Procedure to Build Interference Map in Peer to Peer IEEE 802.22 Networks

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***Abstract*—Peer to peer wireless regional area network (P2PWRAN) is proposed as an extension to support peer to peer communication based on IEEE 802.22 [1]. Multiple channel allocation and reuse of channels in the same time slot in P2PWRAN significantly increase the network capacity compared to standard IEEE 802.22 networks. One of the key issues in bringing P2PWRAN into reality is building the interference map. Interference map has been mentioned in the literature however a protocol to build an interference map is still an open issue. Therefore, we propose a simple and self-adapting interference map building protocol (SIMBP) for P2PWRAN, which can also be used in other multi-channel wireless networks with minor modifications. The simulation results show that SIMBP converges under the P2PWRAN setting, and with number of available channels and growing number of nodes, the capacity of the network is reached eventually.**

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

I. Introduction

To ease the shortage of spectrum, cognitive radio network was proposed for using the “white spaces” in the licensed bands [2]. Later, IEEE 802.22.1 for Wireless Regional Area Network (WRAN) was developed by IEEE 802.22 working group and it became the first cognitive radio standard [3]. WRAN works on the TV bands of 54-862 MHz with different bandwidths of 6, 7 and 8 MHz available internationally. A WRAN operates in a cellular fashion with a base station (BS) and multiple consumer premise equipments (CPEs), in a very large area (with a radius of 33 km to more than 100 km). The BS is in charge of the medium access in the cell, and CPEs in the cell are controlled by BS. Both BS and CPEs sense the spectrum, and the CPEs report the results to the BS. Then the BS merge all the information and manage the channel allocation by synchronizing channel queues [4].

In WRAN, the BS classifies channels into protected, unclassified, disallowed, operating, backup, and candidate channels based on spectrum sensing results of BS and CPEs [4]. The protected and disallowed channels are either used by the primary users currently or preserved by the operators, and unclassified channels are not sensed yet. Operating channels are the ones currently being used by the CPEs and BS. Backup channels will become operational in the following time slots. Candidate channels are viable channels for future use. Every CPE has a channel queue synchronized with the BS, which indicates the time and the channel to use in the following time slots. After every certain time period, the BS and a CPE choose the first channel of the synchronized queue to transmission data. The queue information is controlled by the SCH (Superframe Control Header) which is sent by the BS [3].

The cellular topology of WRAN makes the management of spectrum much easier since it is centralized. However, it also constrains the capacity of the network because every communication in the cell needs to go through the BS. Moreover, since the coverage area of a cell is so large that there are many intra-cell communication requests, which is limited by the cellular topology. Therefore, peer to peer WRAN (P2PWRAN) was proposed in [1] to take advantage of both centralized control and sharing of spectrum amongst CPEs. P2PWRAN supports direct communication between CPEs and the medium accesses is still controlled by the BS. For allocating channel in P2PWRAN, we need information of potential interference amongst flows. The complete picture of the possible interference amongst the CPEs is called interference map (IM). The accuracy of IM influences the channel allocation and network performance very much. Even though similar concept has been mentioned in other studies of wireless network research [5]–[8], there is no protocol to build IM yet. Most of the former works discuss the interference amongst users instead of flows, which cannot be used in P2PWRAN because of power control techniques. And how to build IM is still an open issue. This is one of the first attempts to define a protocol. We propose a self-adapting interference mapping protocol for P2PWRAN. Interference of directional flows is considered in SIMBP, which gives more accurate estimation of interference than the former work. A self-adapting mechanism is introduced in it, which copes with unexpected events in environment. The simulation results show that it converges as expected.

The rest of the paper is organized as follows. We discuss P2PWRAN in Section II in detail. Then related work is summarized in Sectino III. We propose the SIMBP in Section IV and then simulation and results are given in Section V. Finally, we conclude in Section VI.

II. Peer to Peer IEEE 802.22 Networks

The standard IEEE 802.22 network is a cellular network that adopts the cognitive radio technologies. In order to avoid the interference between the primary users (PUs) and Secondary

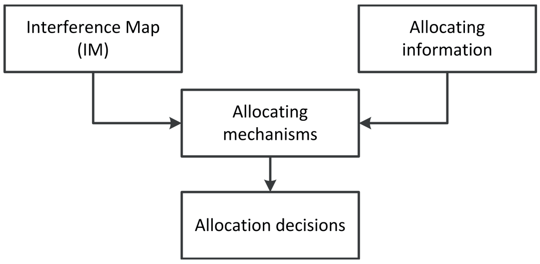


Fig. 1. The channel allocation procedure in P2PWRANs

users[1] (called CPEs in WRANs), the BS in every cell manages the network in a centralized fashion, and it is in charge of the spectrum sensing, sharing and allocation. This centralized spectrum management method is able to provide reliable wireless links and prevent interference to the PUs. However, it should not be disregarded that the cellular topology limits the capacity of the network and utility of channels, which is mainly caused by the single channel allocation in a cell. There are several disadvantages with this single channel allocation mechanism. Firstly, the communication period is prolonged. For example, every CPE to CPE communication needs to be through the BS even though the CPEs are in the same cell, and it is executed in two slots (CPE A to BS and BS to CPE B). Secondly, network capacity is constrained by the ability of the BS. For instance, if the BS has only one antenna then at most one communication can happen in the whole cell in one time slot. Thirdly, it causes the low utility of spectrum. If the BS has one antenna, then only one channel can be allocated even if there are more channels available.

Therefore, peer to peer IEEE 802.22 network (P2PWRAN) is proposed and is based on IEEE 802.22 with the enhancement of supporting direct CPE to CPE communications [1]. The main idea of P2PWRAN is to allocate multiple channels in a time slot to multiple flows in a cell based on IEEE 802.22 by adopting power control technologies, which is able to increase the channel utility and network capacity significantly [1]. The allocation procedure can be summarized as shown in Fig. 1. The work flow of channel allocation contains four modules, which are allocation information, interference map (IM), allocation mechanisms and allocation decisions. The allocation information includes the knowledge of available channels, current channel requests and previous allocations, which are collected by the BS as in the standard IEEE 802.22. The IM is to provide the interference information between two channel requests, which is used to prevent the interference amongst CPEs in a cell. The allocation mechanisms make the allocation decisions in a fair and efficient way without causing interference. Normally, the allocation mechanism transforms the allocation problem into a vertex coloring problem. The allocation decisions are carried out by BS eventually.

Two types of interference can be seen under the P2PWRAN setting. They are, (i) interference between PUs and CPEs and (ii) interference between CPEs. The allocation information module prevents the interference to the PUs by sensing the available channels. The IM tries to map the interference amongst the secondary users (CPEs) when multiple channels are allocated. The allocation mechanisms guarantee the fairness, channel utility, network capacity and interference level by making allocation decisions. The accuracy of IM influences the network performance significantly via the allocation mechanisms. Therefore, building an interference map is important. This is an open issue, which is specifically studied in this paper.

[1]In the rest of the paper we use the term 'user' and 'CPE' interchangeably.

III. Related Work

Multi-channel allocation problem can be transformed into coloring problems or Integer programming problems. We use the notation $\mathbb{U}$ to represent user set and $\mathbb{C}$ for the available channels in the current time slot. The interference map describes the constraints giving an overview of the potential conflicts and interference amongst the requests based on the positions of the CPEs. Zheng et al., [6] studied the collaboration and fairness in spectrum access by formulating the channel allocation problem as a color-sensitive graph coloring (CSGC) problem. They defined a constraint matrix, which indicated the interference amongst possible users when they were using the same spectrum band. This constraint matrix is based on the transmission power and the distance between the two users. Brik et al, [7] introduced a dynamic spectrum access protocol (DSAP), which has a DSAP sever to collect information and to make allocation decisions. A *RadioMap*, which was the same as the IM and contained the information on all users and channels, is saved on sever. The whole allocation was managed by the server in a centralized way. A flow contention graph and a resource constrained graph were defined in [5], which described the interference map in a single channel allocation. The nodes in the map are considered as flows instead of users. Tang et al., [8] discussed the spectrum allocation and scheduling in cognitive radio networks, in which a multi-channel contention graph (MCGC) was proposed as the IM. Besides the interference amongst users conflicts between user and channel was also included in this graph.

Even though the IM (or similar concepts) has been studied in the literature as summarized above, some problems are still open in the context of P2PWRAN. Firstly, a method of building the IM has not been provided. For example similar graphs or matrices were mentioned in [5]–[8], but they are treated lightly. Secondly, some of the studies [6], [8] treat users instead of the flows as the entities in the IM, and Zheng et al., [6] defined the constrained set as a $|\mathbb{U}| \times |\mathbb{U}| \times |\mathbb{C}|$ set. However, when different users are assigned the same channel, whether they interfere depends on the receiver or destination too. Therefore, the IMs should be based on flow set rather than on user set. This problem is discussed further in Section IV. Thirdly, their IMs have to be refreshed in every time slot before every allocation, which is not efficient when there are lots of available channels and requests. This is an implementation issue and affects the scalability of any allocation protocol.

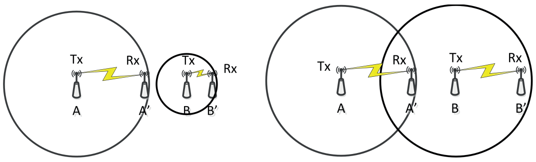
Therefore, we propose a protocol to build the IM for channel allocation in P2PWRAN. However the contributions of this work are not only limited to P2PWRAN, but it can also be applied to many other multi-channel allocation scenarios with minor modification.

IV. A Self-adapting Interference Map Building Protocol (SIMBP)

First we define the channel allocation problem of P2PWRANs in this section. This will articulate the need for IM. Then the protocol for building an interference map is proposed with an example.

A. Problem Definition

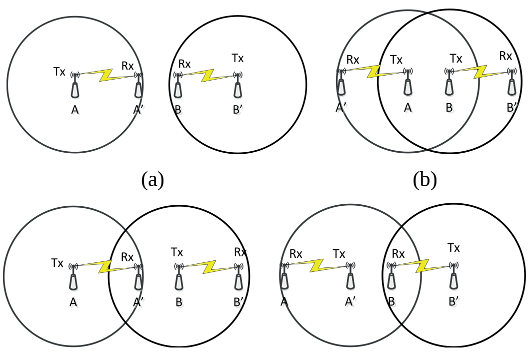
As we mentioned in Section III, some studies about IM can be found in the literature. Some of them adopted user set as the allocated entity. We adopt flows instead of users to allocate the channels to cover the transmitter and the receiver since the interference is dependent on the distance and the transmission power. For example in Fig. 2, we can see in 2(a) that User A and User B do not interfere, however they interfere with each other in 2(b). Furthermore, the flows should be directional,



(a) No interference. (b) With interference.

Fig. 2. An example of user interference.

since the direction of transmissions determines the occurrence of interference. For example, as shown in Fig. 3(a) and 3(b), there is no interference between the directional flows A to A' and B' to B. However, with the same flows but different directions, the receiving CPEs will be interfered by the other flows as shown in Fig. 3(c) and 3(d).



(a) (b) (c) (d)

Fig. 3. Different interference caused by directional flows.

Based the above discussion, we adopt directional flows to build the IM. We assume that the flow set, $\mathbb{F}$, includes all possible directional flows in the P2PWRAN and the element f_{ij} represents a flow from User i to j. The allocation A is a $|\mathbb{F}| \times |\mathbb{C}|$ matrix, and if the element $A_{(ij)k} = 1$, then flow f_{ij} is allocated with channel k, otherwise $A_{ijk} = 0$. The interference map is $\mathbb{M}$, which is a $|\mathbb{F}| \times |\mathbb{F}| \times |\mathbb{C}|$ matrix. If the element $m_{(ij)(pq)k} = 1$ in $\mathbb{M}$, then flow f_{ij} and flow f_{pq} interfere with each other when they use the same channel k, otherwise $m_{(ij)(pq)k} = 0$. We also define the channel utility as $\mathbb{U}(\mathbb{A}) = \sum_{i,j,k} A_{(ij)k}$. Then we can formulate the channel allocation problem as,

$$\max\left(\mathbb{U}(\mathbb{A})\right), \tag{1}$$

subject to

$$\sum_{\forall k \in \mathbb{C}} A_{(ij)k} \leqslant 1, \forall i, j; \tag{2}$$

$$\sum_{\forall i,j,p,q(i \neq j \neq p \neq q) \in \mathbb{U}, \forall k \in \mathbb{C}} A_{(ij)k} A_{(pq)k} m_{(ij)(pq)k} = 0. \tag{3}$$

The condition in Eq. (2) indicates that only one channel can be allocated for each user/flow. The condition in Eq. (3) avoids the interference during channel allocation. As we can see in this allocation problem, the interference map $\mathbb{M}$ plays an important role in channel allocation. We mainly discuss the procedure to build it in the rest of the paper.

B. SIMBP in P2PWRAN

There are two main constraints that should be reflected in $\mathbb{M}$. The first one is the constraint of the antennas. Under the assumption that every user only has one transmitting/receiving antenna, if two flows containing one or two same users, they should not be allocated with channels in the same time slot. The second one is the constraint of interference. If two flows are in each other's transmission area then they should be marked as interfering.

Besides the two constraints, the interference map should also be self-correcting, because the interference environment is very complex and is always changing in reality. Therefore, the procedure to build IM should be self-adaptive to the environment and should converge to depict the reality. We proposed a self-adaptive interference map building protocol (SIMBP) for P2PWRAN with two algorithms, which are applied at the beginning and during operational stage of the network. The algorithms are shown in Algorithm. 1and 2.

As shown in Algorithm. 1, at the start stage of the network, the BS collects the geo-locations of CPEs and adds flows into flow set $\mathbb{F}$. Then the BS builds the initial IM due to the two constraints. Flows with same CPEs are marked as interfering with each others. The BS calculates the transmission area of flows; if overlap is found, then two flows are marked as interfering too in IM. The BS calculates its transmission area due to the network topology and fading models theoretically, for example Rayleigh fading, Rician fading and Weibull fading [9]–[11] models. Algorithm. 2 deals with the unexpected events during the network operation. Whenever a CPE joins or leaves the cell, or interference is detected, the BS updates the IM.

Algorithm 1 The algorithm to build initial IM.

All CPEs register to the BS and report their geo-locations.
// Then the BS builds the interference map in a centralized fashion.
// Firstly, the BS calculates the flow set $\mathbb{F}$ (CPE pairs and CPE-BS pairs).
for every CPE/BS pairs, **do**
  if it is a CPE-BS or BS-CPE pair, **then**
    Add it into $\mathbb{F}$.
  else if it is a CPE-CPE pair and the distance between these two CPEs are shorter than the radius of the cell, **then**
    It is added into $\mathbb{F}$.
  end if
end for
// The BS builds the initial IM.
BS collects the information of available channel set $\mathbb{C}$.
Initialize $\mathbb{M}$ as $0_{|\mathbb{F}|\times|\mathbb{F}|\times|\mathbb{C}|}$.
for every two flows $f_{ij}, f_{pq} \in \mathbb{F}$, and every channel k, **do**
  if f_{ij} and f_{pq} contain the same user, **then**
    $m_{(ij)(pg)k}$ is assigned with 1.
  else
    Calculate the transmission area of f_{ij} and f_{pq} when using channel k.
    if there is overlap transmission area between f_{ij} and f_{pq}, **then**
      $m_{(ij)(pg)k}$ is assigned with 1.
    end if
  end if
end for

Algorithm 2 The self-adapting algorithm of IM.

// Deal with the changes of network topology.
if a new CPE in a cell registers at BS, **then**
  The BS adds new flows from the CPE to $\mathbb{F}$ and update $\mathbb{M}$.
end if
if a CPE leaves the cell, **then**
  The BS deletes all related information in $\mathbb{F}$ and $\mathbb{M}$.
end if
if interference occurs during data transmission, **then**
  The BS marks the flows as interfering and updates $\mathbb{M}$.
end if

C. Discussion

There are some issues that we want to highlight here:

- Hidden terminal issue has been discussed to a great extent in wireless networks [12], [13]. However, it is eliminated in the P2PWRAN with SIMBP. In P2PWRAN, the BS controls the interference level amongst CPEs by using SIMBP, which would not cause hidden terminals.
- Power control can reduce the interference significantly. In P2PWRAN, SIMBP can provide the important information for calculating the proper transmission power for a flow, because the geo-locations of CPEs are reported to the BS at the start of the network.
- The interference map built by SIMBP can be stored in the BS or a database, and the space requirement is $O(|\mathbb{F}|^2 \times |\mathbb{C}|)$. Because the channel fading for different frequencies is different, it may cause different interference patterns.
- At the start of the network, or during the changes in CPEs (for example the location), there is a period of uncertainty when SIMBP has to be adopted. However, the standard WRANs consider relatively static CPEs in a large area. Thus as long as the network is static, the interference map does not need to be updated constantly.
- In SIMBP, co-channel interference [14] is considered, however adjacent-channel interference is not included in our interference map.

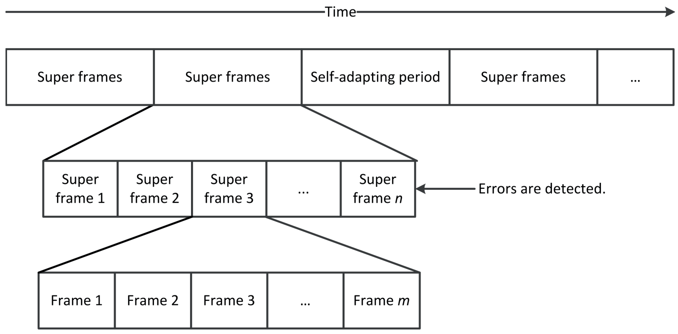


Fig. 4. The structure of frames in P2PWRAN with SIMBP.

V. Simulations Results in P2PWRAN

The SIMBP has been simulated in P2PWRANs with different number of nodes and error ratios in the interference map, and the results are provided and analyzed in this section.

A. Channel management in P2PWRAN by SIMBP

P2PWRANs support peer to peer communications amongst CPEs, and all the spectrum sensing and allocation are managed by the BS in a centralized way as in standard WRAN. SIMBP gives a method to generate the interference map in multi-channel wireless networks, and the BS in a cell maintains the interference map and allocates channels to different flows generated by CPEs. However, SIMBP firstly builds the interference map theoretically based on the network topology and fading models [9]–[11]; this may create an error E compared to the actual. Therefore, we add a self-adapting period to correct the errors in the interference map in between n super frames if some errors are detected in the last n super frames, and every super frame contains m frames as in standard WRAN, which is shown in Fig. 4.

In the super frames, channels are allocated to flows and communication happens during this period. If some interference is detected in this period, then there might be some errors in the interference map. Therefore, the self-adaptation is triggered to correct the IM, and then the BS corrects the wrong information in the map. We assume that in every super frame,

TABLE I
PARAMETERS

Parameters	Symbols	Values
Super frame time	-	80 ms
Frame time	-	10 ms
Self-adapting period	-	2 s
Path loss exponent	γ	2.0
Reference distance	d_0	$1km$
Random variable	X_g	Gaussian random variable
Received power	P_{Rx}	-90 dBm
Tx antenna gain	G_t	12 dBi
Rx antenna gain	G_r	12 dBi

TABLE II
DETAILS OF THE IM.

$\lvert\mathbb{N}\rvert$	$\lvert\mathbb{F}\rvert$	Interference ratio
10	90	29.77%
20	366	26.25%
40	1258	28.57%

every node generates a channel request, then the expected error ratio E_t after t super frames is shown in Eq. (4).

$$E_t = E_0(\frac{|\mathbb{F}|^2 - |\mathbb{N}|}{|\mathbb{F}|^2})^t, \quad (4)$$

where E_0 is the initial error ratio.

B. Scenarios

We consider a P2PWRAN cell with a radius of 40 km and CPEs are randomly deployed in it with the number of three cases – 10, 20 and 40. There are three available channels for allocation. Friis path loss and lognormal shadowing was adopted to generate the initial interference map [15]. We adopt a traffic model where we assume that as soon as a flow is generated by CPEs it is allocated with a channel. The destination CPE is selected randomly. Since channel allocation problem in P2PWRAN can be converted into a vertex coloring problem, the greedy algorithm [16] was adapted in our simulations. The other parameters used in our simulations can be seen in Table I.

C. Results

Three scenarios with different number of CPEs have been studied in our simulations to build the IM. Details of the IM can be seen in Table II, which shows the size of flows and interference ratios with different number of CPEs. The interference ratio is the ratio of number of zeros to the number of all elements in the IM. As we can see, the number of flows grows rapidly with the growth of CPEs. From the interference ratios of all cases we can see that a flow does not interfere with almost one third of other flows, which indicates a high possibility of channel reuse.

In our simulations we considered the initial error ratio in the interference map as 0, 5%, 10%, 20% and 50%. The convergence of the maps is shown in Fig. 5 when there are 10 CPEs in the network. As we can see, naturally higher initial error ratios cause longer convergence time than lower error ratios, but the self-adaptation of the IM is with the same trends.

The frequency of allocation is the total number of allocated times of channels in a second. The results of frequency of allocation in our simulation with different number of nodes are shown in Fig. 6. When the flow request is limited, the BS can satisfy most of the channel requests with three available channels as shown in Fig. 6(a) and Fig. 6(b). However, if the number of CPEs and flow requests keep growing, the frequency of allocation reaches its peak as shown in Fig. 6(c) and Fig. 6(d). The peak of the frequency of allocation can be understood as the network capacity under a certain IM. When the network capacity is reached, the performance of the network does not improve with the number of CPEs(or flow requests) anymore. Different initial error ratios of the IM influence the frequency of allocation slightly as shown in Fig. 6 comparing the 0 initial error ratios cases, because during the allocation stage the BS makes the decision due to the current IM without knowing the error ratios.

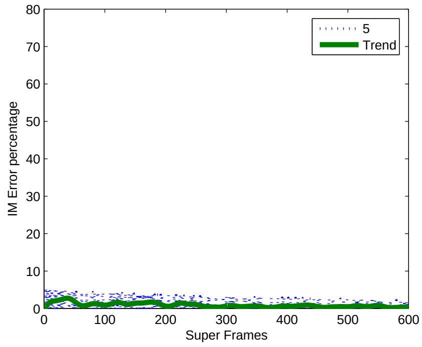
With the results and analysis, the following advantages can be seen with SIMBP in P2PWRAN:

- The BS in a cell manages all the media access in a P2PWRAN cell. SIMBP is a method to build the IM of the cell in a centralized way, which is necessary for the BS to make allocation decisions. This matches the IEEE 802.22 network very well.
- No extra communication is needed to build the IM by SIMBP, because the BS is aware of the state of every CPE in P2PWRAN.
- The IM built by SIMBP considers directional flows, which makes the IM more accurate than considering omnidirectional flows.
- P2PWRAN is a relatively static wireless network. Once the IM is built, it can be valid for a longer period with minor updates when some unexpected events happen.
- The interference environment always has some unexpected events. SIMBP is based on a self-adaptation procedure, and the IM is corrected if some errors are detected during the transmission.
- Even though SIMBP is designed for P2PWRAN, it can be adopted by other multiple channel allocation scenarios with minor modifications.

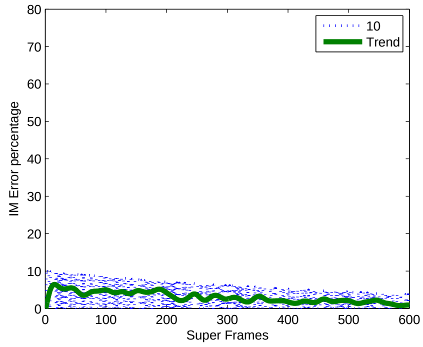
However, there are some disadvantages of SIMBP too. For example, because the IM is based on directional flows, there is a need for large memory ($O(|\mathbb{F}|^2 \times |\mathbb{C}|)$) at the BS. In the SIMBP introduces a self-adaptation period whenever interference is detected during data transmission, which may add extra delay to flows. The extra delay only exists during the convergence period. There is no extra delay of transmission after the IM converges; therefore, the network performance after the convergence is not influenced because no extra delay is not introduced during the data transmission anymore.

VI. CONCLUSION

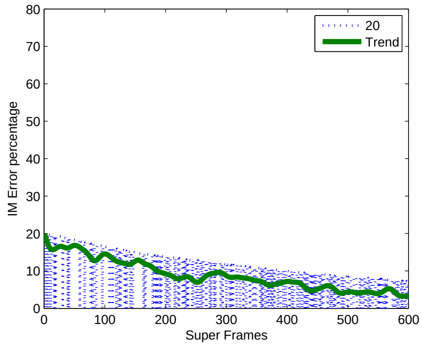
We proposed a self-adapting interference map building protocol (SIMBP) for channel sharing and allocation in P2PWRAN, which can also be used in other multi-channel networks with minor modifications. SIMBP can build an initial



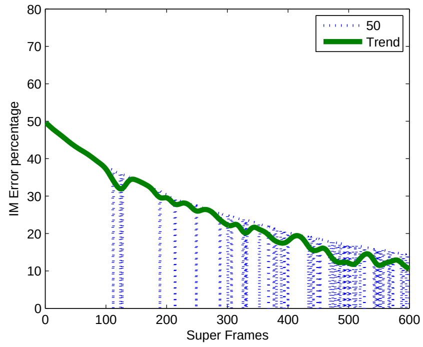
(a) Initial error ratio is 5%.



(b) Initial error ratio is 10%.

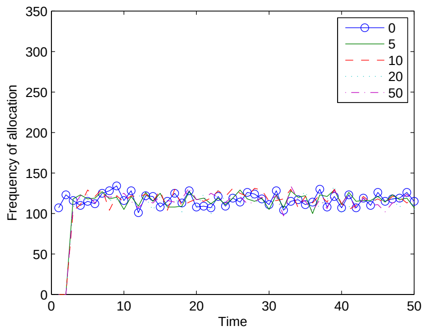


(c) Initial error ratio is 20%.

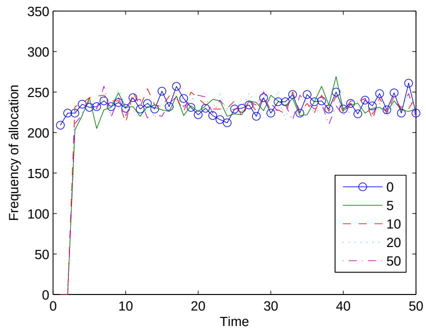


(d) Initial error ratio is 50%.

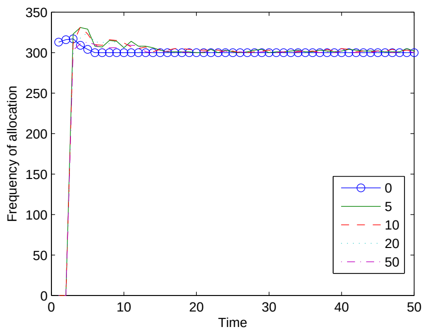
Fig. 5. Error percentage in the interference map when $|\mathbb{N}| = 10$.



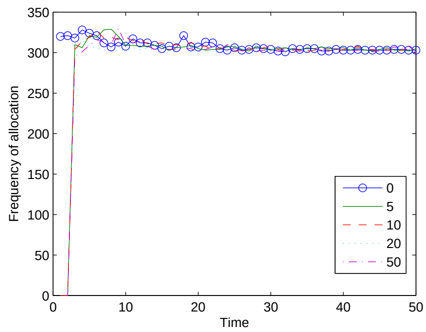
(a) $|\mathbb{N}| = 10$.



(b) $|\mathbb{N}| = 20$.



(c) $|\mathbb{N}| = 30$.



(d) $|\mathbb{N}| = 40$.

Fig. 6. The frequency of allocation with different number of CPEs and initial error ratios of the IM.

interference map using fading models and it converges gradually. The errors in the initial interference map may cause extra delay for some flows, however, after the self-adapting period the network stays in a stable state. SIMBP gives a procedure to build the interference map in a centralized fashion. The co-channel interference is considered in SIMBP when the initial interference map is built. However, there might be adjacent-channel interference in the network too. This will be studied further. Moreover, how to allocate the channels in a fair and efficient way along with the interference map is still an open issue in P2PWRAN, which is our ongoing study.

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