On OFDMA Resource Allocation and Wavelength Assignment in OFDMA-Based WDM Radio-Over-Fiber Picocellular Networks

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***Abstract*—This paper addresses the orthogonal frequency-division multiple access (OFDMA) resource allocation and wavelength assignment problems in wavelength-division multiplexing (WDM) radio-over-fiber picocellular networks with OFDMA as the wireless modulation and access scheme. We consider the case that the number of WDM wavelengths is limited in which one wavelength is shared among multiple picocells. The set of picocells sharing the same wavelength is referred to as a *nanocell* in this paper. Since picocells in the same nanocell cannot be allocated with OFDMA resource block (RB) of the same frequency at a time, the intra-nanocell interference is eliminated. However, picocells in different nanocells may be allocated with OFDMA RBs of the same frequency at a time, thus posing interference to each other. To minimize the inter-nanocell interference, OFDMA RBs of the same frequency are assigned to picocells which pose the least interference to each other. However, this may result in some picocells being allocated with a large number of OFDMA RBs, leading to the limited power share received by each OFDMA RB because of the power constraint of the picocell. To minimize the inter-nanocell interference with consideration of the power constraints of picocells, we recast the OFDMA resource allocation and wavelength assignment problems into graph problems, and then propose corresponding solutions.**

***Index Terms*—picocellular, radio-over-fiber, OFDMA, resource allocation, wavelength assignment**

I. Introduction

RADIO-OVER-FIBER (RoF) picocellular networks [1], [2] are becoming promising options for delivering high speed wireless access services to accommodate bandwidth-demanding applications, such as HDTV. Instead of centrally locating antennas at the base station in conventional wireless networks, the RoF picocellular network distributes antennas over the cell to get closer to mobile users. This can increase the signal to noise ratio (SNR) at the receiver and thereby increase the wireless access data rate. The coverage area of each antenna is greatly reduced as compared to the conventional cell, thus resulting in the sharing of wireless resources among a smaller number of users, and increasing the bandwidth share of each user.

Typically, in RoF picocellular networks, upstream wireless signals are first sent to distributed antennas, and then converted to optical signals and further transmitted to the base station which is usually located at the central office. The downstream signal transmits in the opposite direction. In the physical layer, radio signals are usually delivered directly at high frequencies to/from the base station by utilizing RoF transmission technology. The simple structure of antennas makes the RoF network a promising cost-effective wireless access solution especially for in-building environment such as airports, conference centers, shopping malls, stadiums, and subways [3]. Owing to the high bandwidth provisioning, RoF enables promising applications in many network scenarios such as fourth-generation (4G) wireless systems and wireless local area networks (WLANs) [4].

RoF picocellular networks can be considered as the integration of wireless access and optical access. The wireless access refers to the communication between mobile users and antennas, whereas the optical access refers to the communication between antennas and the base station. In this paper, we consider orthogonal frequency-division multiple access (OFDMA) as the wireless modulation and access method [5], [6]. OFDMA, well known for its immunity to multipath interference, has been adopted by both LTE and WiMAX as the downlink access scheme [7]. OFDMA divides the frequency band into non-overlapping orthogonal OFDMA subcarriers. These subcarriers can be flexibly allocated to individual mobile users at different time slots based on the real-time incoming user traffic demands and wireless channel status.

For the optical access, one solution is to use one single upstream/downstream wavelength to carry traffic of all mobile users. Then, OFDMA subcarriers carried over the wavelength are shared by all users in the picocellular network. However, the single wavelength may not be able to accommodate future bandwidth-demanding multimedia applications. To meet the ever increasing bandwidth requirement, 4G wireless systems are being rapidly developed and deployed, and the optical access systems in particular passive optical networks (PONs) are increasing upstream/downstream wavelengths [8]–[15]. In order to accommodate the growing traffic in wireless networks especially 4G systems, we consider the adoption of wavelength-division multiplexing (WDM) in the optical access. In WDM optical access networks, the downstream optical signals are usually demultiplexed into individual wavelengths and delivered to picocells by using demultiplexing devices such as arrayed waveguide gratings (AWG), optical add-drop multiplexer (OADM), or wavelength filters, and the upstream

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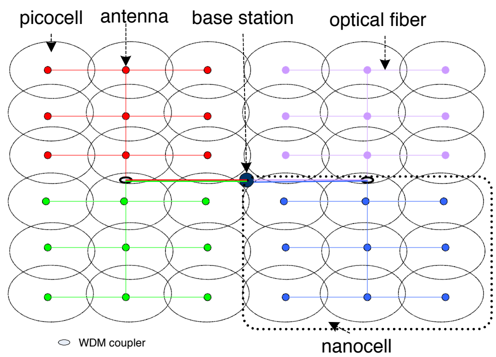


Fig. 1. WDM Radio-over-fiber picocellular network architecture

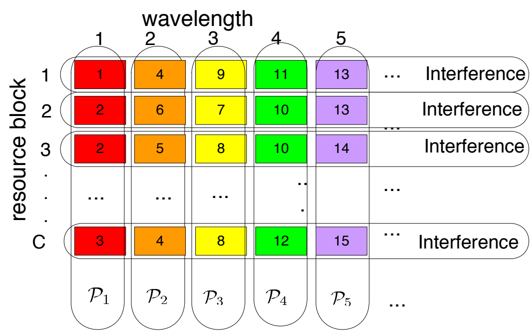


Fig. 2. One example of OFDMA RB allocation at a time instance

optical signals modulated onto certain wavelengths are first generated by lasers at antennas, and then multiplexed onto a single fiber by using multiplexing devices such as couplers [2], [16].

For high bandwidth provisioning, we expect that one or more wavelengths can be dedicated for each picocell. However, a large quantity of wavelengths are needed for a large-scale picocellular network; this further incurs high network cost since the prices of WDM optical devices are usually high when the number of supporting wavelengths is large. For a reasonable network cost, the number of wavelengths may fall below the number of picocells in large picocellular networks. In this case, multiple picocells need to share the same wavelength.

In this paper, in consideration of the scenario that one WDM wavelength is shared among multiple picocells, we investigate the wavelength assignment and OFDMA resource block (RB) allocation problems in the OFDMA-based WDM RoF network. For a better description, we refer to the area covered by picocells sharing the same wavelength as a *nanocell*. Fig. 1 shows one example of the RoF picocellular network. The base station which is typically located at the central office is connected with multiple antennas via optical fibers [4]. In the example shown in Fig. 1, the base station connects with 36 antennas, among which each set of 9 antennas covers a nanocell. Note that a nanocell may not cover a continuous geographic area. Since one OFDMA RB in an OFDMA symbol can only be allocated to one picocell in a nanocell at a time, the inter-nanocell interference is eliminated. However, interferences between picocells in different nanocells may still exist when those picocells are allocated with OFDMA RBs of the same frequency. Such inter-nanocell interference can be minimized by assigning RBs of the same frequency to picocells which pose the least interference to each other. However, this may result in some picocells being over-allocated with many RBs while some others under-allocated with few RBs. In picocells which are allocated with many OFDMA RBs, each OFDMA RB may receive a very limited power share owing to the power constraint of the picocell. Thereby, the signal to interference plus noise ratio (SINR) perceived by users allocated with the RB is small even if the inter-picocell interference can be avoided.

In this paper, we consider the power constraints of picocells and investigate the problem of minimizing the inter-nanocell interference in allocating OFDMA RBs and assigning wavelengths. Specifically, we employ conflict graphs to characterize constraints of OFDMA RB allocation and wavelength assignment. By using conflict graphs, we prove that the problem of maximizing the number of allocated OFDMA RBs is strong NP-hard when no inter-picocell interference is allowed and the power constraints of picocells are considered. We also show that the problem of allocating OFDMA resources at a time instance can be polynomially reducible to graph problems. Finally, we heuristically map the wavelength assignment problem with the objective of maximizing the number of assigned RBs into graph partitioning problems, and then propose algorithms to address these problems.

The rest of the paper is organized as follows. Section II describes the system model, presents the formal formulations of the problems, and discusses related works. Section III discusses the OFDMA resource allocation problem. Section IV investigates the wavelength assignment problem. Section V presents and analyzes extensive simulation results. Section VI presents concluding remarks.

II. System Model, Problem Formulation, and Related Works

A. System model

Similar to WiMAX, we assume the OFDMA radio resource can be partitioned in both time and frequency domains [17]–[19]. Specifically, the frequency resource is divided into multiple non-overlapping OFDMA RBs, each of which contains a subset of OFDMA subcarriers. OFDMA RB in a time slot serves as the minimum unit of resource allocation. Picocells in the same nanocell share OFDMA resources in an OFDMA symbol. Since picocells in the same nanocell are not allocated with the same RB at a time, they do not pose interferences to each other. However, picocells in different nanocells may interfere with each other. Fig. 2 shows one example of the wavelength assignment and RB allocation at a time instance. Let set $\mathcal{P}_w$ contain picocells in the nanocell assigned with wavelength w. In the example, $\mathcal{P}_1 = \{1, 2, 3\}$, $\mathcal{P}_2 = \{4, 5, 6\}$, $\mathcal{P}_3 = \{7, 8, 9\}$, etc., and Picocells 1, 4, 9, 11, and 13 are allocated with RB 1, and interfere each other.

To minimize the inter-nanocell interference, picocells which pose the least interferences to each other should be selected and assigned with the same RB. However, considering the interferences only may result in some picocells being over-allocated with many RBs while some others under-allocated with few RBs. Owing to the power constraint at each picocell, the RB will get small power share if the picocell is allocated with many RBs, thereby reducing the signal power and limiting the user data rate. Therefore, both the inter-nanocell interference and power constraints of picocells need to be considered so as to maximize the total delivered data rates at a time.

We invoke the following assumptions about the interference and user data rate.

- *Assumption 1*: We assume that wireless channel interference dominates the optical wavelength channel interference, and consider the wireless channel interference only.
- *Assumption 2*: Similar to the interference model in [20]–[23], we consider the binary case of the interference between picocells and assume that the wireless channel is RB inselective. Denote $I_{p,p'}$ as the interference between picocell p and picocell p'. If the transmission of RBs in picocell p interfere that in picocell p', $I_{p,p'} = 1$; otherwise, $I_{p,p'} = 0$. We also assume the interference is symmetric, i.e., $I_{p,p'} = I_{p',p}$. Since the wireless channel condition is dynamically changing, the interference $I_{p,p'}$ between two picocells changes over time.
- *Assumption 3*: Considering the power constraint of each picocell, we assume that each picocell is allocated with at most C/P RBs at a time, where C is the number of RBs and P is the number of picocells in a nanocell. We also assume each RB is allocated with the same amount of power.
- *Assumption 4*: We do not investigate the problem of further allocating OFDMA RB to mobile users in this paper, but assume that the maximum rate delivered by any RB at any picocell is the same when there is no inter-nanocell interference.

B. Mathematical formulation

In this paper, we investigate a slot-based wavelength assignment and OFDMA RB allocation scheme. To achieve high throughput, we maximize the total transmitted data rates of all RBs in a time slot.

Let W be the number of WDM wavelengths, and set $\mathcal{Q}$ contain all the picocells which have backlogged traffic in the time slot. The wavelength assignment problem is to divide set $\mathcal{Q}$ into W subsets, each of which is assigned with one wavelength. As defined earlier, $\mathcal{P}_w$ contains picocells in the nanocell assigned with wavelength w. Then, $\cup_{w=1}^{W}\mathcal{P}_w = \mathcal{Q}$ and $\mathcal{P}_w \cap \mathcal{P}_{w'} = \emptyset, \forall w \neq w'$. We assume that each nanocell contains the same amount of picocells. Denote P as the number of picocells in a nanocell. Then, $P = |\mathcal{P}_w| = |\mathcal{Q}|/W, \forall w$.

Denote $x_{w,c}$ as the picocell to which RB c carried by wavelength w is assigned at a time instance. $x_{w,c} \in 0 \cup |\mathcal{Q}|$. $x_{w,c} = 0$ if RB c carried by wavelength w is not assigned to any picocell. Denote $y_{w,c}$ as the indicator of whether RB c on wavelength w is allocated. $y_{w,c} \in \{0, 1\}$. $y_{w,c} = 1$ if $x_{w,c} > 0$; $y_{w,c} = 0$, otherwise. Since the rate delivered by any RB at any picocell is assumed to be the same (see Assumption 4), the data rate delivered to picocell p is proportional to the number of RBs allocated to picocell p, i.e., $\sum_{\{c|x_{w,c}=p\}} y_{w,c}$.

The total transmitted data rates of all RBs in the network is proportional to $\sum_p \sum_{\{c|x_{w,c}=p\}} y_{w,c} = \sum_w \sum_c y_{w,c}$. Then, the joint wavelength assignment and OFDMA RB allocation problem with the objective of maximizing the total transmitted data rates in the network subject to the constraints that no interferences are allowed can be described as follows.

Given: $I_{WP\times WP}$ and set $\mathcal{Q}$
Decide: $\mathcal{P}_w, \forall w$ and $x_{w,c}, \forall w, c$
Objective: maximize $\sum_w \sum_c y_{w,c}$
Subject to:

$$\cup_{w=1}^{W}\mathcal{P}_w = \mathcal{Q} \tag{1}$$

$$\mathcal{P}_w \cap \mathcal{P}_{w'} = \emptyset, \forall w \neq w' \tag{2}$$

$$x_{w,c} \in \mathcal{P}_w \tag{3}$$

$$I_{x_{w,c},x_{w',c}} = 0, \forall c, \forall w \neq w' \tag{4}$$

$$\sum_{\{c|x_{w,c}=p\}} y_{w,c} \leq C/P, \forall w, \forall p \in \mathcal{P}_w \tag{5}$$

Constraints (1) and (2) describe the wavelength assignment constraints. Constraint (4) states that RB c cannot be allocated to two picocells posing interferences to each other. Constraint (5) limits that the number of RBs allocated to any picocell p in any nanocell w cannot be greater than C/P.

To address the problem, we decompose it into two subproblems, i.e., wavelength assignment and OFDMA RB allocation. The OFDMA RB allocation problem can be formulated as:

Given $I_{WP\times WP}$ and $\mathcal{P}_w, \forall w$, determine $x_{w,c}, \forall w, c$ subject to constraints (3 - 5).

A different wavelength assignment scheme $\{\mathcal{P}_w\}_{w=1}^{W}$ may result in different $f(\{\mathcal{P}_w\}_{w=1}^{W})$. Let $f(\{\mathcal{P}_w\}_{w=1}^{W})$ be the maximum number of assigned RBs with respect to a wavelength assignment scheme $\{\mathcal{P}_w\}_{w=1}^{W}$. The wavelength assignment problem can be formulated as:

Given the interference $I_{WP\times WP}$ and set $\mathcal{Q}$, find $\{\mathcal{P}_w\}_{w=1}^{W}$ such that $f(\{\mathcal{P}_w\}_{w=1}^{W})$ is maximized subject to constraints (1) and (2).

Since $I_{WP\times WP}$ is time varying (see Assumption 2), the optimal wavelength assignment changes over time. To dynamically assign wavelengths, antennas need to be equipped with wavelength tunable transceivers, which are currently still cost-prohibitive. If wavelength-fixed devices are employed in the network, the problem of determining the wavelength supported by each optical transceiver can be similarly formulated by replacing the real-time interference matrix $I_{WP\times WP}$ with statistical interference $I_{WP\times WP}$.

We next address the OFDMA RB allocation problem and wavelength assignment problem, respectively. Table I lists notations used in the paper.

C. Related works

Formerly, dynamic power and resource allocation have been proposed to maximize the sum of throughput over all users or equalize user throughput in OFDMA-based cellular networks [24], [25]. Zhu *et al.* [26] presented chunk-based OFDMA subcarrier allocation schemes to simplify the subcarrier allocation algorithm and reduce the overhead. From the combinatorial optimization perspective, Reuven *et al.* [27] investigated the issue of properly selecting packets to be transmitted, determining Phy-profiles for each packet, and

TABLE I
NOTATIONS

Symbol	Definition
W	The number of wavelengths or nanocells
P	The number of picocells in a nanocell
C	The number of OFDMA RBs in an OFDMA symbol
$\mathcal{Q}$	The set of all picocells
$\mathcal{P}_w$	The set which contains picocells in the nanocell assigned with wavelength w
$x_{w,c}$	The picocell to which RB c carried by wavelength w is assigned
$y_{w,c}$	The indicator of whether RB c carried by wavelength w is allocated
$I_{p,p'}$	The binary interference between picocell p and picocell p'
$f(\{\mathcal{P}_w\}_{w=1}^{W})$	The maximum number of assigned RBs with respect to a wavelength assignment scheme $\{\mathcal{P}_w\}_{w=1}^{W}$
$\mathcal{G}(V,E)$	The constructed conflict graph
$\mathcal{G}^{\alpha}(V,E^{\alpha})$	The conflict graph containing interference edges only
$\mathcal{G}^{\beta}(V,E^{\beta})$	The conflict graph containing co-nanocell edges only
$\mathcal{N}(\mathcal{G}(V,E))$	The maximum number of vertices in graph $\mathcal{G}(V,E)$ which can be colored using P colors

constructing OFDMA frame matrix such that the profit gained by the transmitted traffic can be maximized. Lee *et al.* [19] tried to optimally select the MIMO mode (multiplexing or diversity) so as to maximize the proportional fairness criterion with the constraints that only one mode can be selected per user per time interval. For multicell wireless networks, Wang *et al.* [28] investigated the direct sequence code division multiple access (DS-CDMA) microcellular network operating over a multipath Rician fading channel and sharing common spectrum with various narrowband waveforms. To reject the intra-cell as well as inter-cell interference, a suppression filter was equipped at each CDMA receiver and its performance was investigated. Sang *et al.* [29] proposed a scalable cross-layer framework to coordinate the packet-level scheduling, call-level cell selection, and system-level cell coverage for CDMA systems. Gault *et al.* [30] investigated the power and subcarrier allocation issue with the objective of minimizing the total transmitted power based on the statistical knowledge of the user channels.

Resource allocation in WDM access networks also received intensive attention in the past. McGarry *et al.* [31] modeled the wavelength assignment problem into a multiprocessor scheduling problem and proposed to use the longest processing time (LPT) first rule to address the minimizing makespan problem for the case that ONUs can access all the wavelengths. Meng *et al.* [32] studied the joint grant scheduling and wavelength assignment problem. They formulated it into a mixed integer linear programming (MILP) problem, and employed tabu search to obtain the optimal solution. In [33], [34], we theoretically analyzed the capacity of WDM passive optical networks. In [35], with consideration of the laser tuning time, we proposed wavelength scheduling schemes to schedule ONU traffic as early as possible in hybrid WDM/TDM PONs.

Regarding the optical and wireless integration, Sarkar *et al.* [36], [37] proposed a hybrid wireless-optical broadband access network (WOBAN) and employed the Lagrangian relaxation technique to address the problem of optimal placement of ONUs and BSs. In WOBAN, mobile users communicate with a wireless BS, which is connected to the ONU. Koonen *et al.* [38] proposed a fiber-wireless network which uses a flexible wavelength router at a local spitting center to adjust wavelength routing between OLT and ONUs. In this case, the wavelength can be dynamically assigned to each ONU/cell. For the wireless access part, the radio access function is integrated with ONUs [38]. The two integrated optical-wireless networks share one common characteristic, that is, the radio access controller is responsible for the wireless resource allocation of a single cell only, which is different from our case that the base station controls wavelength assignment and OFDMA resource allocation in all picocells.

To the best of our knowledge, our proposal is the first attempt to tackle the wavelength assignment and OFDMA resource allocation problem in OFDMA-based WDM RoF networks, in which wavelength assignment and OFDMA resource allocation need to be properly tackled in consideration of the inter-nanocell interference.

III. OFDMA RESOURCE ALLOCATION

In this section, we first transform the OFDMA resource allocation problem into graph problems, then analyze their complexities, and finally propose solutions to address them.

A. Conflict graph

Following the idea of modeling binary interferences among nodes in wireless networks [20]–[23], [39], we use conflict graph to model the interferences in this paper. Besides the interference, we characterize the co-nanocell scheduling constraints by using the conflict graph as well. Denote $\mathcal{G}(V,E)$ as the conflict graph. In $\mathcal{G}(V,E)$, vertices represent picocells, and $|V| = WP$. Edges characterize the scheduling constraints among picocells. Two vertices are connected if they cannot be allocated with the same RB at a time.

There are two kinds of edges in $\mathcal{G}(V,E)$. When $I_{p,p'} = 1$, picocell p interferes with picocell p', and hence vertices p and p' are connected. These edges are referred to as *interference edges*. When picocell p and picocell p' are within the same nanocell, they cannot be allocated with the same RB at a time, and hence are connected. These edges are referred to as *co-nanocell edges*. Note that an edge can be both co-nanocell edge and interference edge. We further denote the graph containing interference edges only as $\mathcal{G}^{\alpha}(V,E^{\alpha})$, and that containing co-nanocell edges only as $\mathcal{G}^{\beta}(V,E^{\beta})$. Then, $E = E^{\alpha} \cup E^{\beta}$.

Fig. 3 shows one example of the conflict graph. The network contains 16 picocells, among which four nearby picocells constitute a nanocell. Fig. 3 (b) shows the conflict graph with the interference edges only, and Fig. 3 (a) shows the conflict graph with the co-channel edges only. Some edges are both co-nanocell edges and interference edges as shown in Fig. 3 (c).

By using conflict graphs, the OFDMA RB allocation problem is transformed into the problem of labeling the vertices by RB id such that no two adjacent vertices are labeled with the same RB id. The objective of maximizing the number of allocated RBs is equivalent to that of maximizing the sum of labels labeled on all vertices. Note that one vertex can be labeled with more than one RB id since one picocell can be

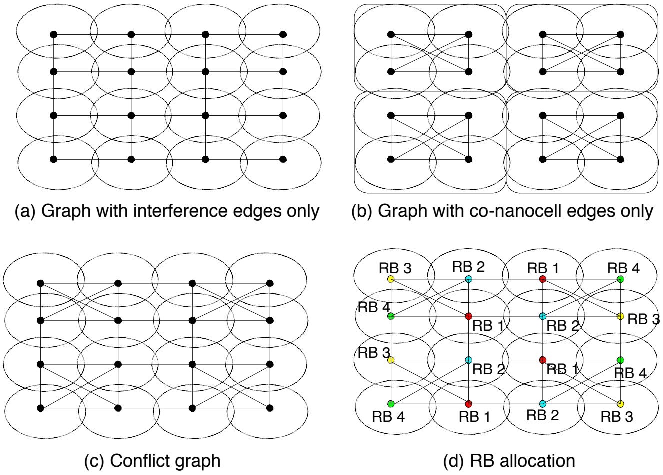


Fig. 3. An example of conflict graph and its coloring.

allocated with more than one RB at a time. Fig. 3 (d) shows one RB labeling scheme with four RBs for the conflict graph as shown in Fig. 3 (c).

B. Computational Complexity

We show that the OFDMA RB allocation problem is NP-hard in the strong sense.

Theorem 1. *The OFDMA RB allocation problem with the objective of maximizing the number of allocated RBs at a time is strong NP-hard.*

Proof: We prove the strong NP-hardness property of this problem by showing that the maximum independent set problem is reducible to this problem.

Given a graph $G(V, E)$, the independent set is a set containing vertices of which no two vertices are adjacent. The maximum independent set problem is to find the independent set with the largest size.

Consider an arbitrary instance of the maximum independent set problem for graph $G(V, E)$. We construct an equivalent OFDMA RB problem. Let both the total number of picocells PW and the number of wavelengths W be $|V|$, and graph $G(V, E)$ be the conflict graph. Then, $P = 1$, each picocell has a dedicated wavelength, and each vertex v in the conflict graph can be labeled with at most C RBs.

We show that the optimal labeling scheme is to label all vertices in the maximum independent set of graph $G(V, E)$ with all RBs, and leave all the other vertices unlabeled. The vertices labeled by any RB id must be in an independent set. So, the maximum number of vertices a RB can be labeled equals to to the size of the largest independent set. This scheme achieves the maximum number. Therefore, finding the optimal labeling is equivalent to finding the maximum independent set. The independent set problem is known to be strong NP-hard. Thus, the RB allocation problem is strong NP-hard. ■

Owing to the NP-hardness property of the problem, we may employ the brute force search to find the optimal solution. To examine whether or not the brute-force search is practical, we evaluate the running time of the brute force search for this problem.

Lemma 1. *The running time of the brute-force search for the optimal solution to the OFDMA resource allocation problem is $O(P^{CW})$.*

Proof: Each RB can be allocated to any picocell in a nanocell, and thus the number of choices is P. For the total of C resource blocks, the number of choices is P^C in a nanocell. For the total of W nanocells, the total choices is P^{CW}. It is exponential both in C and W. ■

Typically, the number of resource blocks C is 25, 50, 75, 100 in 3GPP LTE; the number of WDM wavelengths W in PONs is 2, 4, 8, 16, 32; the number of picocells P in a nanocell can be in the order of tens. Therefore, the brute force scheme is highly impractical.

C. OFDMA RB allocation algorithms

Here, we develop optimal and heuristic algorithms to address the OFDMA RB allocation problem.

1) Vertex-coloring-based RB allocation: The first algorithm we propose is vertex-coloring-based RB allocation. First, we consider the problem under two extreme cases of the nanocell size P.

Based on the proof of Theorem 1, we can derive the following Lemma 2.

Lemma 2. *When the number of picocells P in a nanocell equals to 1, the RB allocation problem is equivalent to the maximum independent set problem.*

Proof: See the proof of Theorem 1. ■

Lemma 3. *When the number of picocells P in a nanocell equals to the number of RBs, i.e., C, the RB allocation problem is polynomially reducible to the vertex coloring problem.*

Proof: When $P = C$, each picocell can be allocated with at most one RB based on Assumption 3. The objective of maximizing the number of labels labeled on all vertices is equivalent to that of maximizing the number of labeled vertices. If the conflict graph is C-colorable, by regarding each color as a RB, we obtain a labeling to achieve PW labeled vertices. When $n < PW$, for any feasible labeling with n labeled vertices, the graph after removing $PW - n$ unlabeled vertices along with their connecting edges is C-colorable. There are $\binom{PW}{n}$ choices of choosing n vertices from the total of PW vertices. That is to say, the decision problem of determining whether n is achievable is polynomially reducible to the vertex coloring problem. Therefore, the RB allocation problem is polynomially reducible to the vertex coloring problem when $P = C$. ■

The maximum independent set problem can be considered as a special case of vertex-coloring problem, where the number of colors is one. Therefore, problems under both these two extreme cases are polynomially reducible to the vertex-coloring problem. Thereby, we propose a vertex-coloring-based RB allocation approach as described in Algorithm 1.

The main idea of Algorithm 1 is to color vertices as much as possible using P colors. First, the algorithm tries to color all vertices by using P colors. If it cannot be achieved, the algorithm removes one vertex, and tries to color all the remaining vertices by using P colors. The process repeats

Algorithm 1 Vertex-coloring-based RB allocation

1: Divide RBs evenly into P groups, and include RBs $(j-1)C/P+1,...,jC/P$ into the jth group $(1 \le j \le P)$.
2: $n = PW$
3: $ind = 0$
4: **while** $ind = 0$ **do**
5:   Determine whether P colors can color n vertices
6:   **if** Yes, **then**
7:     Color these n vertices, and include vertices colored by color j into set ψ^j
8:     Label RBs in group j onto vertices in ψ^j
9:     $ind = 1$
10:   **else**
11:     $n = n - 1$
12:   **end if**
13: **end while**

until the maximum number of vertices colored by P colors is found. Let n equal to the maximum number of colored vertices. For vertices colored by the same color, Algorithm 1 labels each of them with C/P RBs among all RBs. Let ψ^j include vertices colored by color j. The total number of labels equals to $\sum_{j=1}^{P} |\psi^j| C/P$.

Besides the above two extreme cases, Algorithm 1 can achieve the optimal value in every scenario of P and C.

Theorem 2. *The optimal solution to the OFDMA RB allocation problem can be obtained by using Algorithm 1*

Proof: Let n be the maximum number of vertices colored by P colors. That is there are at most n vertices contained in the union of P independent sets of the conflict graph. In Algorithm 1, any P of these C RBs are allocated to n vertices. The total number of labels labeled on vertices equals to nC/P. Assume there exists a scheme that achieves $m (m > nC/P)$ labels, then there must exist P RBs being allocated to more than n vertices. Vertices allocated with the same RB constitute an independent set. Then, there exist P independent sets whose union is of size greater than n. This contradicts the fact that n is the maximum number of vertices colored by P colors. ∎

The following corollaries pertain to the optimal value and the graph which can achieve the upper bound CW.

Corollary 1. *The maximum number of allocated RBs at a time equals to $\mathcal{N}(\mathcal{G}(V,E))C/P$, where $\mathcal{G}(V,E)$ is the conflict graph, and $\mathcal{N}(\mathcal{G}(V,E))$ is the maximum number of vertices in graph $\mathcal{G}(V,E)$ which can be colored by using P colors.*

Proof: According to Theorem 2, the maximum number of RBs allocated at a time equals to $n \cdot C/P$, where n is the maximum number of vertices which can be colored by P colors in graph $\mathcal{G}(V,E)$. Thus, we have proved this corollary. ∎

Corollary 2. *The total number of RBs which can be allocated at a time achieves the upper bound CW if and only if the conflict graph is P-colorable.*

Proof: If the conflict graph is P-colorable, $\mathcal{N}(\mathcal{G}(V,E)) = PW$, and the total number of allocated RBs equals to $PW \cdot C/P = WC$; otherwise, $\mathcal{N}(\mathcal{G}(V,E))$ is less than PW, and thus the total number of allocated RBs is less than CW. ∎

Computational Analysis: In Algorithm 1, the vertex coloring problem, which is known to be strong NP-hard, needs to be addressed. The brute force search scheme for a graph with $|V|$ vertices and P colors runs in time $O(P^{|V|})$. Line 4 of Algorithm 1 involves checking whether n among PW vertices can be colored by P colors. For a given n, the running time from Line 3 to Line 11 is $O(\binom{PW}{n}P^n)$. Thus, the running time of Algorithm 2 is $O(\sum_{n=1}^{PW}\binom{PW}{n}P^n) = O((1+P)^{PW})$. By eliminating the dependence on C which can be up to 100, the vertex-coloring-based scheme has a smaller running time as compared to the brute-force search solution to the original problem, which is $O(P^{CW})$. However, it is still impractical since the running time is exponential in both P and W.

2) Independent-set-based RB allocation: To obtain a more efficient algorithm, we propose an independent-set-based RB allocation scheme, as described in Algorithm 2.

Algorithm 2 Independent-set-based RB allocation

1: Divide RBs evenly into P groups, and include RBs $(i-1)\frac{C}{P}+1,...,i\frac{C}{P}$ into the ith RB group $(1 \le i \le P)$.
2: Let $G = \mathcal{G}(V,E)$,
3: **for** $i = 1 : P$ **do**
4:   Find the maximum independent set in graph G, and denote the set as ϕ^i
5:   Label all vertices in ϕ^i with RBs in group i.
6:   Remove vertices in ϕ^i along with their connecting edges from graph G.
7: **end for**

In Algorithm 2, RBs are first divided into P groups, where group i contains RB $\{(i-1)\frac{C}{P}+1, (i-1)\frac{C}{P}+2, ..., i\frac{C}{P}\}$. Graph G is initialized as $\mathcal{G}(V,E)$. Then, we find the maximum independent set in graph G, and label all vertices in the independent set with RBs in a RB group. After that, graph G is updated by removing all vertices in the independent set along with their connecting edges. The process is repeated until all RBs are labeled.

Denote ϕ^i as the maximum independent set in the ith iteration. The number of vertices labeled with RB j with $(i-1)\frac{C}{P}+1 \le j \le i\frac{C}{P}$ equals to the size of ϕ^i. The total number of labels labeled on all vertices equals to $\sum_{i=1}^{P}|\phi^i|\frac{C}{P}$.

In the ideal case, $|\phi^i| = W, \forall i$. Then, each RB is labeled on W vertices, and the number of total labels labeled on vertices equals to $P \cdot (W\frac{C}{P}) = WC$, which is the upper bound of the optimal value. However, the size of the independent set may decrease iteration by iteration. This happens for conflict graphs with optimal values below the upper bound WC. Another reason may be due to the greedy nature of Algorithm 2. Algorithm 2 greedily selects the maximum independent set in each iteration. This may decrease the size of the maximum independent set in the subsequent iterations.

Fig. 4 shows one simple example with two nanocells and four picocells. In iteration 1, the independent set contains picocell 1 and 4, whereas the independent set in iteration 2 can only contain either picocell 2 or 3. Let RB^i denote the

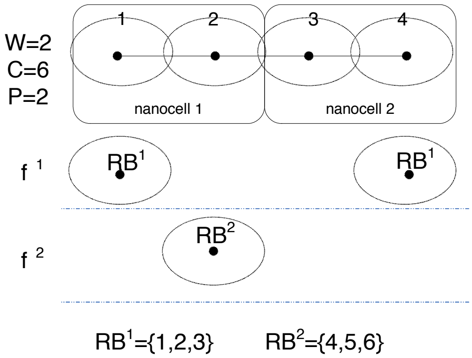


Fig. 4. One example of Heuristic-1 for $P = 2$ and $W = 2$.

ith RB group. Then, RBs in set RB^2 can only be labeled on one vertex. It is not difficult to see that the optimal solution is to let $\phi^1 = \{1, 3\}$ and $\phi^2 = \{2, 4\}$.

Computational Analysis: Algorithm 2 involves addressing the maximum independent set problem, which is known to be NP-hard. The brute force approach of checking every vertex subset for a graph with $|V|$ vertices runs in time $O(2^{|V|})$. The problem can be solved by more efficient exact algorithms, for example, the algorithm with time bound of $O(2^{|V|/3})$ proposed by Tarjan [40], and the measure and conquer approach with time bound of $O(2^{0.287|V|})$ [41]. The best known is the one with time bound of $O(2^{0.276|V|})$ proposed by Robson [42]. In Algorithm 2, the graph sizes in these P iterations are PW, $PW - |\phi_1|$, $PW - |\phi_1| - |\phi_2|$,..., $PW - \sum_{i=1}^{P-1} |\phi_i|$. Thus, the running time of Algorithm 2 is $O(P2^{0.276PW})$ if Robson's algorithm is used. The running time is approximately $P(1.21/(1+P))^{PW}$ of that of Algorithm 1.

3) Greedy RB allocation: Although Algorithm 2 has a reduced running time as compared to that of Algorithm 1 and the brute force approach to the original problem, it is still exponential in P and W, and becomes impractical when P and W are large. To further reduce the running time, heuristic graph coloring or maximum independent set algorithms can be employed.

There are numerous heuristic graph coloring and maximum independent set algorithms. We by no means apply each of them into Algorithm 1 and Algorithm 2, and discuss their performances. For computational efficiency, we consider incorporating the following greedy graph coloring algorithm and greedy maximum independent set algorithm into Algorithm 1 and Algorithm 2, respectively.

Greedy maximum independent set algorithm: include the vertex with the least degree in the independent set, and remove vertices connected to the vertex from the graph. This process repeats until no more vertex can be included.

Greedy vertex coloring algorithm: order the vertices in the ascending order of their degrees, and assign vertex v with the smallest available color which is not used by adjacent vertices of vertex v, and add a fresh color if needed.

After applying the above greedy graph coloring algorithm and greedy maximum independent set algorithm, both Algorithms 1 and 2 are reduced to the following greedy Algorithm 3. In Algorithm 3, vertices are first ordered in the ascending order of their degrees, and then colored by one of these P available colors. When there are multiple colors available, the one with the smallest index is selected. Good performance requires the number of uncolored vertices to be as small as possible.

Algorithm 3 Greedy RB allocation

1: Divide RBs evenly into P groups, and include RBs $(j-1)C/P+1, ..., jC/P$ into the jth group $(1 \le j \le P)$.
2: Sort vertices in the conflict graph in the ascending order of their degrees.
3: **for** $i = 1 : PW$ **do**
4:   $j = 1$
5:   **while** vertex i has not been colored & $j \le P$ **do**
6:     **if** vertex can be colored with color j **then**
7:       color it
8:     **else**
9:       $j = j + 1$
10:     **end if**
11:   **end while**
12: **end for**
13: Label vertices colored by color j with RBs in group j

Computational Analysis: By using a proper ordering algorithm, the complexity of the ordering process in Line 1 of Algorithm 3 is $O(PW \log(PW))$. For each vertex, the process of selecting colors is of complexity $O(P)$. Thus, the complexity of the greedy RB allocation is $O(PW \log(PW) + P^2W)$.

Here, we analyze the performance of Algorithm 3. In Algorithm 3, if the condition "$j \le P$" in the "while" loop is removed, the algorithm becomes a greedy vertex coloring algorithm. For the greedy vertex coloring algorithm, denote $\mathcal{X}$ as the number of colors required to color all vertices, and $\psi^i (1 \le i \le \mathcal{X})$ as the set containing all vertices colored by color i. Then, $\sum_{i=1}^{\mathcal{X}} |\psi^i| = PW$. It can be easily obtained that the total number of vertices which can be colored by P colors using Algorithm 3 equals to $\sum_{i=1}^{P} |\psi^i|$. If the conflict graph is a clique, each vertex needs to be colored by a distinct color, and P colors can only color P vertices. In this case, Algorithm 3 is the optimal solution. If the conflict graph is not a clique, according to Brooks' theorem [43], $\mathcal{X} \le \Delta$, where Δ is the maximum degree of vertices in the conflict graph. Then,

- When $\Delta \le P$, Algorithm 3 can color all vertices by P colors, and it achieves the optimal solution.
- When $\Delta > P$,

$$\sum_{i=1}^{P} |\psi^i| \ge P/\mathcal{X} \cdot \sum_{i=1}^{\mathcal{X}} |\psi^i| \tag{6}$$

$$= P/\mathcal{X} \cdot PW \ge P/\Delta \cdot PW \tag{7}$$

Condition (6) holds since $|\psi^i| > |\psi^j|$ if $i < j$. Thus, the total number of allocated RBS is lower bounded by $P/\Delta \cdot PW \cdot C/P = CW \cdot P/\Delta$, where CW is the upper bound of the number of allocated RBs.

IV. Wavelength Assignment

The above discusses the OFDMA RB allocation problem for a given conflict graph.

As stated in Corollary 1, the maximum number of allocated RBs at a time equals to $\mathcal{N}(\mathcal{G}(V,E))C/P$, where $\mathcal{N}(\mathcal{G}(V,E))$ is the maximum number of vertices that can be colored by P colors in conflict graph $\mathcal{G}(V,E)$. $\mathcal{N}(\mathcal{G}(V,E))$ depends on the connectivity of the conflict graph, i.e., the edges in graph $\mathcal{G}(V,E)$.

The edges in the conflict graph are contained in set $E = E^\alpha \cup E^\beta$, where E^α and E^β refer to interference edges and co-nanocell edges, respectively. The wavelength assignment can be further formulated as deciding E^β for given interference edges E^α such that $\mathcal{N}(\mathcal{G}(V,E))$ is maximized. However, owing to the NP-hardness property, $\mathcal{N}(\mathcal{G}(V,E))$ cannot be explicitly expressed as a function of the edge set E.

Intuitively, the more the connecting edges in graph $\mathcal{G}(V,E)$, the smaller the $\mathcal{N}(\mathcal{G}(V,E))$. Based on this intuition, we heuristically treat minimizing $|E|$ as the objective in assigning wavelengths. The problem is further transformed into minimizing $|E^\alpha \cup E^\beta|$ for given $|E^\alpha|$.

$$\begin{aligned} &|E^\alpha \cup E^\beta| \\ &= |E^\alpha + E^\beta - E^\alpha \cap E^\beta| \\ &= |E^\beta| + |E^\alpha - E^\alpha \cap E^\beta| \\ &= WP(P-1)/2 + |E^\alpha - E^\alpha \cap E^\beta| \end{aligned}$$

$|E^\beta| = WP(P-1)/2$ follows from the fact that the graph with E^β only contains W fully connected subgraphs of sizes P. Again, owing to this property of E^β, minimizing $|E^\alpha - E^\alpha \cap E^\beta|$ for given E^α is equivalent to the problem of partitioning graph into parts such that the parts are of the same sizes with few connections among them, i.e., the graph partitioning problem.

The graph partitioning problem is also NP hard. The brute force search approach involves checking every partitioning choice; the total number of choices can be as large as $\prod_{w=1}^{W}\binom{w\cdot P}{P}$. Many heuristic algorithms have been proposed, among which Kernighan-Lin Algorithm has running time of $O(|V|^2 \log |V|)$ [44].

V. Simulation Results and Analysis

For the OFDMA RB allocation, the above presents three algorithms: vertex-coloring based approach, independent-set based approach, and greedy algorithm. With optimal vertex coloring, the vertex-coloring based approach can produce the maximum number of allocated RBs with running time of $O((1+P)^{PW})$. At the sacrifice of the performance in some degree, the independent-set based approach reduces the running time to $O(P2^{0.267PW})$ by using Robson's maximum independent set algorithm. The greedy algorithm is the most efficient with running time of $O(PW\log(PW)+P^2W)$at the expense of the most compromised performance.

Assume each operation takes around $1ns$. Table II compares the running time of the three algorithms for some P and W. The overall frame length in 3GPP LTE is around 10 ms, and the typical WiMAX frame length ranges from 2.5ms to 20 ms. Hence, it is usually impractical if the resource allocation algorithm takes longer than 1 ms. Table II(a) shows that the vertex-coloring based approach is impractical even with two wavelengths and five picocells per nanocell. The independent-set based approach can be employed in real systems when the number of wavelengths and the nanocell size are below some thresholds, as indicated red in Table II(b). The greedy algorithm takes less than $10\mu s$ even with 16 wavelengths and 20 picocells per nanocell, as shown in Table II(c).

TABLE II
The Running Time of Three OFDMA RB Allocation Algorithms

(a) Vertex-coloring-based approach

W \ P	5	10
2	0.06 s	6.7×10^{11} s
4	3.65×10^6 s	

(b) Independent-set-based approach

W \ P	5	10	15	20
2	31.82 ns	405 ns	3.87 μs	32.8 μs
4	202 ns	16.4 μs	1 ms	53.8 ms
8	8.2 μs	26.5 ms	66.2 s	1.45×10^5s
16	13.4 ms	7.2×10^4s	2.9×10^{11}s	1×10^{18}s

(c) Greedy algorithm

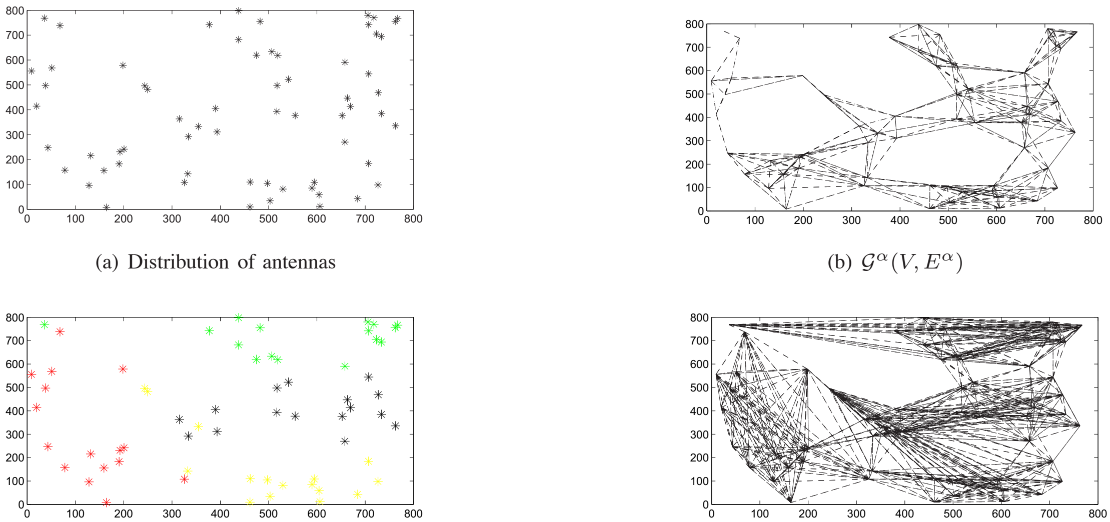
W \ P	5	10	15	20
2	0.0964μs	0.3329μs	0.6844μs	1.1458μs
4	0.1929μs	0.6658μs	1.3688μs	2.2915μs
8	0.3858μs	1.3315μs	2.7377μs	4.5830μs
16	0.7715μs	2.6630μs	5.4753μs	9.1660μs

As shown in Corollary 1, the maximum number of allocated RBs at a time equals to $\mathcal{N}(\mathcal{G}(V,E))C/P$, which determines the system performance. In the simulation, we assume $C = P$, and investigate the relationship between $\mathcal{N}(\mathcal{G}(V,E))$ and the conflict graph $\mathcal{G}(V,E)$.

We consider a topology with n antennas uniformly distributed in an $800m \times 800m$ square area. Assume the communication range is $r/2$, and then the interference range is r. Fig. 5 shows one example of 64 picocells and 4 wavelengths. The communication range is 100 m. Fig. 5 (a) illustrates the geographical distribution of these distributed antennas. Fig. 5 (b) is the conflict graph $\mathcal{G}^\alpha(V,E^\alpha)$ containing interference edges only. In Fig. 5 (c), picocells are grouped into four groups as indicated by four different colors. Picocells in the same group constitute a nanocell. In the simulation, we use Kernighan-Lin Algorithm to partition the graph. The final conflict graph is shown in Fig. 5 (d).

In Fig. 6, we vary the interference range and observe its impact on $\mathcal{N}(\mathcal{G}(V,E))$ and $|E^\alpha - E^\alpha \cap E^\beta|$ for $n = 64$ and $W = 4$. The displayed results are the average values of 10 simulations. The greedy RB allocation algorithm is performed. When the interference range is small, the number of interference edges and $|E^\alpha - E^\alpha \cap E^\beta|$ are small. In this case, almost all these 64 vertices can be colored by using $P = 16$ colors. With the increase of the interference range, the number of interference edges increases, and the less likely a vertex can be colored. When the number of interference range equals to 800 meters, $|E^\alpha - E^\alpha \cap E^\beta|$ increases to around 800, and $\mathcal{N}(\mathcal{G}(V,E))$ is reduced to around 20.

In Fig. 7, we fix the interference range to be $r = 200$ meters, and vary the number of picocells in the area and the wavelength number to observe the variation of $\mathcal{N}(\mathcal{G}(V,E))$. The displayed value is the average results of 10 simulations.



(a) Distribution of antennas

(b) $\mathcal{G}^{\alpha}(V, E^{\alpha})$

(c) Wavelength assignment

(d) $\mathcal{G}(V, E)$

Fig. 5. $n = 64$, $W = 4$, $r = 200$ m, where $\mathcal{G}^{\alpha}(V, E^{\alpha})$ denotes the conflict graph containing interference edges only, and $\mathcal{G}(V, E)$ denotes the final constructed conflict graph.

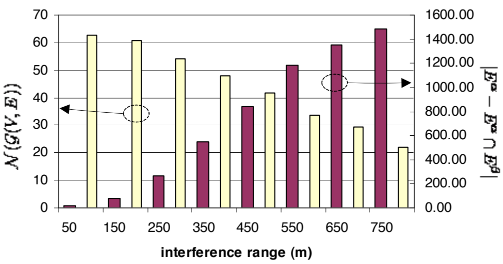


Fig. 6. $\mathcal{N}(\mathcal{G}(V, E))$ and $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$ vs. r when $n = 64$, $W = 4$, where $\mathcal{N}(\mathcal{G}(V, E))$ denotes the maximum number of vertices in graph $\mathcal{G}(V, E)$ which can be colored using P colors, and $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$ equals to the total number of edges in the conflict graph $\mathcal{G}(V, E)$ minus $WP(P-1)/2$.

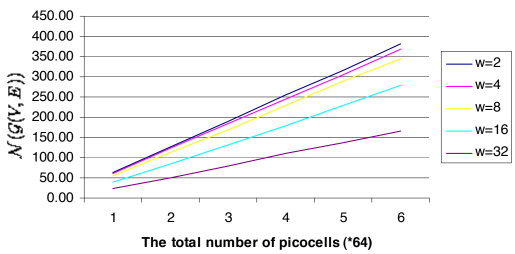


Fig. 7. $\mathcal{N}(\mathcal{G}(V, E))$ vs. W and n when $r = 200$, where $\mathcal{N}(\mathcal{G}(V, E))$ denotes the maximum number of vertices in graph $\mathcal{G}(V, E)$ which can be colored using P colors.

For a given n, small W implies large P, large $|E^{\beta}|$, and small $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$. In the extreme case of $W = 1$, $|E^{\alpha} - E^{\alpha} \cap E^{\beta}| = |E^{\beta}|$, and $P = n$. The conflict graph with n vertices is a fully connected graph, and it is P-colorable since $P = n$. Simulations show that, when $W = 2$, $\mathcal{N}(\mathcal{G}(V, E))$ almost equals to n, which agrees with the theoretical analysis. When W is large, P is small, and $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$ is large. Then, the number of colored vertices becomes small. Fig. 7 shows $\mathcal{N}(\mathcal{G}(V, E))$ decreases with the increase of the wavelength number.

When discussing the wavelength assignment problem in Section IV, we transform the wavelength assignment problem into the graph partition problem based on the assumption that the larger the $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$, the smaller the $\mathcal{N}(\mathcal{G}(V, E))C/P$. Here, we test the assumption by simulations. In Fig. 8, we set $P = 16$, $W = 8$, and $r = 200$, run 1000 simulations, and plot $\mathcal{N}(\mathcal{G}(V, E))$ vs. $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$ in each simulation. Although $\mathcal{N}(\mathcal{G}(V, E))$ fluctuates for a given $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$, the general trend is that $\mathcal{N}(\mathcal{G}(V, E))$ decreases with the increase of $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$.

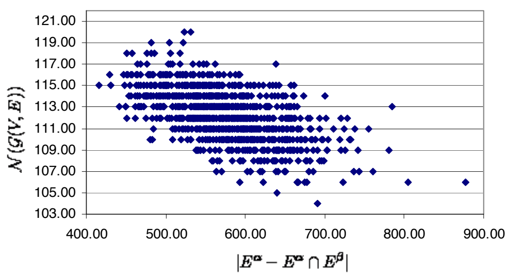


Fig. 8. $\mathcal{N}(\mathcal{G}(V, E))$ vs. $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$ in 1000 simulations when $n = 128$, $W = 8$, and $r = 200$, where $\mathcal{N}(\mathcal{G}(V, E))$ denotes the maximum number of vertices in graph $\mathcal{G}(V, E)$ which can be colored using P colors, and $|E^{\alpha} - E^{\alpha} \cap E^{\beta}|$ equals to the total number of edges in the conflict graph $\mathcal{G}(V, E)$ minus $WP(P-1)/2$.

VI. Conclusion

This paper investigates the OFDMA resource allocation and wavelength assignment problems in WDM radio-over-fiber picocellular networks. With the assumption that the data rate delivered by each resource block in each picocell is the same, the problem of maximizing the sum of data rates is reduced to the problem of maximizing the total number of allocated OFDMA resource blocks. We have shown that the problem of maximizing the total number of allocated RBs is strong NP-hard. Then, we propose three algorithms to address it: the vertex-coloring based approach, the independent-set based approach, and the greedy algorithm. Vertex-coloring based algorithm can obtain the optimal result, but is computationally intensive. The independent-set based approach reduces the complexity at minor expense of performances. The greedy algorithm, though has the worst performance among the three, is efficient and scalable. For the wavelength assignment problem, we heuristically formulate it into a connectivity minimization problem, and employ graph partitioning algorithms to address it. This assumption is shown to be reasonable by simulations. Simulation results also show that the performances of the greedy resource allocation algorithm conform closely with the theoretical analysis.

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