Adapting IEEE 802.22 OFDMA System for P2PWRANs

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Abstract—**IEEE 802.22 is the first standard to uitilize cognitive radio technology for wireless regional area networks (WRANs). It has adopted a cellular topology containing one base station (BS) and multiple customer premises equipments (CPEs) in a cell. It covers a very large area with radius ranging up to 100 km. Orthogonal frequency-division multiple access (OFDMA) system is employed and it is further slotted in time-domain. In one slot only one CPE can be allocated, and every intra-cell packet needs to be routed through the BS. This point-to-multi-point structure significantly limits the network capacity in the case of CPE-CPE communication, which is predicted to happen, and even the use of OFDMA does not help much. Therefore, peer-to-peer WRAN (P2PWRAN) has been proposed to support direct intra-cell communication in order to extend the network capacity. In this paper, the IEEE 802.22 OFDMA system is adapted to P2PWRAN to support direct CPE-CPE communications. The downstream burst allocation in P2PWRAN is similar to the OFDMA system of IEEE 802.16, which has been widely studied in the literature. Therefore, in this paper we look at the unexplored upstream burst allocation where slots can be reused among CPEs and the BS with power control mechanisms. We propose a burst allocation algorithm that maximizes the network capacity greedily. The algorithm is examined under various conditions such as, number of CPEs, size of requests, length of US subframes and type of requests (CPE-BS or CPE-BS). We also show that our algorithm performs better than the existing solutions.**

Index Terms—**IEEE 802.22, WRAN, OFDMA, cognitive radio, channel allocation, burst allocation.**

I. INTRODUCTION

Many standardization efforts on cognitive radio networks can be found in the literature [1]. IEEE 802.22 is the first worldwide standard based on cognitive radio that operates on TV channels from 2 to 69 (54 MHz to 862 MHz) with bandwidth of 6, 7, or 8 MHz depending on countries [2]. WRANs are formed in a point-to-multi-point (P2M) fashion with one base station (BS) and multiple customer premise equipments (CPEs) in a cell. Orthogonal frequency-division multiple access (OFDMA) is used in IEEE 802.22 so that multiple CPEs are able to access to the BS simultaneously in a cell. Because of the large coverage area of a WRAN cell, more intra-cell communications may be seen compared to other networks such as, IEEE 802.11 and 802.15.4. It is envisaged that in the near future, applications such as, file sharing, peer-to-peer video streaming, voice and video calls (e.g., Skype) between the users who are inside a single large cell would increase. For example, the rapid growth of peer-to-peer applications generate tremendous traffic [3]. It is also envisaged that CPEs in WRANs may generate much heavier

traffic than single-user devices, because one IEEE 802.22 CPE may support more than one user. For example, a CPE may support all the devices in a family or even a small company [2]. However, the network capacity is severely constrained, because one slot can only be used by one CPE. Even though more channels (non-adjacent) are available, only one channel can be used for communication according to IEEE 802.22, and all intra-cell communications need to go through the BS.

To increase the spectrum efficiency and network capacity significantly when there is lot of intra-cellular traffic, P2PWRAN has been proposed [4]. P2PWRAN is similar to Device-to-Device communication in heterogeneous networks [5], and can be considered as a special case with centralized spectrum control, multiple operating channels and power control. P2PWRAN is based on IEEE 802.22 standard with minimal changes to enable P2P communications. In our earlier work we have not addressed the details of how P2PWRAN is enabled [4]. In this paper, we look into the details in the OFDMA system and resource allocation. Our main contributions are:

- We designed the upstream (US) subframe in a P2PWRAN frame. One OFDMA slot can be allocated to multiple transceivers without causing interference to each other.
- The OFDMA slot allocation problem (so called burst allocation problem) is formulated and analysed in different scenarios. We prove it is a computationally hard problem.
- Burst allocation in the US subframe is studied too. A greedy algorithm is proposed considering both the CPE-BS and CPE-CPE requests in the upstream of a cell.
- Our proposal and the existing solutions are simulated and compared in various scenarios.

The rest of this article is organized as follows. In Section II the OFDMA system in IEEE 802.22 standard and its limitations are described. Then the framework of the OFDMA system in P2PWRAN is presented and the burst allocation is studied in Section III. Section IV shows the simulation scenarios and results. We conclude in Section V.

II. OFDMA IN IEEE 802.22

Before we explain the role of OFDMA in IEEE 802.22, we first list all the important terms used in this paper in Table I. The table also consolidates OFDMA system as used in IEEE 802.22. We also define the network capacity of a WRAN is the average throughput of the network under saturated network traffic. With saturated traffic, every CPE has one request at a

TABLE I
TERMINOLOGY.

Terms	Description	In IEEE 802.22 standard
Subchannel	A group of subcarriers and the smallest allocation unit in the frequency domain of the OFDMA system.	One subchannel contains 28 subcarriers.
Channel	A TV channel that contains multiple subchannels.	TV channels with a bandwidth of 6, 7, or 8 MHz. One channel consists 60 subchannels.
Symbol	The smallest allocation unit in the time domain of the OFDMA system.	There are 26 to 42 symbols in a frame.
Slot	One symbol on a subchannel. The smallest allocation unit in the OFDMA system.	60×26 to 60×42 slots in a frame.
CPE request	The required number of slots from a CPE for either CPE to BS or CPE to BS communication.	CPEs send their requests to the BS.
Burst	The slots that allocated to one CPE or multiple CPEs according to the requests.	A burst on a subchannel has to cross at least 7 symbols.
Burst allocation	Allocate slots to different CPEs according to their requests.	The BS makes the burst allocation decision with vertical bursts in the DS subframe and horizontal bursts in the US subframe.
Link	A transceiver pair with a CPE and the BS (CPE-BS or BS-CPE) or two CPEs (CPE-CPE). It is used interchangeably with *transceiver pair* in this paper.	CPE-BS links and BS-CPE links in a cell. Direct CPE-CPE links are not supported.
Slot (re)use	When a slot is allocated to link, this slot is (re)used. It is interchangeably used with *channel (re)use* in this paper.	
Slot reuse times	The number of links that use a certain slot simultaneously in a frame.	Maximally one link can be allocated to a slot.
DS	Downstream. Direction of the data flow. Links in the DS are from the BS to CPEs.	
US	Upstream. Direction of the data flow. Links in the US are from CPEs to the BS or between two CPEs.	Only the links that from CPEs to the BS are supported.

time, and a CPE sends a new request to the BS as soon as the previous request from this CPE has been processed. Therefore, the network capacity can give an overview of the processing ability of the network.

In IEEE 802.22, a superframe/frame structure and OFDMA is adopted as shown in Fig. 1 [2]. We provide a brief description to the IEEE 802.22 OFDMA system here. Frames are divided both in frequency and time domain. Therefore the smallest information carrier is one symbol on one subchannel, which is called an *OFDMA slot* or simply a *slot*. For every 7 slots, both in the time and frequency domain, there is a pilot. The time-domain duplex (TDD) is adopted in the OFDMA. A frame contains a downstream (DS) subframe and an upstream (US) subframe. The DS MAP and US MAP in the DS subframe contain the burst allocation information. First two subchannels in the US subframe are reserved for ranging, bandwidth requests and urgent coexistence situation (UCS) with the Primary users (PUs). The slots in the DS subframe are allocated vertically (spread over the frequency domain first) to shorten the decoding latency for CPEs. A horizontal burst allocation (spread over the time domain first) is employed in the US subframe to limit the instantaneous transmit power of CPEs. Further details can be found in [2].

With the defined superframe structure and OFDMA system, the network capacity with IEEE 802.22 standard is constrained. The reasons are listed below:

1) One slot can only be allocated to one CPE in a frame. Multiple links are not able to share the same slot simultaneously.
2) All packets in a cell have to go through the BS, including the intra-cell packets. Thus additional packet delay and traffic may be found for intra-cell communications.
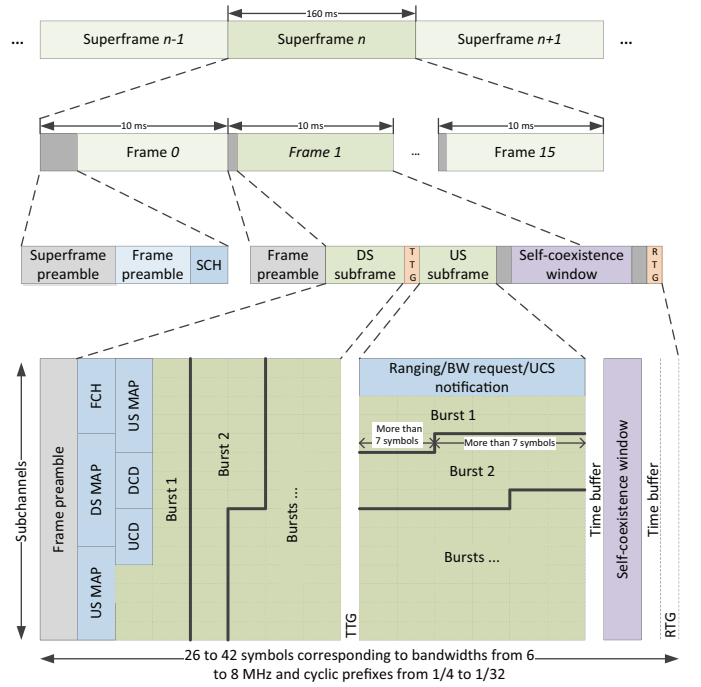3) Even though channel bonding is suggested in [2], the

Fig. 1. The superframe structure and OFDMA system in 802.22 [2]. FCH: superframe control header; DS: downstream; US: upstream; DCD: downstream channel descriptor; UCD: upstream channel descriptor; TTG: transmit-receive turnaround gap; RTG: receive-transmit turnaround gap; BW: bandwidth; UCS: urgent coexistence situation.

available channels that are not adjacent cannot be operated on simultaneously.
4) The BS needs to schedule QPs constantly to sense the usage of channels [6].
5) Multi-input multi-output is not supported because of the

size of antennas in IEEE 802.22 [2].

P2PWRANs target the first three points above to achieve higher capacity. Preliminary ideas are discussed in [4] and details about implementing such a system has not been explored before. As evident from the above description it is not straight-forward to use the above OFDMA system in P2PWRANs. In the next section, we demonstrate the OFDMA system for P2PWRAN in this paper, which concentrates on the single channel scenarios.

III. OFDMA AND BURST ALLOCATION IN P2PWRANS

The OFDMA system and burst allocation problem in P2PWRANs are studied in this section.

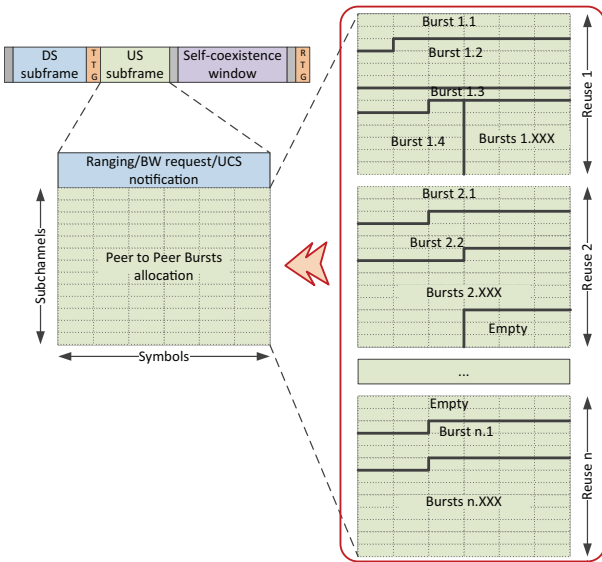### A. OFDMA And Burst Allocation in P2PWRANs

Fig. 2. The US subframe in P2PWRANs.

The OFDMA system in IEEE 802.22 standard (Fig. 1) is not suitable for P2PWRANs anymore because of the slot reuse and CPE-CPE communication. We keep the superframe structure and also the DS subframe as is but modify the US subframe. The DS subframe is still used for communication from the BS to CPEs, which contains the burst allocation information in the DS MAP and US MAP. The US subframe is for P2P communication, which also includes upstream data from CPEs to the BS. As shown in Fig. 2, the first two subchannels are still reserved for special functions. The rest of the slots in the US subframe are for data transmission.

As mentioned before, with transmit power control, a slot can be reused by different CPEs simultaneously as long as no interference is caused. Therefore, slots can be shared by different links simultaneously and multiple times in the US subframe, e.g., Reuse 1, 2,..., n in Fig. 2, but slots can only be used once in IEEE 802.22 standard (Fig. 1). To meet the requirement of IEEE 802.22 standard, in the US burst allocation of P2PWRANs, a subchannel in a burst should contain at least 7 symbols.

Bursts of OFDMA system are the joint slots that are allocated to one or multiple CPEs. In the US of IEEE 802.22 standard, one burst is only allocated to one CPE. Burst allocation is the procedure of allocating the OFDMA slots to different CPEs. The burst allocation directly influence the network and CPE performance, and similar studies can be found in the literature. Therefore, we first summarize the existing studies of burst allocation in IEEE 802.16 and 802.22 in the following content, then it is analysed in the domain of P2PWRANs.

B. Burst Allocation in IEEE 802.16 and 802.22

IEEE 802.22 standard is developed based on IEEE 802.16 (WiMAX: worldwide interoperability for microwave access), therefore the burst allocation problem in IEEE 802.22 and 802.16 are similar [2]. In the literature, many studies on burst allocation in IEEE 802.16 can be found. There are two core technologies in the burst allocation in 802.16, which are (a) queuing mechanism and, (b) allocation method. The queuing mechanism queues the requests from different users, and then the slots are allocated according to this sequence. The requests of users can be queued based on different criteria, e.g., energy consumption [7], different QoS requirements [8], fairness [8], channel quality [7]–[9], and size of the requests [9], [10]. The choice of these queuing mechanisms depends on the preference of the service providers. The allocation method indicates which slot is allocated first, e.g., from top to bottom and left to right in [11], from bottom to top and right to left in [12], row by row from right to left in [13], and from right to left with largest requests considered first in [14]. Del-Castillo, et al. [10] proved that the last allocation method (in [14]) has the least wasted slots (slots without data) in WiMAX.

There are some differences in the burst allocation between IEEE 802.22 and IEEE 802.16. In IEEE 802.16, all bursts in the DS subframe should be rectangular in time and frequency. This allocation problem is NP-hard [8]. However, the bursts are not required to be rectangular in IEEE 802.22. Instead, vertical and horizontal burst allocations are adopted in IEEE 802.22. Therefore, the main consideration in the DS burst allocation of IEEE 802.22 networks is the queuing mechanism, which can be borrowed from IEEE 802.16 networks. These DS queuing mechanisms can also be used in P2PWRAN because the DS subframes are not different between the IEEE 802.22 standard and P2PWRANs. However, because of channel reuse and direct CPE-CPE communication, the burst allocation in the US of the P2PWRANs is totally different from IEEE 802.16 and 802.22. Hence, we mainly discuss the burst allocation in US subframes in the rest of this paper.

C. Analysis of The US Subframe Burst Allocation

Contrary to the DS subframes, the burst allocation in the US subframe is much more complicated in P2PWRAN than in IEEE 802.16 and 802.22 because of the slot reuse. The main differences are:

1) To avoid the harmful interference between US links (CPE-CPE or CPE-BS), an interference map (IM) is

needed to supply information of possible interfering links. We use interference map to allocate the channels.

2) The US burst allocation problem is computationally hard in P2PWRANs, which is studied in this paper later, but not in IEEE 802.22.

3) One of the important goals in WiMAX, which is minimizing the number of wasted slots, is not important in P2PWRAN, because channel reuse is involved. The main goal of the US subframe burst allocation in P2PWRAN is to increase the slot reuse times (i.e., increasing the throughput and/or capacity.

Because of the huge differences in the burst allocation among P2PWRANs, IEEE 802.16 and 802.22 standards, it is not possible to use the existing algorithms/solutions of WiMAX or WRANs for P2PWRANs. Before new solutions are proposed, we first analyze the problem thoroughly by considering its constraints and complexity in different scenarios. We assume that S_U and S_D are the length of the US and DS subframes respectively. Let C_U be the total number of subchannels in the DS and US subframes. When $S_U < 14$, the spectrum sharing problem becomes a maximum independent set problem, which is NP-hard. When $S_U \geqslant 14$, the spectrum sharing problem is similar to the vertex coloring problem, which is also NP-hard. Therefore, we formulate the problem in different cases and analyze it in the following content.

D. Problem Formulation of US Burst Allocation

Different levels of quality of service (QoS) are defined in IEEE 802.22 [2]. To guarantee the QoS in a P2PWRAN, we use a burst allocation mechanism that considers the requests with higher priorities first. However, the allocation of requests with the same QoS levels, as a subproblem, is still an open issue. We discuss this problem on the BS side, which means each CPE only has at most one request at a time. Until the allocation of the existing request, a CPE does not generate further requests to the BS, even if there is a waiting US queue in the CPE.

With the above assumption, requests are allocated in the forms of bursts. Therefore, we first transform the requests into bursts horizontally as shown in Fig. 3. We assume B_{ij} is the burst from CPE i (transmitter) to CPE j (receiver), and $A_{(ij)k}$ is the burst allocation of B_{ij} on kth subchannel. In Fig. 3, B_{ij}^x is the number of extra slots, and B_{ij}^y is the number of subchannels in this burst. We also define B_{ij}^0 as the start of the extra slots, therefore $1 \leqslant B_{ij}^0 \leqslant S_U - B_{ij}^x + 1$. With B_{ij}^x, B_{ij}^y and B_{ij}^0, the shape of a burst can be decided, as shown in Fig. 3.

$A_{(ij)k}$ indicates whether B_{ij} is allocated with subchannel k as in Eq. (1). Note that $A_{(ij)k}$ is different from $A_{(ji)k}$, because the transmitter and the receiver are not the same but they are interchanged.

$$A_{(ij)k} = \begin{cases} 1, & \text{if } B_{ij} \text{ is allocated with subchannel } k, \\ 0, & \text{otherwise.} \end{cases}$$
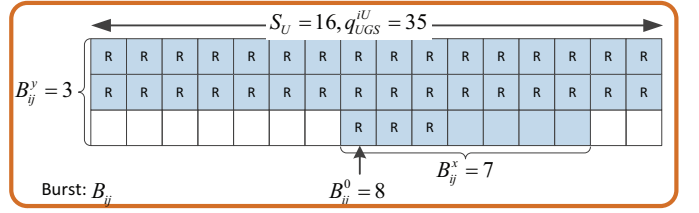
(1)

Fig. 3.   The shape of a burst.

Let $m_{(ij)(pq)k}$ be the element of the interference map, which indicates whether a link from i to j interferes with a link from p to q if the kth subchannel is allocated to these links as described in Eq. (2). A method of building the interference map is studied in [15].

$$m_{(ij)(pq)k} = \begin{cases} 1, & \text{if } B_{ij} \text{ interferes with } B_{pq} \text{ on } k, \\ 0, & \text{otherwise.} \end{cases}$$

(2)

Then we formulate the burst allocation in the US subframe of P2PWRAN in different cases: $S_U < 14$ and $S_U \geqslant 14$. As the first step of our work on the burst allocation in the framework of OFDMA, we only consider the goal of maximizing the throughput, and other secondary goals, e.g., fairness, minimizing energy consumption and transmit power will be studied in our future work.

Case-1 (When $S_U < 14$**:** The burst allocation can be formulated as follows:

$$\max \left(\sum_{i,j,k} A_{(ij)k} \right),$$

(3)

subject to:

$$\sum_k A_{(ij)k} \leqslant B_{ij}^y, \forall i,j.$$

(4)

$$k_p - k_q \leqslant B_{ij}^y - 1, \forall p, q \in (1 \leqslant p \neq q \leqslant B_{ij}^y).$$

(5)

$$\sum_{i,j,p,q,k(i \neq j \neq p \neq q)} A_{(ij)k} A_{(pq)k} m_{(ij)(pq)k} = 0.$$

(6)

The goal of the problem (Eq. (3)) is to maximize the number of times slots are used. The first constraint (Eq. (4)) indicates that every burst can only be allocated once and the allocated subchannels should not be larger than requested. Another constraint should be considered is that the subchannels allocated to the same burst are adjacent as shown in Eq. (5). The purpose of adjacent subchannels is to *decrease* the size of the US MAP. Eq. (6) is the interference constraint, which describes that any two burst allocating with the same subchannel should not interfere with each other.

Case-2 (When $S_U \geqslant 14$**):** In this case, one subchannel may fit into two or more bursts without overlapping of slots, and multiple subchannels might be allocated to one burst, and one subchannel can be allocated to multiple interfering bursts without overlapping slots. Therefore, the condition in Eq. (6) is not suitable anymore. We can modify the constraint in Eq. (6) as Eq. (7), which describes that if two interfered bursts are

allocated within the same subchannel, then there should be no overlap symbols.

$$A_{(ij)k} A_{(pq)k} m_{(ij)(pq)k} \neq 0,$$
$$\text{only if } B_{ij}^0 + B_{ij}^x \leqslant B_{pq}^0, \text{ or } B_{ij}^0 \geqslant B_{pq}^0 + B_{pq}^x, \qquad (7)$$
$$(\forall i, j, p, q, k, \text{ and } i \neq j \neq p \neq q).$$

E. Burst Allocation Mechanism in P2PWRANs

According to the above discussions, burst allocation in the US subframe is a computationally hard problem. However, the BS needs to make allocation decisions for both the DS and US subframes every 10 ms, therefore, a simple mechanism should be adopted. Greedy algorithm is a simple, efficient, and widely used algorithm for vertex coloring problems [16], which suits well for the burst allocation problem. The main idea of the greedy algorithm is to color the vertex with least number of connections with others first. Therefore, we define an *interference degree* for each request, which is the number of interfering requests (in the current set) if they have overlapping slots. Interference degree reflects the chances of interfering with other requests. During the allocation, we first allocate the CPE-BS US requests firstly that they are allocated in **Reuse 1** as shown in Fig. 2. A CPE-BS is allocated first if the CPE experiences lesser accessing opportunities in the previous frames. Then CPE-CPE requests attempt to reuse the slots after the allocation of CPE-BS requests. The CPE-CPE requests are queued according to D_{ij} in an ascending order. The requests with lesser D_{ij} are considered first during the allocation on every possible position in the US subframe. If such a position is found for a request that does not interfere with the already allocated requests, then it is allocated. The burst allocation is an iterative process, and the unallocated requests are saved in the waiting list and considered in the next frame. The complexity of this algorithm is $O(C_U S_U |A|^2)$, in which $|C_U|$ is the number of subchannels in a frame and $|A|$ is the number of requests. Details of the allocation algorithm can be seen in Algorithm 1.

IV. SIMULATION AND RESULTS

The OFDMA system and the burst allocation algorithm in the US subframe of P2PWRANs are examined. We consider a P2PWRAN cell with a radius of 40 km and up to 200 CPEs. Certain percentage of the US requests is for communication to the BS and the rest are CPE-CPE requests within the transmission radius. The simulations have been carried out in Matlab. A saturated traffic model is adopted in which every CPE generates a new request (either to other CPEs or to the BS) as soon as its previous requests is allocated. We examine the trends of the network throughput and the percentage of requests served when the number of nodes (Fig. 4), size of the requests (Fig. 5), and length of the US subframe (Fig. 6), respectively. Two well-known burst allocation algorithms for the WiMAX: (i) the Ohseki, et al. algorithm [13] and, (ii) the enhanced One Column Striping with non-increasing Area first mapping (eOCSA) [14], are simulated and compared with our algorithm (Algorithm 1). Rest of the simulation parameters are

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Algorithm 1 Greedy US burst allocation in P2PWRAN.

1: Queue the CPEs with the CPE-BS requests according to the previous allocation information, and the least allocated CPEs are in the head of the queue.
2: Allocate the CPE-BS requests fairly amongst the CPEs according to the queue.
3: //Allocate the CPE-CPE requests.
4: Count the interference degrees of the CPE-CPE requests and sort them in the ascending order and place them in a queue.
5: **for** every CPE-CPE request B_{ij} in the queue, **do**
6:    **for** every subchannel k, **do**
7:       Allocate this request starting from k_{th} subchannel in all possible positions.
8:       Examine whether it interferes with the already allocated requests.
9:       **if** interfering, **then**
10:          Withdraw the allocation, exit this loop and try next subchannel.
11:       **else if** this request does not interfere with any other already allocated requests, **then**
12:          Allocate with the deployment, exit the loops and examine the next request.
13:       **end if**
14:    **end for**
15: **end for**
16: Move the unallocated requests (CPE-CPE and CPE-BS) to the waiting list.

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listed in Table II. Detailed information on the construction of interference map can be found in [15].

TABLE II
SIMULATION PARAMETERS.

Parameters	Values
Radius of cells	40 km
Channel bandwidth	6 Mhz
MCS	64-QAM
Number of US subchannels (C_U)	58
Antennas of BSs	Omni-directional
Antennas of CPEs	Directional (angle: $\frac{\pi}{4}$)
Traffic generation	Saturated

The results are shown in Fig. 4, 5, and 6. When the number of nodes and size of requests grow, the throughput of P2PWRAN grows rapidly because of the increase in requests (Fig. 4(a) and 5(a)). The dip in the number of requests served, as seen in Fig. 4(b) and 5(b), is because the increase in allocations is not commensurate with the increase in requests. The throughput of the P2PWRAN also increases with the increase in the US subframe, since more slots are made available (Fig. 6(a)). The same reason applies to Fig. 6(b). The P2PWRAN still outperform the eOCSA and the algorithm by Ohseki et al. Further in most of the above situations, the figures show a large gap between our algorithm and two from the literature. Ohseki et al. achieves better performance than
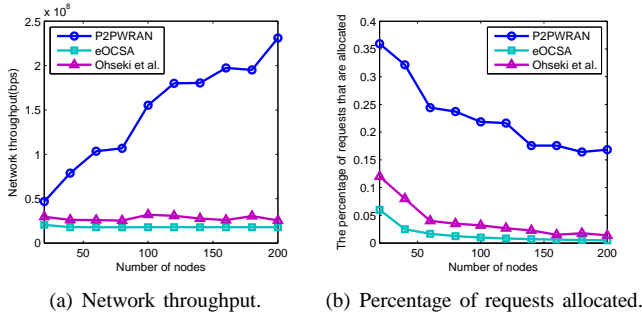
(a) Network throughput.

(b) Percentage of requests allocated.

Fig. 4. Burst allocation in the US subframe with growing number of CPEs, when $S_U = 26$, 50% requests are CPE-BS, B_{ij}^y is randomly from 1 to C_U and B_{ij}^x is randomly from 1 to S_U.

(a) Network throughput.

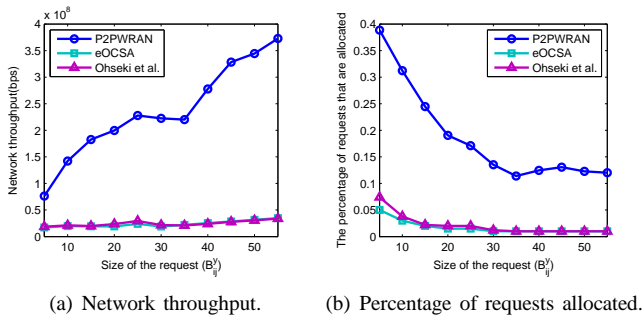(b) Percentage of requests allocated.

Fig. 5. Burst allocation in the US subframe with growing sizes of requests ($B_{ij}y$) from 1 to C_U (a whole subframe), when there are 200 CPEs, $S_U = 26$, 50% requests are CPE-BS, and B_{ij}^x is randomly from 1 to S_U.

eOCSA in most cases, because of fewer wasted slots and more allocation of requests. That is different from the results in WiMAX, as it is proved that eOCSA has better performance than the algorithm by Ohseki et al. in [10]. That is because the bursts are required to be rectangular in WiMAX, but not in WARNs and P2PWRANs.

V. CONCLUSIONS AND FUTURE WORK

The cellular topology of IEEE 802.22 networks provides an easy network management but constrains the network performance significantly. Therefore, P2PWRAN has been proposed to enhance the network capacity by supporting
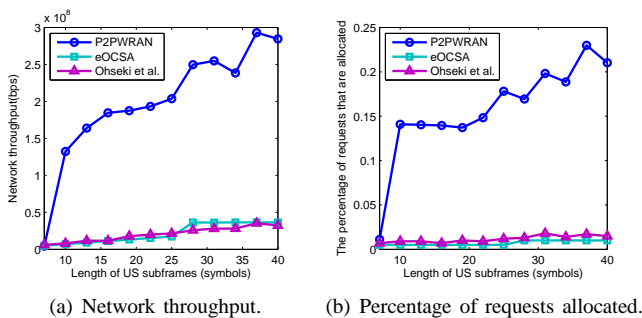

(a) Network throughput.

(b) Percentage of requests allocated.

Fig. 6. Burst allocation in the US subframe with growing length (S_U) from 7 to 42, when there are 200 CPEs, 50% requests are CPE-BS, B_{ij}^y is randomly from 1 to C_U, and B_{ij}^x are randomly from 1 to S_U.

direct CPE-CPE intra-cell communications without causing much extra managing cost. We adapted the OFDMA system in IEEE 802.22 standard to P2PWRANs and analyzed the burst allocation problem under different circumstances in this paper. Furthermore, the OFDMA system and the allocation algorithm are examined. The network capacity can be extended significantly, and more CPE requests can be satisfied.

The self-coexistence and channel sharing between cells are also important issues in P2PWRANs, which will be studied in our future work.

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