amount of allocation in the past. In the existing method, the channel mapping along the frequency and time axes is allocated in ascending order of the BS index $n$ or determined by classic random mapping.

Figures 2(b), 2(c) and 2(d) show a comparison of the satisfaction, TC and FC for the number of BSs. Here, the TC and FC are the total values for all timeslots in equations (6) and (7) divided by the total number of allocated channels. The proposed algorithm can improve the satisfaction by 31%, TC by 101% and FC by 8%. Figure 2(e) shows a comparison of the time required to solve problem (9). The proposed algorithm reduces the computational time compared to that of the case without steps (6)–(9) and steps (13)–(17) of proposed Algorithm 1. Validating three weights $\alpha_1$, $\alpha_2$ and $\alpha_3$ in the objective function can offer insights and improvements, but we leave that for our future work.

6 Conclusions

In this paper, we have presented an optimization problem for channel allocation that improves the spectrum efficiency by allowing different MNOs to use the same shared spectrum channel and then proposed an algorithm to solve the problem in practical time. Our numerical evaluation demonstrates that our proposed algorithm can improve the satisfaction, TC and FC simultaneously and reduce the computational time required to solve the problem.

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