Fairness and Network capacity Trade-off in P2P IEEE 802.22 networks

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***Abstract*—Cognitive radio technology was introduced to solve, or at least ease, the severe shortage of radio bands [1]. Wireless Regional Area Networks (WRAN), IEEE 802.22 standard, is the first one to adopt cognitive radio technology, which utilizes the TV white spaces [2]. WRAN is typically a centralized cellular network with base station (BS) and customer-premise equipments (CPEs). However this may lead to limited network capacity, since every CPE needs to communicate to the BS and only one channel can be used to communicate in the whole cell per time slot with one BS antenna. Peer to Peer WRAN (P2PWRAN) was proposed [3] to circumvent this, where CPEs can communicate with each other directly. P2PWRAN increases network capacity compared to the standard WRAN, since multiple communication channels can be simultaneously allocated and reused in one time slot. In this paper, we formulate the spectrum allocation problem in P2PWRAN similar to the vertex coloring problem, however the problem is a quadratically constrained programming (QCP) problem. We prove that it is a computationally hard problem. Well-known Greedy Coloring Algorithm (GCA) for vertex coloring problems causes severe unfairness in allocation of channels. Thus a Fair Greedy Coloring Algorithm (FGCA) is proposed to guarantee a fair allocation by queuing flows considering previous allocations. GCA provides good performance but causes significant unfairness; FGCA guarantees fairness but leads to decrease in performance of P2PWRAN. Therefore, a Trade-off FGCA (TFGCA) is proposed considering fairness and network performance at the same time during allocation. Simulation results show that with the adjustment of two factors in TFGCA, network performance and fairness can be balanced.**

***Index Terms*—IEEE 802.22, WRAN, cognitive radio, power control, Intra-cell communication, fairness, channel allocation.**

I. Introduction

Cognitive radio networks is now stepping into people's lives, thanks to the efforts of IEEE 802.22 and IEEE 802.22.1, which are the standards for Cognitive Wireless Regional Area Networks (WRAN) for operation in TV Bands[1] and Enhanced Interference Protection of the Licensed Devices[2] respectively. WRAN works in the white spaces of 47 TV channels from 54 to 862 MHz with a bandwidth of 6, 7 or 8 MHz. WRAN is a cellular network, with one BS and multiple users (CPEs) in a cell. The BS is in charge of spectrum sensing, channel allocation, and routing messages to CPEs. CPEs communicate with BS directly whenever they intend to send messages to BS or to other CPEs (either in the same cell or in another the cell). However, this typical cellular mode leads to limited network capacity, because only one CPE can access the channel in a time slot. Even though there may be many channels available, only one channel can be used in each of the three sectors of the cell per time slot without causing interference.

Therefore, we propose peer to peer WRAN (P2PWRAN) that allows direct CPE to CPE communication [3]. This mode is useful in cases where there are closely knit communities amongst CPEs and message exchange happens quite often between them. Moreover, since each BS has a large coverage area (with a radius of minimum of 30km), there is always a possibility to enable P2P communication amongst CPEs. The main idea in P2PWRAN is to extend WRAN (IEEE 802.22) for P2P communication in a cell by using non-interfering channels in one time slot and also reusing an already allocated channel multiple times by employing transmission power control (see [3] for more details). To achieve this we need a simple scheme to the standard WRAN channel allocation mechanism.

In this paper, we formulate the channel allocation problem in P2PWRAN, and model it as a problem similar to vertex coloring problem. We also prove that it is a computationally hard problem. Greedy Coloring Algorithm (GCA) is a well-known heuristic solution for vertex coloring problem. Sometimes it may lead to severe starvation for some CPEs and thus causing unfairness while trying to maximize the network capacity. Therefore, we propose a Fair Greedy Coloring Algorithm (FGCA), which mainly addresses the fairness and tries to find a fair channel allocation. However, FGCA decreases network capacity. On one hand, some CPEs starve when GCA is adopted, and on the other hand, the network capacity is lowered when FGCA is employed. Hence, balancing fairness and network capacity in P2PWRAN channel allocation becomes an important issue. In this paper we propose a Trade-off FGCA (TFGCA), which is a heuristic and can balance the capacity and fairness. We present simulation results to prove that our scheme works.

The rest of the paper is organized as follows. In Section II, P2PWRAN is introduced. Section III describes existing solutions. Section IV mainly discusses channel allocation in P2PWRAN, and FGCA and TFGCA are proposed in it. The simulation scenario and results are shown in Section V, and the conclusion and further work is described in Section VI.

[1]Approved as a standard by IEEE on July 1st 2011 [4].

[2]Approved as a standard by IEEE on November 1st 2010.

II. Peer to peer WRAN

An IEEE 802.22 cell consists of a BS and multiple CPEs, spread in an area within a range of approximately 30 km (can be even more with higher transmission power) around the BS. The BS is the central controller for the whole cell, and manages all channels sensing (along with CPEs), medium access, data routing, and other functions. Two antennas are on every CPEs, one of which is omnidirectional and is in charge of spectrum sensing and geo-location information. The other one is directional for communication with BS. The BS collects spectrum sensing results from CPEs and analyzes them with more information from databases and regulatory or policy inputs. Afterwards, it queues all available channels as protected, unclassified, disallowed, operating, backup and candidate channel lists [5]. Then the BS synchronizes the lists with CPEs by broadcasting on every available channel with Superframe Control Header (SCH). The channels are allocated to CPEs via queuing, broadcasting and synchronization.

Cellular networks can provide reasonable inter-cell communication, however they cannot provide fast intra-cell communication. This is mainly because the BS has to route every message in the cell. Therefore, the network capacity is constrained by number of time slots. Few users can communicate with BS per time slot due to the number of BS antennas and interference. Due to the large coverage area by one cell in WRAN (30km or more), more intra-cell communication can take place compared to other wireless networks such as WiFi. However, in WRAN mostly only one channel can be allocated in a cell per time slot to each antenna of the BS, which significantly limits the network capacity. Thus in this context, P2PWRAN [3] is proposed to support direct peer to peer (CPE to CPE) communication in a WRAN cell, which leads to many channels being allocated and re-used. This not only increases the network capacity greatly, but can also decrease the power consumption with power control than the standard WRAN [3]. P2PWRAN is implementable since WRAN is centrally controlled and managed, making it easy to allocate channels.

Channel allocation in P2PWRAN is different from WRAN, multiple channels and users are involved in one time slot. Hence, maximizing the network capacity and guaranteeing fairness amongst CPEs need to be considered in P2PWRAN. In the following section we describe the existing solutions for these issues in Cognitive Radio networks.

III. Existing Solutions

Graph coloring is usually proposed for channel allocation in cellular networks, where each base station is allocated with a non-interfering channel with respect to its neighboring base stations. It is known that both edge and node coloring of graphs are NP complete [6] in general. Several edge coloring heuristics have been proposed for link scheduling in multi-hop wireless networks [7] [8]. These solutions if applied to Cognitive Radio ad hoc networks will result in degraded performance since all of them assume static channel availability. A better approach of spectrum allocation with fairness was proposed in Zheng's work [9] on fairness. In [9], a weighted, color-sensitive graph $G(U, E_C, L_B)$ is used to represent the topology of the Cognitive Radio ad hoc network, where vertices U, a set of colored edges E_C, and link weights L_B. An optimization framework is proposed with the graph coloring and utility functions to optimize bandwidth and fairness. The spectrum allocation for CRs is developed based on vertex coloring; each vertex is assigned a set of channels (colors) based on the 'Progressive Minimum Neighbor First' heuristic. The utility functions govern the fairness achieved. Three functions are defined: (a) *Max-Sum Bandwidth* - to maximize the total spectrum utilization in the system; (b) *Max-Min-Bandwidth* - to maximize the bottleneck user's spectrum utilization; and (c) *Max-Proportional-Fair* - to obtain a fair allocation. Both cooperative and non-cooperative approaches are discussed. Centralized and distributed solutions are proposed that implement the utility functions. It is shown that cooperative approaches perform better than non-cooperative methods, and the distributed approaches perform almost as good as the centralized one.

P2PWRAN has been proposed in [3], where the BS in each cell manages all spectrum information, CPEs, and their Geo-location information (network topology) and channel allocation. BS allocates available channels so as to maximize the allocation. Even though network capacity and fairness are considered in the utility functions in [9], the results show severe unfairness when the scheme tries to maximize network capacity. Therefore, we propose a trade-off fair greedy algorithm (TFGCA) especially for P2PWRAN, which can balance the fairness and network capacity in a dynamic way during the multi-channel allocation. In the following section, we formalize the channel allocation problem and prove that it is a computationally hard problem.

IV. Channel allocation in Peer to Peer WRAN

We consider channel allocation in one time slot in this paper. Let $\mathbb{U} = \{u_i | i = 1, 2, ...\}$ be the set of users (CPEs). Let $\mathbb{F} = \{f_j | j = 1, 2, ...\}$ be the set of flow requests, where $f_j = (u_x, u_y)$ i.e., f_j is a flow between u_x and u_y. It is a set with 'no conflict' flow requests. Conflict free flows means that one user (or CPE)[3] can only have one flow request in a time slot i.e., u_x or u_y will not be present in any other flow in $\mathbb{F}$. In fact, this assumption reduces the complexity of the problem, at least the number of competing flows. Even then we prove that the problem is hard. Further, a CPE cannot cater to two flows in the same slot since they have only one Tx/Rx frontend. We now formulate the problem as follows:

Let the available channels in the current time slot be $\mathbb{C} = \{c_k | k = 1, 2, ...\}$. Given $|\mathbb{U}|$ users and $|\mathbb{F}|$ flows, the interference between the flows needs to be considered. We represent the interference between flows by using the interference map $M = \{m_{ij} | i, j = 1, 2, ..., |\mathbb{F}|\}$. It is defined as

$$m_{ij} = \begin{cases} 1 & \text{if } f_i, f_j \text{ interfere with each other,} \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

[3]In the rest of the paper we use the terms 'CPE' and 'User' interchangeably.

Based on this interference map, an interference graph can be built, with flows as vertices and interference as edges. To illustrate let us take an example as shown in Fig. 1. Flow 1 interferes with flows 3, 4, 5, and 6, which means if a channel is allocated to flow 1 already in a time slot, it cannot be allocated to any of 3, 4, 5, and 6. In the literature, several

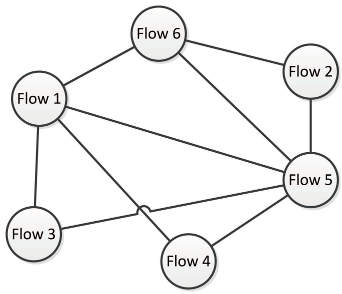


Fig. 1. An interference graph

methods of generating interference maps have been described. For example the one used in [9] is based on distance, i.e., when users of two flows are in transmission range of each other, then those flows are said to interfere with each other. A detailed description for generating interference map (called network conflict graph) based on the network topology is in [9]. Our challenge is to design fair channel allocation methods with considerations to network capacity given the interference map. While the problem seems to be abstracted out of wireless domain, the problem and the solutions proposed here are directly applicable to P2PWRAN.

We define an allocation A as $\mathbb{F} \times \mathbb{C}$ matrix, where $A_{ij} = 1$ if flow i is allocated with channel j. An allocation is valid if there is no interference among allocated flows. Then the channel utility function for the whole network is,

$$U(A) = \sum_{i=1}^{|\mathbb{C}|} \sum_{j=1}^{|\mathbb{A}|} (A_{ij}), \tag{2}$$

where the total channel allocation time of all channels is treated as channel utility. The channel utility can also be considered as the network capacity, because it implies how many flows can be satisfied in the whole network. Therefore, maximizing the channel utility is in turn maximizing network capacity.

A. Problem definition

Based on the assumptions and channel utility functions, the multi-channel allocation problem in P2PWRAN can be defined as the following optimization problem,

$$\max \ U(A) \tag{3}$$

subjected to

$$\sum_{j} A_{ij} \leqslant 1 \ \forall j \in C, \tag{4}$$

$$\sum_{j \in \mathbb{C}, k \in \mathbb{F}, k \neq i} A_{ij} A_{kj} m_{ik} = 0, \forall i \in \mathbb{F}. \tag{5}$$

In this optimization problem, given the sets of available channels $\mathbb{C}$ and flow requests $\mathbb{F}$, an optimal allocation A leads to the maximum channel utility without causing any interference at the same time. Eq. (4) imposes that one flow can only be allocated once. Eq. (5) is a quadratic constraint which imposes that two flows can be allocated with the same channel only if they do not interfere with each other. This optimization problem is a QCP problem and we consider different cases based on the value of $|\mathbb{C}|$.

When $|\mathbb{C}| = 1$:

Lemma 1: When there is only one available channel, then the optimization problem in Eq. (3) is NP-hard.

Proof: We can construct a graph G, in which, the flows are nodes and if $m_{ij} = 1$ then there is an edge between f_i and f_j. The optimization problem in Eq. (3) becomes a typical NP-hard problem, which is to find the maximum independent set in it [10]. ■

When $1 < |\mathbb{C}| < |\mathbb{F}|$:

In this case, we can formulate Eq. (3) into a problem in graph theory on the interference graph, in which the flows are the vertices and the interference between them are edges. The problem can be redefined as the decision of the maximum number of colored vertices n ($n = |S|$, $S \subset \mathbb{F}$, and S is the set of flows with assigned channels) with certain number ($|\mathbb{C}|$) of colors.

Lemma 2: When there is more than one available channel, the optimization problem in Eq. (3) is a hard problem.

Proof: When $|\mathbb{C}| \leqslant n \leqslant |\mathbb{F}|$, we prove it is a hard problem by contradiction. We assume that it is not hard, then n can be obtained in a reasonable time. Two possibilities can be seen, when $n = |\mathbb{F}|$, it is a typical vertices coloring problem (to determine whether the interference map is $|\mathbb{C}|$-colorable), which is NP-hard [10]. When $n < |\mathbb{F}|$, our assumption reduces to say that the graph is $|\mathbb{C}|$-colorable in reasonable computing time. It is not true, because to determine a graph is $|\mathbb{C}|$-colorable is also a NP-hard problem, which cannot be solved in reasonable computing time with current algorithms. Moreover, recall here that to select a set of n flows as a subset of $\mathbb{F}$, and then finding all the combination of n flows out of $\mathbb{F}$ is indeed factorial in n. Thus our assumption that we can solve in a reasonable amount of time does not hold. ■

The problem of maximizing the utility i.e., $\max U(A)$ can be seen as a variant of the vertex coloring problem. The problem at hand is, given $|\mathbb{C}|$ colors and $|\mathbb{F}|$ flows, how do we maximize the utility. In other words, what is the maximum number of flows, n, of $|\mathbb{F}|$ flows, that can be colored with $|\mathbb{C}|$ colors. In contrast to the vertex coloring problem, where the number of colors required to color a given graph $G = (V, E)$ with $|V|$ vertices is to be determined, our problem is to determine the maximum set of vertices given the colors.

The next step is to determine the complexity of this problem. We describe two ways to arrive at the complexity here. (a) We know that determining chromatic index $\chi(G)$ is a NP-Hard problem i.e., it takes polynomial time for a non-deterministic Turing machine to get an optimal coloring of G. However, there can be exponential number of optimal colorings for G.

In this set of optimal colorings, we need to find out with $|\mathbb{C}|$ colors the maximum number of vertices that can colored. Hence the problem is Σ_2P-Hard [11] or it takes exponential time for a non-deterministic Turing machine to find the optimal value of n. (b) Given $|\mathbb{F}|$ vertices, there are $2^{|\mathbb{F}|}-1$ ways of selecting vertices to form sub-graphs of $G=(|\mathbb{F}|,E)$. For each sub-graph, we need to determine if it is $|\mathbb{C}|$-colorable, which is an NP-Hard problem. At the end, we take the set of all $|\mathbb{C}|$-colorable sub-graphs and we need to find out which sub-graph has the maximum number of vertices that is $|\mathbb{C}|$-colorable. Evidently, this problem is Σ_2P-Hard.

The complexity of finding optimal solution can be written as:

$$C_{c-colorable} = \cup_{k\in N} NTIME(|\mathbb{F}|^k), \tag{6}$$

$$\max U(A) = NTIME(2^{C_{c-colorable}}). \tag{7}$$

When $|\mathbb{C}| \geqslant |\mathbb{F}|$:

This is a trivial case where channel can be allocated at most once to satisfy the flow request. Therefore, we can simply allocate different channels to different flows in this situation. When there is only one available channel, the problem becomes accessing a common single channel. When there are fewer requests than available channels, every request can get a non-interfering channel. Therefore, we only discuss the situation when $1 < |\mathbb{C}| < |\mathbb{F}|$ in the following sections. We assume the interference map is a graph $G=(V,E)$, in which $V=\{v_i|i=1,2,...\}$ indicates the flow request set as the vertices, and $E=\{e_i|i=1,2,...\}$ stands for the interference edges and the color set is C.

B. *Greedy vertex coloring algorithm (GCA)*

Greedy algorithm is commonly used as heuristic in graph coloring problems. It queues the vertices according to a rule and then allocates to v_i the smallest available color not used by its neighbors, and adding a new color if necessary [12]. When the vertices are queued based on to their degrees, the greedy coloring is called Welsh-Powell algorithm (WPA), which results in at most one more than the graph's maximum degree [13]. One problem with the greedy algorithm is, if there is more than required number of available channels, then some channels may be allocated multiple times in a time slot, but some are not allocated at all. Theoretically it is possible to reuse a channel in a cell when there are no conflicts. However, in practice, by using all the available channels, the chances of interference due to various wireless environmental factors could be mitigated. That is why we want to spread the selection of all the available channels.

When allocating channels in GCA we first consider the least used channels which have been already allocated to others, and a new channel is added if necessary. However, both the queuing of flows and channels may cause unfairness among nodes, which leads to starvation of flows and bad link quality. This happens because the flows with less interference may be allocated with channels while some highly interfered flows may never be allocated with channels.

C. *Fair greedy coloring algorithm (FGCA)*

We propose a fair greedy coloring algorithm (FGCA), to prevent starvation amongst flows. When the vertices (flows) are queued, the vertices with fewer previous allocation times are queued at the front of the list, which are allocated first with colors (channels) that does not cause any interference. The algorithm with flow fairness can be seen in Algorithm 1.

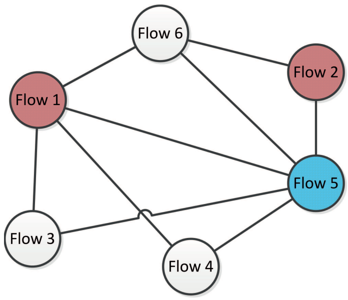
Algorithm 1 The fair greedy coloring algorithm.

```
Merge the set of waiting flow requests R' from the previous
time slot into the set of current flow request V.
Find the conflict flows in V and put them into R'.
while V is not ∅ do
  Queue the vertices (flows) V as V' according to their
  allocation times in previous time slots.
  for all v'_i vertices in V' do
    Queue the colors (channels) C as C' according to their
    total allocation times in current time slot.
    for all c'_j colors in C' do
      if v'_i is possible to be allocated with c'_j without caus-
      ing conflicts with already allocated vertices then
        Allocate the channel.
      else
        Move v'_i to R'.
      end if
    end for
    Move v'_i out of V.
  end for
end while
```

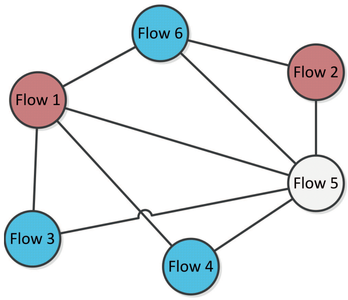
D. *Trade-off fair greedy coloring algorithm (TFGCA)*

In FGCA, fairness is the most important factor for allocation, which may cause major dip in network performance in some cases. For instance in Fig. 1, we assume that there are two available channels, and let flows 5 and 1 were allocated the least in the previous time slots. The channels will be allocated as shown in Fig. 2(a) by FGCA, in which flows 1 and 2 are allocated with the same channel, and flow 5 is allocated with the other channel. However, the best allocation with two available channels is shown in Fig. 2(b), in which 5 flows are allocated with channels. Therefore, a trade-off fair greedy coloring algorithm (TFGCA) is proposed, which provides a balancing mechanism between performance and fairness in allocation. In TFGCA, weights ($\mathbb{W}=\{w_i|, i=1,2,...,|V|\}$) are assigned to flows, and they are queued according to their degrees and number of times being allocated with channels as shown below,

$$w_i = \begin{cases} K_d e^{\frac{\bar{d}_i - d_i}{\bar{d}_i}} & \text{if } \bar{n}_i = 0,\ \bar{d}_i \neq 0; \\ K_f e^{\frac{\bar{n}_i - n_i}{\bar{n}_i}} & \text{if } \bar{d}_i = 0,\ \bar{n}_i \neq 0; \\ 0 & \text{if } \bar{d}_i = 0,\ \bar{n}_i = 0; \\ K_d e^{\frac{\bar{d}_i - d_i}{\bar{d}_i}} + K_f e^{\frac{\bar{n}_i - n_i}{\bar{n}_i}} & \text{otherwise.} \end{cases} \tag{8}$$



(a) FGCA.



(b) The best case.

Fig. 2. Examples for FGCA and the best case.

Here, $d_i \in \mathbb{D}$ and $n_i \in \mathbb{N}$ are the degree and number of previously allocated channels for vertices (flows) v_i respectively; $\bar{d}_i$ and $\bar{n}_i$ are the averages. K_d and K_f are two factors that adjust the priorities of vertex degree and fairness, which are in $[0, 1]$. In Eq. (8), the exponential functions compress the values of degree difference ($\frac{\bar{d}_i - d_i}{\bar{d}_i}$) and the allocation time difference ($\frac{\bar{n}_i - n_i}{\bar{n}_i}$) into $[0, e]$, which measure two types of differences on a similar level. Moreover, we can find that $w_i \in [0, 2e]$. Flows with smaller degree and lesser previous allocation get higher weights, which increases the possibility of assignment with available channels. TFGCA balances the fairness and performance by merging both WPA and FGCA with different weights.

V. Simulations

A. Scenarios

We consider a WRAN with 600 CPEs randomly deployed within a cell of $40km$ radius. The intra-cell communication in P2PWRAN supports one hop routing. For example besides the direct flows as CPE-CPE and CPE-BS, there are also routing flows as CPE-CPE-CPE and CPE-BS-CPE. However, in our simulations, we only considered the direct flows, because the flows with one hop routing can be broken into short flows, which has been introduced in [3]. 80% of randomly chosen CPEs generate no-conflict peer to peer flow requests in every time slot. In order to examine the performance of WPA, FGCA and TFGCA with different number of channels, we vary the available channels from 2 to 10. The interference map M is generated based on the scheme as given in [9], where two flows interfere if and only if the CPEs of one flow is in the transmission range of CPEs of the other flow. Friis path loss along with lognormal shadowing was used in simulations when generating interference maps, as shown in Eq. (9) [14].

TABLE I
Parameters

Parameters	Symbols	Values
Path loss exponent	γ	2.0
Reference distance	d_0	$1km$
Random variable	X_g	Gaussian random variable
Received power	P_{Rx}	-90 dBm
Number of Channels	-	2 to 10
Tx antenna gain	G_t	12 dBi
Rx antenna gain	G_r	12 dBi

$$PL = P_{Tx_{dBm}} - P_{Rx_{dBm}} = PL_0 + 10\gamma \log_{10} \frac{d}{d_0} + X_g, \quad (9)$$

where PL is the total path loss between two communicating CPEs with a distance of d. $P_{Tx_{dBm}}$ and $P_{Rx_{dBm}}$ are the transmitted and received power in dBm, which can be calculated from transmitted and received power (P_{Tx} and P_{Rx}) in watt. Viable values of P_{Tx} for CPEs can be obtained by Eq. (9), to achieve power control and interference control. PL_0 is the path loss at the reference distance d_0. Other parameters of the simulations are listed in Table I.

The simulations were carried out in MATLAB[4]. The CPEs are randomly deployed. Flows between a pair of nodes in a time slot is generated randomly avoiding the conflicting flows as described in Section IV. Hence, on average one flow interferes approximately with half of the total flows. As mentioned before. The conflict avoidance here is limited to the fact that a node is not part of two flows in the same time slot. Once the flows are generated, the interference between them is found using distance based interference map, which is generated with considerations to path loss component, fading, etc. Then the flows are allocated with channels by sharing mechanisms i.e., WPA, FGCA and TFGCA.

B. Results

We have examined the optimal solution vs. the number of channels based on the problem definition in Eq. (3), (4) and (5) with IBM ILOG CPLEX Optimizer [15]. We have tested the cases with 40 flows and the number of channels grows from 1 to 15. As we can see in Fig. 3, when the number of channels (from 1 to 8 in this case) is much less than the number of flows, the optimal solution grows linearly. When the number of channel keep growing, the optimal solution still grows. Therefore, we can predict that the optimal solution grows linearly in our simulations with 600 CPEs and 2 to 10 channels, because the number of channels are much less the number of flows.

To analyze and compare the performances of WPA, FGCA and TFGCA, three different metrics are used. They are (a) average flow allocation, (b) average channel allocation, and (c) fairness among flows indicating the fairness amongst CPEs.

[4]Physical layer simulation is not considered here, that means, in a certain time slot, if a packet is transmitted without experiencing any collision, it can be received by all the receiving devices in the range with probability 1.

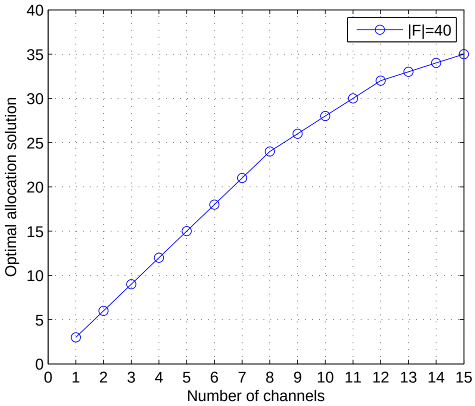
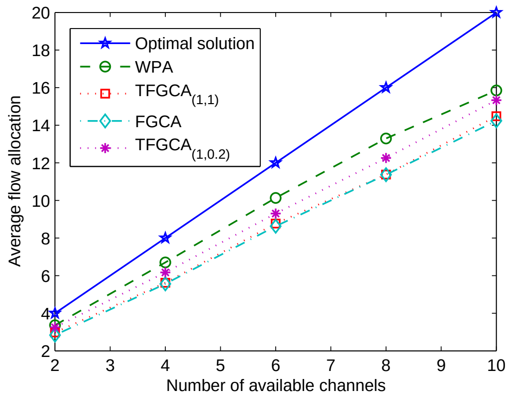


Fig. 3. Optimal solution vs. number of channels.

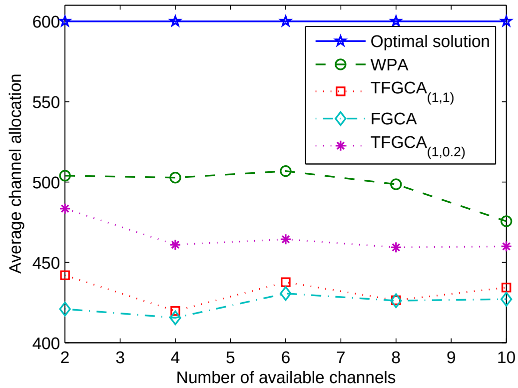
For TFGCA, we simulated with different values of K_d and K_f to show the "trade-off" ability of TFGCA. We also found out the optimal allocation solutions with different number of available channels by IBM ILOG CPLEX Optimizer [15], which maximized the channel utility. The results of our simulations are shown in Fig. 4.

The average flow allocation is the number of times of channel allocation divided by the number of flows (in Fig. 4(a)), i.e., $U(A)/|\mathbb{F}|$. It indicates the network capacity from the point of view of flows. We can see in Fig. 4(a) that, when WPA was adopted, every flow was allocated more number of times than TFGCA, while FGCA allocated the least. It is because WPA queues the flows according to the degrees, and flows with lesser degrees obtain higher chance of being allocated than others. FGCA only considers fairness of flows; however, it leads to least number of flows being allocated with channels. When the number of available channels increases, all three values grow because flows with different channels do not interfere with each other. Moreover, when TFGCA was adopted, differences can be seen in Fig. 4(a). When the weight of flow is formed with higher preference to the degrees of vertices than fairness, the average number of flow allocation increases because fairness is being given lesser importance than performance in this case. The average channel allocation is defined by $U(A)/|\mathbb{C}|$. Due to the reasons as mentioned above, WPA allocates more channels than TFGCA, and TFGCA works better than FGCA. However, average channel allocation does not increase with the number of available channels but decrease slightly. It is because when more channels are allocated to the same number of flows, the selection range of flows for every channel is less, which leads to lesser flows allocated with one channel. When $K_d > K_f$, the channels were allocated more than when $K_d = K_f$. The reason is that if fairness is considered with less importance during the queuing of flows than degrees, then the flows with less interference than others get more priority during the channel allocation. Fairness amongst flows is measured by Jain's index [16].

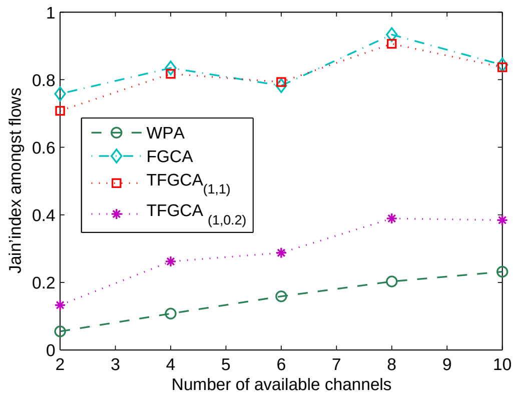
The base solution is shown in Fig. 4(a) and 4(b). The gap



(a) Average flow allocation.



(b) Average channel allocation.



(c) Fairness amongst flows.

Fig. 4. Simulation results with the optimal solution, WPA, FGCA, $\text{TFGCA}_{(K_d=1,K_f=1)}$ and $\text{TFGCA}_{(K_d=1,K_f=0.2)}$.

between the optimal solution and solutions of our schemes in our simulations is because that FGCA and TFGCA are based on GCA, which cannot provide the optimal solution for hard problems, but only provides possibly good solutions.

In our analysis, the total number of times a flow (f_i) being allocated with a channel is used to find the Jain's Index (x_i). Hence, Jain's index in Fig. 4(c) shows the fairness of channel allocation amongst flows. WPA created severe unfairness and FGCA is the fairest. FGCA queues the flows based on their previous allocations, and tries to give high priority to flows which have been allocated less channels than others. TFGCA is a trade-off with fairness and network capacity therefore, its fairness is higher than WPA but lower than FGCA. The values of Jain's index in the case of $K_d = K_f = 1$ are much higher than in the case of $K_d > K_f$, because in the first case fairness is considered to have higher priority than vertex degrees, which gives more fairness but lesser allocation.

With the above results, we can see that WPA achieves higher network capacity but with severe unfairness, FGCA leads to much fairer allocation but with lesser network capacity, and TFGCA is moderate on both counts, where the weights of fairness and performance can be adjusted by K_d and K_f.

VI. Conclusions and Further Work

Due to limited network capacity in WRAN, P2PWRAN was proposed to provide direct peer to peer communication through a centrally controlled mechanism matching with IEEE 802.22. However, the channel allocation is different from standard WRAN, because multiple channels can be allocated and the same channel can be re-allocated more than once per time slot. We found that the allocation problem is a variant of vertex coloring problem, and we formulated it as a QCP problem. Then we proved it to be computationally hard. WPA being a greedy coloring algorithm causes severe unfairness amongst flows during channel allocation. Therefore, FGCA is proposed in this paper, which tries to obtain fair channel allocation amongst flows but it could sometimes reduce the network capacity. To balance the fairness and the achievable network capacity, TFGCA is proposed. TFGCA is a simple scheme to implement and our simulation results confirm this feature. Our next step is to fine-tune our channel allocation algorithms to take it closer to implementation and deployment, considering dynamic nature of the wireless channels, parameters with respect to PHY layer and fairness. There are still many open issues in P2PWRAN too, such as inter-cell communication, intra-cell routing issues, transmission power control strategies, and flow allocation problems. These should be addressed to improve the fair channel allocation and increasing the network capacity in WRAN when P2P communication is needed.

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