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A framework for development and evaluation of a dynamic subchannel allocation scheme in an OFDMA system

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Abstract This paper presents a framework for allocating radio resources to the Access Points (APs) introducing an Access Point Controller (APC). Radio resources can be either time slots or subchannels. The APC assigns subchannels to the APs using a dynamic subchannel allocation scheme. The developed framework evaluates the dynamic subchannel allocation scheme for a downlink multicellular Orthogonal Frequency Division Multiple Access (OFDMA) system. In the considered system, each AP and the associated Mobile Terminals (MTs) are not operating on a frequency channel with fixed bandwidth, rather the channel bandwidth for each AP is dynamically adapted according to the traffic load. The subchannels assignment procedure is based on quality estimations due to the interference measurements and the current traffic load. The traffic load estimation is realized with the measurement of the utilization of the assigned radio resources. The reuse partitioning for the radio resources is done by estimating mutual Signal to Interference Ratio (SIR) of the APs. The developed dynamic subchannel allocation ensures Quality of Service (QoS), better traffic adaptability, and higher spectrum efficiency with less computational complexity.

Keywords Access point controller · OFDMA system · Frequency reuse · Hierarchical radio resource management · Decision functions · Dynamic subchannel allocation

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1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a multiple carrier technique that has been proved to be robust for communication over fading channels. OFDM systems divide a broadband channel into many narrowband orthogonal subcarriers [3, 9] where a group of subcarriers forms subchannels. When multiple accesses are desired, OFDM can be combined with Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA) or a mix of both. The combination of OFDM and TDMA is called Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA is being considered as a modulation and multiple access method for the fourth generation wireless networks. The total network consists of a fixed network part and a wireless access system. The fixed network provides connections between Access Points (APs). These APs are responsible to provide connections to the wireless Mobile Terminals (MTs). The APs are distributed over geographical area where it is necessary to provide coverage.

In OFDMA systems, radio resource allocation is still a critical issue in optimizing the performance of the system since the rapid increase in the size of the wireless mobile community and its demand for high speed multimedia communications rather stand in clear contrast to limited spectrum resources that have been allocated in international agreements. In this regard, a feasible or nearly optimal dynamic subchannel allocation technique can be used for the resource allocation of an OFDMA system in order to optimize its performance.

An advantage of the OFDMA system is the elimination of intracell interference avoiding CDMA (Code Division Multiple Access) type of multi-user detection [10]. But intercell interference could occur in the OFDMA system when there is frequency reuse between the APs. Frequency reuse implies that there are several APs that use the same set of frequencies or subchannels due to propagation path loss of the radio signal [18]. These APs are called cochannel cells (here cell is the synonym of AP), and the interference between signals from these APs is called cochannel interference. Cochannel interference, which requires to be handled intelligently for having better spectral efficiency, is a critical problem in the OFDMA system.

The motivation of this work is to allocate OFDMA subchannels to the APs in a centrally controlled manner using Dynamic subChannel Allocation (DCA) scheme with effective frequency reuse by removing the co-channel interference remarkably. The newly developed DCA scheme works much better than the Fixed subChannel Allocation (FCA) scheme with optimal Fixed Reuse Partitioning (FRP) [7] and the complexity of the algorithm is $O(n2.m) + O(k.n2)$, n is number of cells, k is number of subchannels, m is the number of users in the system.

DCA has been well studied in multicellular system networks [7]. But according to [11], applying existing DCA algorithms to a broadband OFDMA system is nontrivial for several reasons. First of all, unlike the traditional DCA schemes that assume a predetermined SINR (Signal to Interference and Noise Ratio) threshold (for homogeneous applications such as voice), modern data networks utilize adaptive modulation which makes channel assignment decision nonbinary from SINR standpoint [9]. Terminals employ different modulation and coding schemes with different SINR [2], thus different throughput are obtained at different SINR levels. Secondly, channels are frequency selective and their data rate requirements are also different. The third challenge associated with the DCA is the measurement and signaling overhead. Since OFDMA channels are broadband, fully centralized schemes are often too heavy for implementations as all the interference information on all channels has to be gathered at a central controller. As a result, the execution time of the DCA scheme increases exponentially.

To mitigate the overhead of fully centralized radio resource management, in this paper, we have developed a framework which allows hierarchical resource allocations. In this framework, a hierarchical radio resource management (HRRM) scheme has been developed. In the HRRM scheme, an Access Point Controller (APC) handles interference aware dynamic subchannel allocation to the APs and the APs assign resources to the MTs using an OFDMA scheduler. By handling the interference between the APs, the APC makes the APs lightweight reducing their measurement and signaling overhead. The APC gains knowledge about the interference situation investigating the mutual SIR measurements of the APs. The APC uses the mutual SIR measurements to take nonbinary reuse decisions. In this paper, we consider three decisions: *reusable*, an AP can fully reuse its interferer AP's resources; *partially-reusable*, an AP can partially reuse its interferer AP's resources, and *not-reusable*, an AP cannot reuse it's interferer AP's resources. The APC uses two decision making functions, *utilization function* and *reuse decision function* for the subchannel allocation. The *utilization function* is aimed to prioritize an AP which has high resource requirement, whereas the *reuse decision function* is considered to prioritize an AP which can reuse less resources of other APs. In this paper, we have shown that combined use of these two decision making functions ensures more fairness than the use of the *utilization function* merely.

The remainder of the paper is organized as follows. In Sect. 2, some previous works related to DCA scheme in OFDMA systems are presented. Section 3 is used to describe the developed framework architecture and to explain the HRMM scheme. Section 4 discusses the developed DCA scheme, whereas Sect. 5 summarizes the algorithm and its computational complexity. Section 6 briefly describes the deployed OFDMA system. Section 7 presents the overall working structure of the proposed APC in this system. The simulation results to evaluate the dynamic subchannel allocation algorithm executed by the APC is provided in Sect. 8 and finally, Sect. 9 concludes the paper with some potential guidelines for further enhancement of this work.

2 Related work

Several DCA algorithms have been proposed, but their complexities are rather high [7]. In [15], the best channel reuse pattern was selected by doing the capacity prediction for all possible combination of the channel patterns. However, this type of solution is in practice impossible, especially where the number of cells and channels are many. Furukawa and Akaiwa [6] have mentioned that despite the absence of intra-cell interference in OFDMA systems, optimum channel allocation is still a NP-hard problem which is basically complex. Moreover, individual user's rate requirements further complicate the problem. Kim and Lee [8] and Pietrzyk and Janssen [14] have developed a channel allocation scheme based on [2] with less computational complexity. But in [14], a lot of iterations are needed to solve the problem and the linearization in [8] cannot be generalized to all types of modulations. Yin and Liu [17] have investigated noniterative algorithms to reduce computational complexity.

3 The framework architecture

In the developed framework, an APC is used like HiperLAN/2 and IEEE802.16 to select the radio resources for the APs dynamically. The resources can be either time slots or frequencies (subchannels). When the APC uses frequencies as resources, it exploits Frequency Division Reuse Partitioning (FDRP), whereas when it uses time slots as resources, it exploits Time Division Reuse Partitioning (TDRP) [4]. The APC can allocate resources to the APs using different resource allocation schemes, such as dynamic, static, hybrid, and random.

The AP, which is usually connected to a wired network backbone, provides radio connections for the MTs. The basic cellular system architecture with an APC is shown in Fig. 1. However, there are also ad hoc networks where MTs are responsible to allocate their radio resources, i.e., no central controller is used for the resource allocation in MTs.

Using the framework, we have developed a hierarchical radio resource allocation scheme where resource allocation is done in two steps. In the first step, the APC takes high level resource allocation decision and in the second step, the AP takes detailed allocation decisions using decisions of the APC. The dynamic resource allocation to the APC level can be considered as a slow adaptation to the traffic load and interference. The resource allocation on the AP level is done in a fast adaptation manner (frame-by-frame) to react on the changing channel conditions (e.g., fading). The working process of the APC is synchronized with the MAC frames. The APC updates subchannels of the APs in some defined frames. The frame level interaction diagram is shown in Fig. 2. In this figure, the APC updates resources of the APs in a super frame level. The term super frame indicates that the APC updates resources of the APs in a frame interval, but not at each frame.

The APC uses a low complexity traffic load adaptive and interference aware subchannel allocation scheme and the AP uses an OFDMA scheduler to assign resources to the MTs.

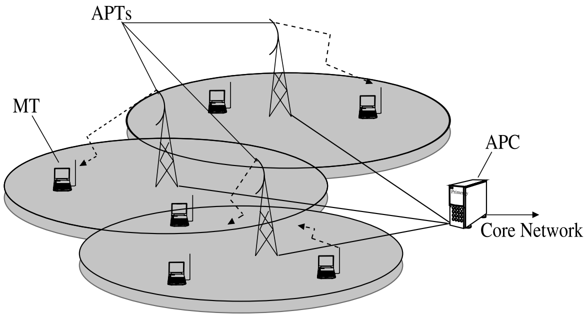


Fig. 1 Basic cellular system architecture with APs and MTs

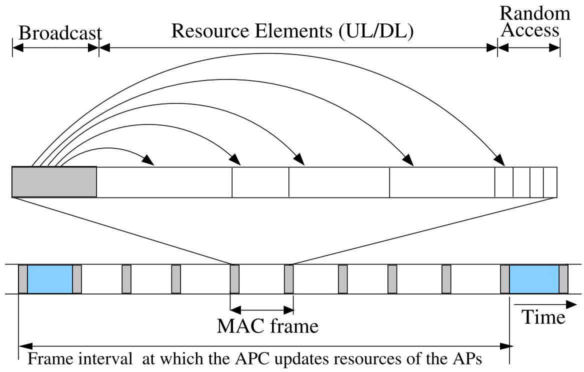


Fig. 2 Frame level interaction between the APC and the AP

The complexity of optimizing resource allocation is a NP-hard problem where execution time of the algorithm increases exponentially [17]. Moreover, a lot of messaging and computational overheads are incurred if resource allocation is done only by the APs. In this situation, HRRM can play a good role by splitting allocation activities between the APC and the APs. This hierarchical radio resource management not only can optimize the allocation of subchannels to the MTs but also simplify management, improve performance, and increase security of the large wireless network. The APC can create and enforce different policies to make the APs lightweight.

4 Developed DCA scheme

In the developed subchannel allocation scheme, traffic load is estimated based on the utilization of the assigned subchannels, and the interference estimation is done based on the received signal power measurements. For this, the HRRM of an OFDMA system has been used. The APC aims both to handle intercell interference and to allocate subchannels to the APs dynamically. Its functionalities are divided into two phases: *reuse decision phase* and *allocation phase*. In the first phase, the APC gains knowledge about the interference situation by investigating the mutual SIR of the APs. In the second phase, the APC allocates subchannels to the APs using the obtained knowledge of interference. Both phases are discussed as follows:

4.1 Reuse decision phase

The frequency reuse depends on the spatial distances of the APs and the level of received signal quality. Due to the propagation path loss of the radio signal, the average power received from a transmitter at distance d is proportional to $P_T d^{-\gamma}$ where γ is a number ranges between 2–5 depending on the physical environment and P_T is the average transmitter power. As the communication environment is amorphous, and different obstacles, which can change the power level and the direction of the radio signal, could be in the communications paths, it is challenging to determine the cochannel interference using mathematical model. Moreover, judiciously assigning appropriate radio subchannels to each AP is an important process that is more difficult in practice than in theory. According to [18], the propagation path loss seldom follows the propagation path loss assumption. Therefore, fixed reuse partitioning [7] or forming cochannel cells is not a good solution for utilizing radio resources.

As the APs are always fixed, the adaptive reuse partitioning mainly depends on the position of the MTs. Several researchers have investigated Adaptive Channel Allocation (ACA) with Reuse Partitioning (RUP) for obtaining better system capacity. With ACA reuse partitioning of any channel in the system can be used by any AP as long as the required SIR is maintained. Based on this fact, a number of approaches, such as flexible reuse schemes and self-organizing schemes have been proposed [7]. The self-organized reuse partitioning (SORP) [6] is based on signal power measurements. In this method, each AP has a table in which average power measurements for each channel for all the APs are stored. When a request arrives, the AP measures the received power of the requesting MT (in order to locate the MT's position) and selects a channel, which shows the average stored power of that channel closest to the measured power. The content of the table for the chosen channel is updated with the average value of the measured power and the power of other MTs using the same channel. The updated power levels of MTs are broadcasted by this AP to the other APs. As a consequence of this procedure, in each AP, channels that correspond to the same power are grouped autonomously for self-organized partitioning. In this paper, we follow the concept of SORP, but in a resource optimizing and centralized manner. In order to form adaptive reuse partitioning, we have exploited the received signal power of the broadcast bursts. Following the HiperLAN/2 model and the deployed model of this paper, all the APs broadcast control information at the first slot of the frame. This first slot of a frame is reserved for the signaling overhead. We estimate the mutual SIR using the measured received power of the broadcast bursts. By comparing the mutual SIR, the APC decides which AP can reuse which APs' resources. Then the APC saves this value in a table named Reuse Partitioning Table (RPT). The table is updated periodically.

The positive side of our approach is that the mutual SIR can be calculated without having any extra slots. As the transmission power is higher in the broadcast phase than the downlink/uplink phase, the reuse partitioning of the APs is generated for the worst case behavior of the interference. By realizing this worst case behavior, we have set the SIR threshold to 15 dB which allows maximum Packet Error Rate (PER) 0.001 that is set in the simulation parameter. The value 15 dB is also considered as the target SINR in this work. The mapping of SINR and the PER is shown in Fig. 3.

In order to form the reuse partitioning of the APs or downlink cochannel cells or APs reuse patterns, the APC periodically triggers the APs to measure the received signal power of the MTs. After getting the invocation from the APC, the AP triggers its associated MTs to measure the received signal power level of the broadcast bursts. Then the associated MTs measure the received signal power level from all the APs and send the measured values to their controller AP. The controller APs then inform the APC about the received signal power values and the APC thereafter estimates the mutual SIR of the APs using the received signal power values. The sequence diagram for estimating mutual SIR is shown in Fig. 4.

Let us consider a small scenario with three APs: AP_0, AP_1, and AP_2 (cf., Fig. 5). Each AP has four associated MTs. In this scenario, the distance of AP_0 and AP_1 is 500 m, AP_0 and AP_2 is 790 m, AP_1 and AP_2 is 790 m and each cell radius is

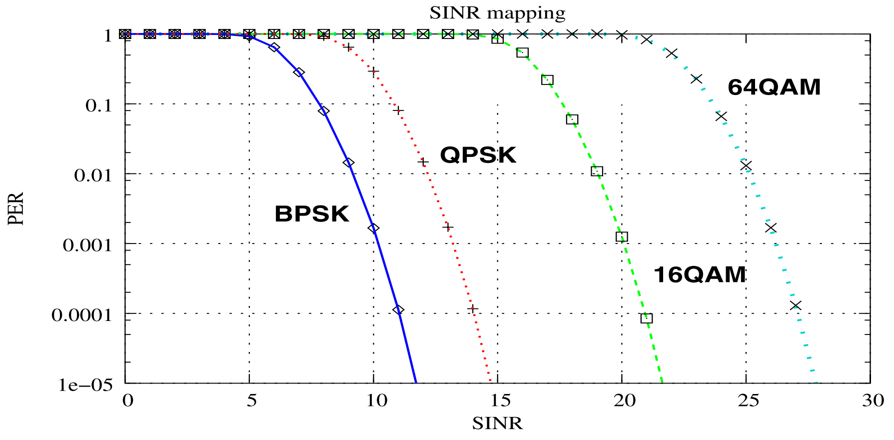
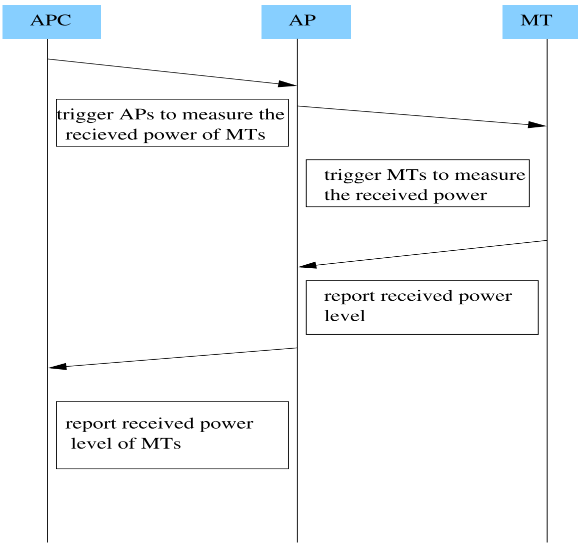


Fig. 3 SINR mappings

Fig. 4 Sequence diagram for SIR estimations



200 m, where cells are not overlapping. As AP_2 is far apart from AP_0 and AP_1, it can reuse resources of both AP_0 and AP_1. On the other hand, as AP_0 and AP_1 are not far apart, they have a very low chance to reuse each other resources due to higher interference. The estimated mutual SIR values are shown in Table 1. The APC forms cochannel cells according to the mutual SIR values by comparing these with a predefined reuse threshold (here it is considered 15 dB) and stores the binary reuse decisions: *reusable*(y) and *not-reusable*(n) in the RPT.

Different Reuse Constraints (RCs) can be used to form co-channel cells such as *minimum mutual SIR*, *mean mutual SIR* and *weighted mutual SIR*. One of the goals of the APC is to provide the reuse of resources as much as possible while mitigating

Table 1 Mutual SIR values for three-cell scenario of Fig. 5

	$MT_{0,i}$/SIR	AP_0/AP_0	AP_0/AP_1	AP_0/AP_2
AP_0	$MT_{0,100}$	–	16.54	24.07
	$MT_{0,101}$	–	13.54	25.25
	$MT_{0,102}$	–	$\underline{12.45}$	$\underline{21.9}$
	$MT_{0,103}$	–	18.46	29.41
	$MT_{1,i}$/SIR	AP_1/AP_0	AP_1/AP_1	AP_1/AP_2
AP_1	$MT_{1,104}$	16.13	–	27.09
	$MT_{1,105}$	13.53	–	$\underline{25.63}$
	$MT_{1,106}$	$\underline{12.39}$	–	25.65
	$MT_{1,107}$	18.68	–	25.64
	$MT_{2,i}$/SIR	AP_2/AP_0	AP_2/AP_1	AP_2/AP_2
AP_1	$MT_{2,108}$	$\underline{24.07}$	$\underline{24.43}$	–
	$MT_{2,109}$	33.03	33.41	–
	$MT_{2,110}$	45.49	45.69	–
	$MT_{2,111}$	33.12	33.29	–

the interference. So in this paper, we have compared the delay and efficiency of the APs by generating cochannel cells with different RCs. The three RCs are discussed as follows:

Minimum mutual SIR RC (min RC) Using this constraint, the APC estimates the minimum mutual SIR for all the MTs associated to an AP. It is the strictest condition for forming cochannel cells. Here it is considered that two APs can reuse resources, if and only if minimum mutual SIR values of both APs for their associated MTs are greater than or equal to the predefined SIR threshold. Due to the mobility of the MTs, sometimes it could happen that the positions of one AP's MT will allow reuse but other AP's MTs will not. For example, in the scenario shown in Fig. 5, AP_1's MTs allow it to reuse AP_0's resources but the position of AP_0's MTs do not allow it to reuse AP_1's resources.

In this case, if AP_0 and AP_1 send data at the same time using the resources of AP_0, then AP_0's MTs will be interfered. In order to avoid AP_0's MTs to experience such interference, it is considered that the both APs' min mutual SIR values should be greater than or equal to the predefined SIR threshold.

As the link adaptation has been implemented and the target SINR of this simulator value is 15 dB, we have considered mutual SIR threshold as 15 dB for all modulation schemes. The mappings of SINR with different modulation schemes are shown in Fig. 3. The minimum SIR of all the APs are given in Table 2 and the corresponding APs' reuse pattern is shown in Table 3. In the reuse pattern, the following given legend will be used:

reusable (y): if the mutual SIR value is equal to or greater than the predefined threshold 15 dB.

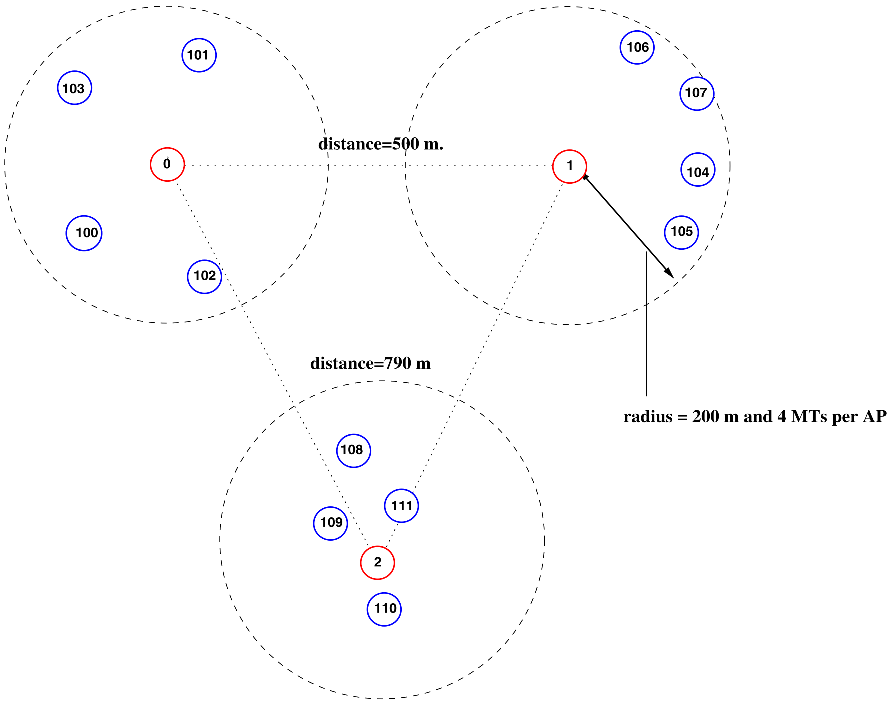


Fig. 5 3-cell exemplary scenario

Table 2 Mutual SIR values after applying *Min RC*

Source/Interferer	AP_0	AP_1	AP_2
AP_0	–	12.45	21.9
AP_1	12.39	–	25.63
AP_2	24.07	24.43	–

Table 3 Reuse pattern of the APs for *Min RC*

Source/Interferer	AP_0	AP_1	AP_2
AP_0	y	n	y
AP_1	n	y	y
AP_2	y	y	y

not-reusable (n): if the mutual SIR value is less than the predefined threshold 15 dB.

partially-reusable (p): two APs share resources partially (will be discussed later).

When both the source and the interferer APs are same, the mutual SIR is infinite which always greater than the predefined threshold. To represent this, we have used the symbol "–." In Table 2, the first entry $\{AP_0, AP_0\}$ thus indicates that AP_0 can reuse

Table 4 Mutual SIR values after applying *Mean RC*

Source/Interferer	AP_0	AP_1	AP_2
AP_0	–	15.24	25.15
AP_1	15.18	–	26.00
AP_2	33.92	34.00	–

Table 5 Reuse pattern of the APs for *Mean RC*

Source/Interferer	AP_0	AP_1	AP_2
AP_0	y	y	y
AP_1	y	y	y
AP_2	y	y	y

Table 6 Mutual SIR values after applying *Weighted RC*

Source/Interferer	AP_0	AP_1	AP_2
AP_0	–	10.66	5.03
AP_1	9.86	–	5.2
AP_2	22.04	23.8	–

it's own resources, the second entry $\{AP_0, AP_1\}$ shows the value 12.45 which is below the predefined threshold 15 dB, and thus, they cannot reuse each other resources, and the third entry $\{AP_0, AP_2\}$ shows the value 21.9 which is above the threshold, and thus, they can reuse each other resources. Similarly, for the other rows. The resulting reuse pattern is shown in Table 3.

Mean mutual SIR RC (mean RC) This is the mean mutual interference of all MTs in the AP. This is the most flexible reuse constraint. In this constraint, formation of cochannel cells in APs does not rely on a single MT's position unlike the *min RC*. It considers position of all the associated MTs. If the average mutual SIR of all the associated MTs of the other two APs exceeds the predefined threshold then they can use the same resources. Tables 4 and 5 show the average mutual SIR and the corresponding reuse pattern of the APs, respectively.

Weighted mutual SIR RC (weighted RC) To reduce the bad impact of the *min* (strict) and *mean* (flexible) RCs, *weighted RC* has been introduced. In this case, a weighted value is multiplied with the mutual SIR value obtained by applying *mean RC*. The weighted value is calculated considering the utilization of the interferer AP which is (1-*utilization*). If the utilization of the interferer AP is low then the source AP is capable of reusing the interferer AP's resources since low utilization indicates that the data transfer in the interferer AP's side is low. For example, if the average utilization of $AP_0 = 0.35$ and $AP_1 = 0.30$ and $AP_2 = 0.80$, then the Table 6 can be obtained by applying the *weighted RC* in Table 1. The corresponding reuse pattern of the APs is shown in Table 7.

However, it is not possible to remove the interference remarkably by considering merely this binary reuse decisions due to the indirect resource sharing. When two

Table 7 Reuse pattern of the APs for *Weighted RC*

Source/Interferer	AP_0	AP_1	AP_2
AP_0	y	n	n
AP_1	n	y	n
AP_2	y	y	y

APs form cochannel cells, another AP could be interfered if it can only be able to form co-channel cells with one of the two APs. The APC filters this type of indirect interference by finding out a conflicting set of APs where APs interfere with each other by reusing other APs' resources. The APC updates the RPT introducing another reuse decision: *partially reusable* (p) for those conflicting APs. For example, in the above mentioned scenario, AP_0 and AP_2 and AP_1 and AP_2 can form co-channel cells by using *min RC*, but AP_0 and AP_1 cannot (see Table 3). Therefore, if AP_0 and AP_1 use the same resources of AP_2, they will interfere with each other.

To overcome this problem, the APC partially assigns AP_2's subchannels to AP_0 and AP_1 in an orthogonal manner which is shown in Fig. 6. The APC then assigns a weighted value to each decision where the *reusable* decision is assigned value 1 and the *not-reusable* is 0. The value for the *partial* decision is calculated based on the number of candidate APs using another AP's exclusive resources in an orthogonal manner. For example, in the scenario explained earlier, AP_0 and AP_1 will partially reuse AP_2's resources. As there are two APs to reuse AP_2's orthogonal subchannels, the value of the partial decision will be 0.5. The sum of each AP's decision values called Reuse Decision Values (RDVs) are shown in Fig. 7 (bottom-right part).

4.2 Allocation phase

In this phase, the subchannel requirements of the APs are calculated by multiplying the value of the *utilization function* (weighted mean of the utilization [15, 16]) with the previously assigned subchannels of APs. The higher *utilization function* value indicates higher resource requirement for an AP. Then the priority level of an AP is calculated for the assignment of orthogonal subchannels by dividing the subchannel requirements with the corresponding RDV. The steps in the reuse decision phase are as follows:

- Calculate the required subchannels using estimated utilization and previously assigned subchannels
- Loop until all the subchannels are assigned (allocation of orthogonal subchannels)
  - Calculate priority levels
  - Select the AP with the highest priority
  - Assign subchannel to the selected AP
  - Reduce the priority level
- Distribute reusable subchannels based on the RPT.

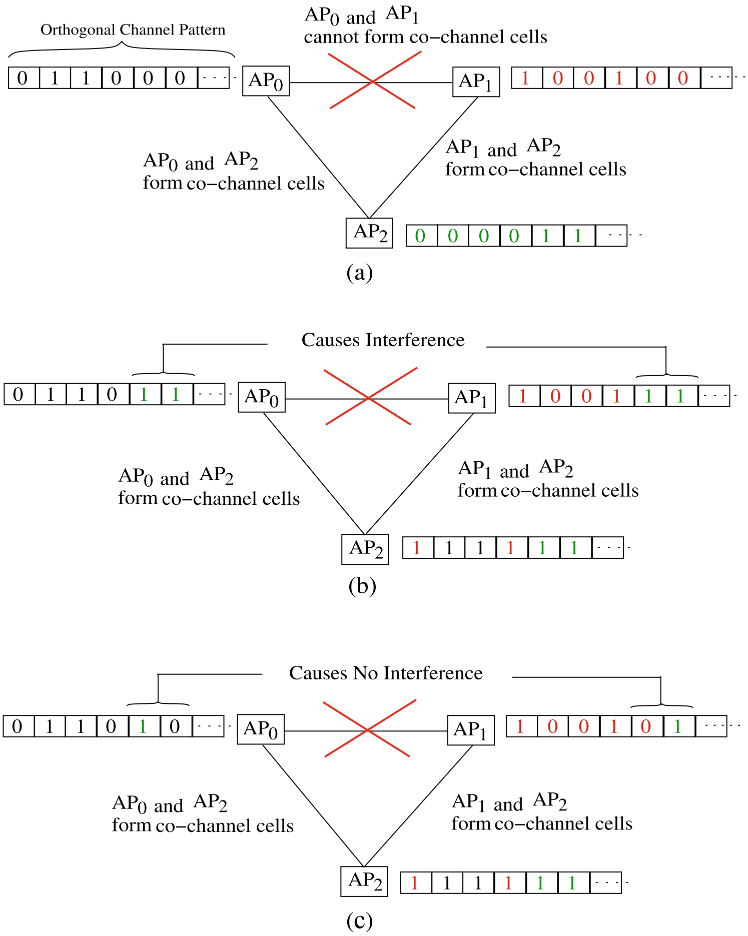


Fig. 6 Filtering interference

5 Algorithm summary and complexity

In the subchannel allocation algorithm, we have used two patterns: reuse pattern of the APs and reuse pattern of the subchannels. Both patterns are created dynamically. The reuse pattern of each AP is determined based on the mutual SIR in the *reuse decision phase*. For generating subchannel reuse pattern, at first the orthogonal subchannel pattern for each AP is created using two decision making functions: *utilization function* (gives the weighted mean of the subchannel utilization for each AP) and *reuse decision function* (gives the RDV for each AP). While the utilization function helps to choose the AP with highest utilization of resources, the reuse decision function maintains the fairness in the allocation decision. It prohibits assigning subchannels to the APs which can reuse other APs resources and assigns resources to the APs which cannot reuse other APs' resources. The effect of multiple decision making functions is discussed in simulation results section. The subchannel reuse pattern is

Source/Interferer	AP0	AP1	AP2
AP0	– –	12.45	21.9
AP1	12.39	– –	25.63
AP2	24.07	24.43	– –

Reuse Threshold =15dB

Source/Interferer	AP0	AP1	AP2
AP0	y	n	y
AP1	n	y	y
AP2	y	y	y

As AP0 and AP1 cannot reuse same resources, they will not able to use AP2's resources but can share partially

Reuse decisions
y: reusable
n: notreusable
p: partially reusable

Source/Interferer	AP0	AP1	AP2
AP0	y	n	p
AP1	n	y	p
AP2	y	y	y

RDV[AP0] = 1.5
RDV[AP1] = 1.5
RDV[AP2] = 3.0

Fig. 7 Working steps of reuse decision phase

finally created using the table in which the reuse decisions are stored. The flow chart of this dynamic subchannel allocation algorithm in the APC level is shown in Fig. 8.

The complexity to calculate mutual SIR is $O(n^2.m)$. Here two loops involve the n number of APs associated to the APC and one loop involves m number of MTs associated to an AP. The complexity of generating RDV matrix is $O(n^2)$ where two loops involve the n number of APs associated to the APC. The complexity of the orthogonal subchannel allocation scheme is $O(k.n^2)$ as it involves three loops. The outer most loop involves k number of subchannels and the inner two loops involve n number of APs. The complexity of distributing reusable subchannels is $O(n^2.k)$ as it also involves two loops for the n number of APs and one loop for k subchannels. So, the overall complexity of this algorithm can be written as $O(n^2.m) + O(k.n^2)$ which is better than previous works cited in Sect. 2.

6 Deployed OFDMA system description

The MAC structure is based on IEEE 802.16a, whereby the Physical Layer (PHY) differs significantly. The channel bandwidth of the system is 80 MHz which is subdi-

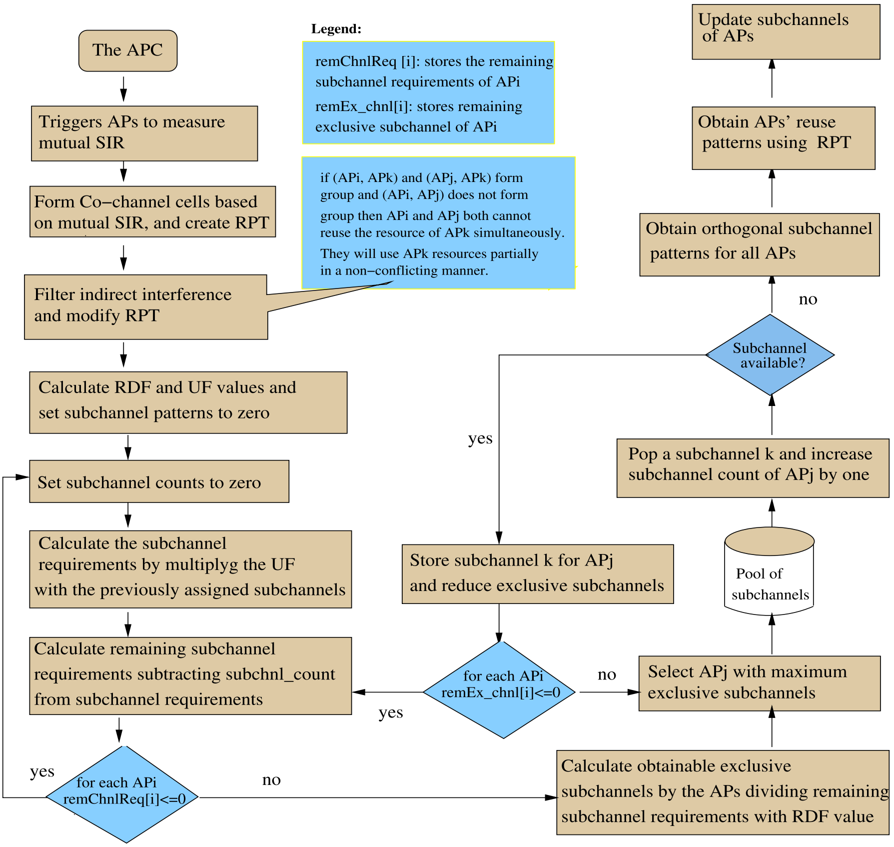


Fig. 8 Flow chart of the interference aware dynamic subchannel allocation algorithm

vided into 1,024 subcarriers with a spacing of 78.125 kHz. Due to orthogonality, the total symbol length is 13.6 μs including a guard interval of 0.8 μs to mitigate inter-symbol interference in multipath environment. An OFDMA subchannel consists of 32 subcarriers, whereby 2 subcarriers per subchannel are reserved for the transmission of pilot signals. The subchannels are directly mapped onto a contiguous fraction of the frequency channel. This is in contrast to IEEE 802.16a, where the subcarriers of a subchannel are evenly distributed over the frequency channel in a pseudo-random manner [9]. This certainly reduces the flexibility of the scheduling since the diversity of the subchannel is lost. Three different combinations of modulation schemes are used for the performance evaluation, namely QPSK 3/4, 16QAM 3/4 and 64QAM 3/4. These schemes are called PHY mode in this work. An important feature of the OFDMA PHY is the possibility of exploiting multiuser diversity. The general MAC structure is based on a centrally controlled scheme like IEEE 802.16. The frequency channel is divided into MAC frames.

Within the repeating time period, the frame represents the data to be transmitted split into the time and frequency. The used frame structure in the algorithm develop-

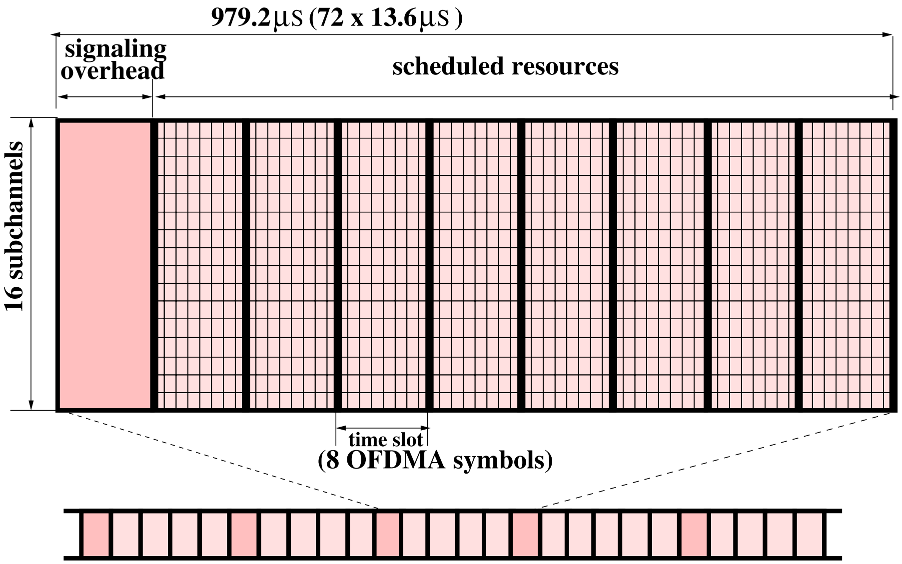


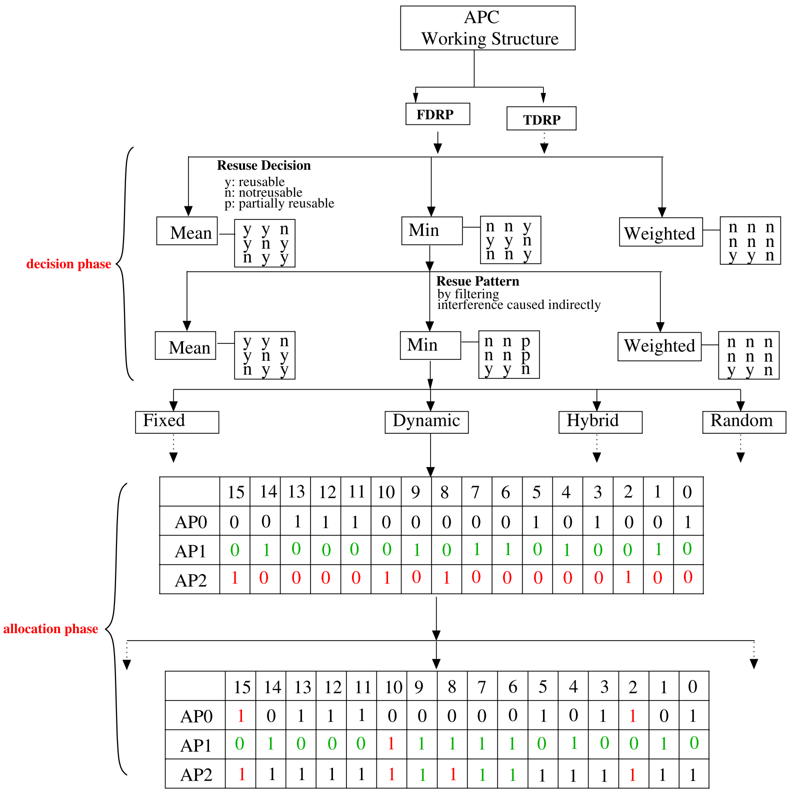
Fig. 9 OFDMA frame

ment is shown in Fig. 9. In this work, the frame length is calculated using the symbol length and the number of slots per frame. Here it is considered that the symbol length or duration is 13.6 µs and symbols per slot are 8. In the figure, there are 16 subchannels, so the total frame duration is $((8 + 1) \cdot 8) \cdot 13.6 = 979.2$ µs. Slots could be taken as any number greater than 2 because one slot is reserved for the signaling overhead. The signaling overhead includes the transmission of control data packets. These packets comprise messages for channel estimation and resource allocation. The remaining slots are scheduled for downlink transmissions as uplink was beyond the scope of this work. Overall, a fixed signaling overhead of one time slot is assumed independent of the amount of used resources.

7 Working structure of the APC

In the framework, the APC can exploit different types of subchannel allocation schemes namely, fixed, dynamic, hybrid, and random with different reuse constraints in order to assign resource to the APs. In this paper, the APC can assign resources either using the FDRP or the TDRP approach. In the FDRP approach, the APC assigns subchannels to the APs, whereas in the TDRP approach, it assigns different time slots. Although, both the FDRP and the TDRP approaches, and the subchannel allocation algorithms have been implemented, in the performance evaluation part, we focus on the FDRP approach and compare the delay and the efficiency of the DCA and the FCA schemes with three RCs.

The flow diagram for overall working procedure of the APC is shown in Fig. 10. In this figure, the result of an exemplary dynamic subchannel allocation pattern for the scenario shown in Fig. 5 is presented. Different colors are used to indicate the orthogonal subchannel assignment of each AP.



	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
AP0	0	0	1	1	1	0	0	0	0	0	1	0	1	0	0	1
AP1	0	1	0	0	0	0	1	0	1	1	0	1	0	0	1	0
AP2	1	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
AP0	1	0	1	1	1	0	0	0	0	0	1	0	1	1	0	1
AP1	0	1	0	0	0	1	1	1	1	1	0	1	0	0	1	0
AP2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 10 Flow diagram of the APC's working process

8 Evaluation of the framework

The simulation of this work is performed extending NS2 [12] whereby the statistical evaluation is conducted following [13]. For the traffic source model, a two-state Markov Modulated Poisson Process (MMPP) [5] is used. The two-state MMPP is in either ON state or is in OFF state. In this model, packets are only generated in the ON state with fixed arrival rate α. The time spent in ON and OFF states is exponentially distributed with mean α^{-1} and β^{-1}, respectively. It is also called Interrupted Poisson Process (IPP) with fixed interarrival time. The position of the MTs is updated at each 1 ms whereby the displacement of the MTs is characterized by the Brownian motion mobility model [1]. In this model, MTs move in the adjacent segment with reflecting the mobility region and the position of the mobile user is always changed by 5 m. The simulation results are presented in the subsequent subsections.

8.1 Correctness of the algorithm

Before going to the performance analysis of our DCA scheme, the correctness of the algorithm must be proved. In this regard, we have to show whether the algorithm is

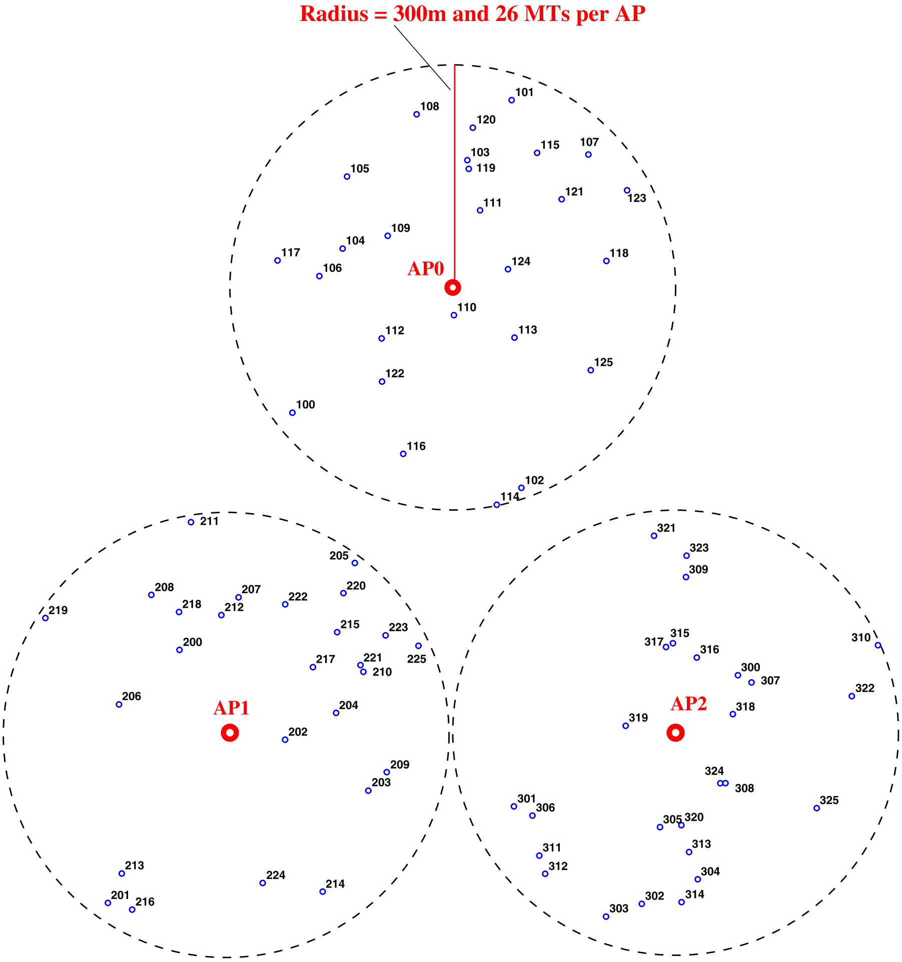
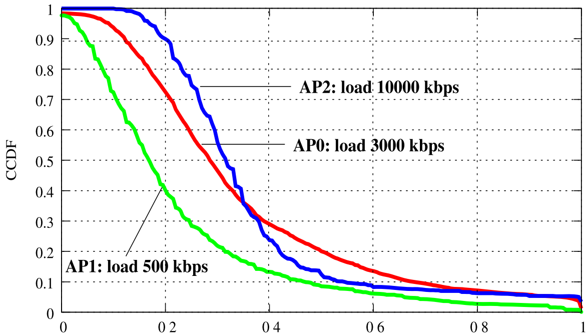


Fig. 11 Three cell scenario

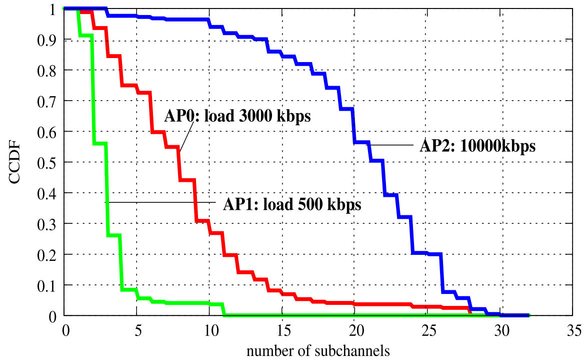
reacting on the various traffic situation or not. Reacting on various traffic load means that the APC will assign more subchannels in case of high traffic load situation than the case of low traffic load situation. In order to prove it, we have simulated a three cell circular scenario where each cell has 26 MTs and the radius of the mobility region is 300 m. In the scenario (Fig. 11), each AP has been assigned different traffic loads per downlink connections. The APC updates resources at the frame interval 10 while it updates the mutual SIR value at the frame interval 20. AP_0 is assigned load 3,000 kbps, AP_1 is 500 kbps and AP_2 is 10,000 kbps. In this scenario, for the traffic load the *mean on* time is 0.1 and *mean off* time is 0.4, OFDMA subchannels are 32 and time slots are 17.

There is no reuse of subchannels as the spatial distances between the APs are not sufficient for the resource reuse. The resource utilization curve is shown in Fig. 12(a). The X-axis is for the utilization that ranges from 0 to 1 and Y-axis is for the Comple-

Fig. 12 Resource utilization and subchannel assignment on various traffic load



(a) Utilization



(b) Subchannels

mentary Cumulative Distribution Function (CCDF) of the corresponding utilization. The CCDF decreases with the increasing assigned utilization. In the curve on average AP_0 is utilizing 35% of the assigned resources, AP_1 is 18% and AP_2 is 37%. These average values indicate that the APs are utilizing resources according to the assigned traffic loads. The APC has balanced the resource utilization of all the APs by assigning subchannels according to the traffic load. This effect can be seen in Fig. 12(b). In the curve the subchannels assignment to each AP with the corresponding traffic load is shown. As AP_2 has highest resource requirement, it has got the highest number of subchannels whereas as AP_1 has lowest resource requirement, it has obtained lowest number of subchannels. In case of AP_0, the number of subchannel assignment is in the middle position. It has obtained a higher number of subchannels than that of AP_1 and a lower number of subchannels than that of AP_2. So, from analyzing the number of obtained subchannels and utilization with various traffic loads, we can say that the developed algorithm in this paper works correctly.

8.2 Effect of using multiple decision making functions

In our developed algorithm, two decision making functions: *Utilization Function* (UF) and *Reuse Decision Function* (RDF) are used. In the algorithm, higher the ratio of UF and RDF values, higher the chance to get a subchannel. However, in case of

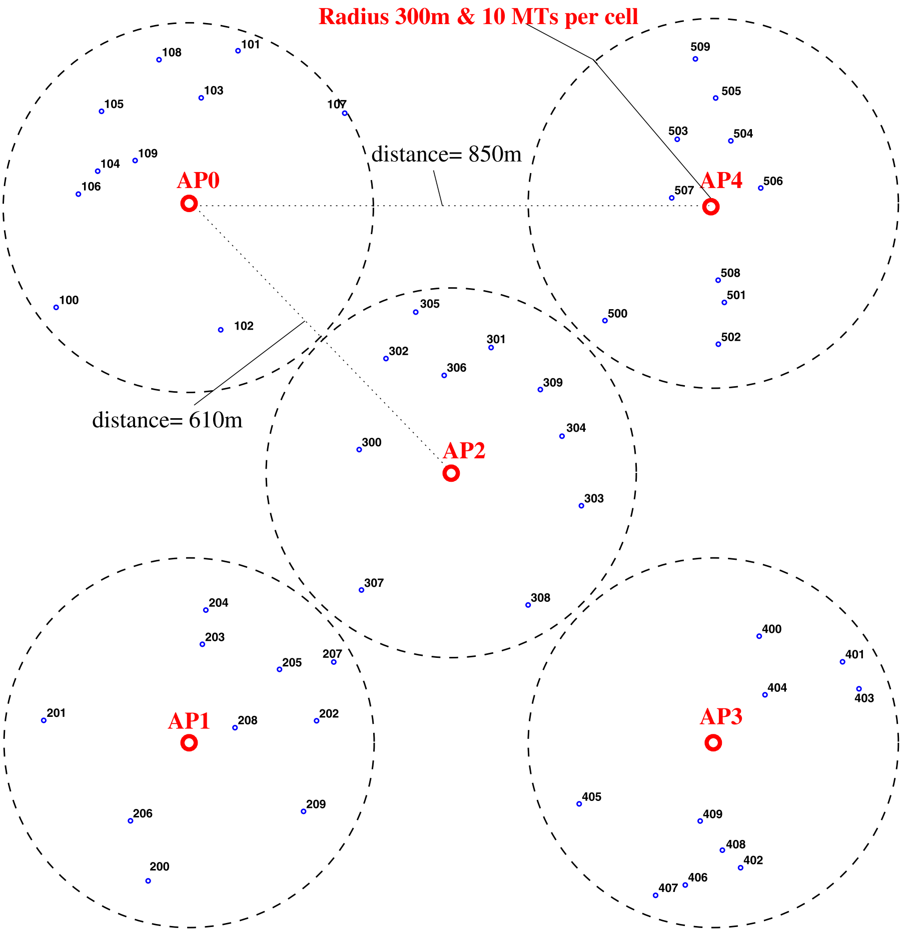
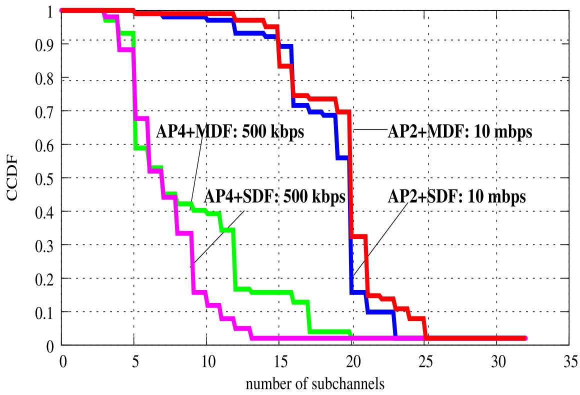


Fig. 13 Scenario with 5 cells and scaling of distance 1

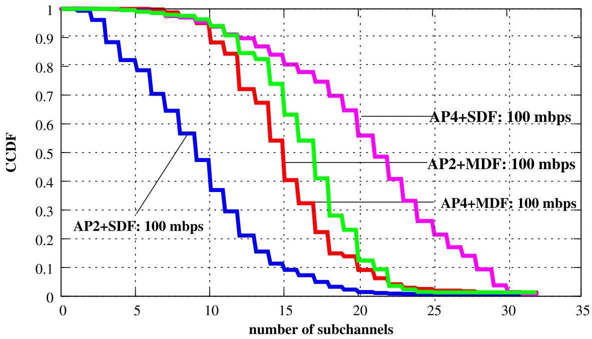
low load situation, considering only UF, i.e., single decision making function (SDF) value is enough to take subchannel allocation decision. But in case of high load situation, it is not feasible to use only the SDF. In this case, if both the UF and RDF are used, the decision of the APC for the subchannels assignment balances resource utilization.

To verify the effect of these multiple decision making functions (MDF), a scenario with five APs: AP_0, AP_1, AP_2, AP_3, and AP_4 is considered. In this scenario, shown in Fig. 13, the radius of all the APs is 300 m and the coverage regions of the APs are not overlapping. There are 10 MTs associated with each AP. This scenario is considered for the rest of the performance evaluations. For the traffic load, the *mean on time* is 0.2 and *mean off time* is 0.4. At first, we have assigned low traffic load to the APs. AP_0, AP_1, AP_3, and AP_4 are assigned 500 kbps and AP_2 is 10 mbps at *on state*. Then we have increased the traffic load of AP_2 and AP_4 to 100 mbps. In case of traffic load 500 kbps and 10 mbps, the simulation results show (cf., Fig. 14(b))

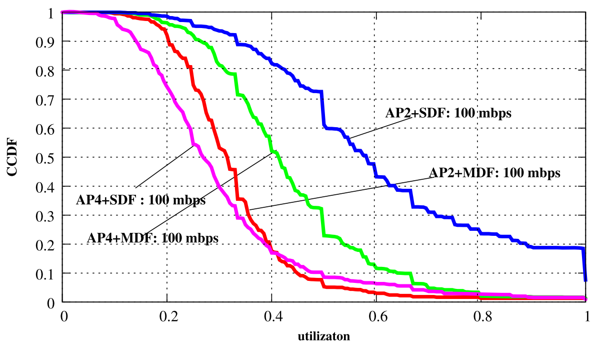
Fig. 14 Effect of using multiple decisions making functions



(a) Subchannels in low load



(b) Subchannels in high load



(c) Resource utilization

that the performance of SDF and MDF are rather similar as AP_4 has low resource requirements.

However, in Fig. 14(a), the simulation result shows that when the APC considers merely SDF, it assigns a higher number of orthogonal subchannels to AP_4 and finally, due to the reuse of other APs resources, it obtains higher number of subchannels than that of AP_2. Because AP_2 is not in the position to reuse other APs resources, it gets a lower number of subchannels. As a result in the same load situation, AP_4 gets higher number of subchannels than that of AP_2. This indicates an unfairness in the subchannel allocations. On the contrary, the use of MDF prohibits AP_4 to get more subchannels than that of AP_2. The simulation results in Fig. 14(a) show that when the traffic loads are increased both in the AP_2 and the AP_4, using MDF, the APC assigns nearly same number of subchannels to AP_2 and AP_4, whereas using SDF, it assigns more subchannels to AP_4 than that of AP_2. The corresponding resource utilization with the SDF and the MDF are shown in Fig. 14(c). The curves show that resource utilization of the AP_2 for the SDF and MDF are rather similar in the case of low traffic load, whereas in the case of the high traffic load, MDF balances the resource utilization of the AP_2.

8.3 Comparison with different reuse constraints (RCs)

For conducting the comparison study between the three RCs: *min*, *mean*, and *weighted*, the five cell scenario (cf., Fig. 13) discussed in the previous subsection is used. Different simulations are done by varying the load of AP_2 and AP_4 while keeping fixed the loads of AP_0, AP_1, and AP_3 for creating irregularity in the traffic situation. The scaling of distance between APs is also considered to show the performance difference of the RCs. Two scaling values 1 (one) and 2 (two) are used and these values are multiplied to the position of the APs while keeping fixed the mobility region radius. For example, the scenario shown in Fig. 13 uses scaling value one and scenario shown in Fig. 15 uses scaling value two.

The mean downlink delay and mean Packet Error Rate (PER) are shown in Figs. 16(a) and (b) for the scenario shown in Fig. 13. The curves show that the mean delay in case of *min RC* is the lowest as the PER for the *mean RC* and the *weighted RC* are higher than that of *min RC*. The *mean RC* and *weighted RC* have higher PER due to the reuse of subchannels. The mean subchannel allocation for the three RCs are shown in Fig. 17 for scaling value one. This figure shows that the *min RC* (cf., Fig. 17(a)) allows least reuse of subchannels, whereas the *mean RC* (cf., Fig. 17(b)) allows maximum reuse of subchannels. The *weighted RC* (cf., Fig. 17(c)) allows more reuse of subchannels at low traffic load than that of high traffic load as (1-*utilization*) value of the interferer increases at high traffic load (see later for details). The increased PER causes retransmission of packets and increases mean delay. But when the scaling value two is used (cf., Fig. 15), the *mean RC* works better than the *min RC*. As APs are spatially separated, the cochannel interference is lower (PER is reduced shown in Fig. 16(d)) and as a result in case of *mean RC* the mean delay is lower than that of the other RCs (cf., Fig. 16(c)) due to higher reuse of subchannels.

The *weighted RC* performs better than *mean RC* in case of scaling value one, because in that case, cochannel interference is reduced for the limited reuse of resources between the APs by multiplying (1-*utilization*) value with the mean mutual SIR value of each AP at the high traffic load situation. At the high load, the value of (1-*utilization*) is low as the utilization of the APs is high. As AP_0, AP_1, and AP_3 get lower number of subchannels with increasing load of AP_2 and AP_4 (cf. Fig. 17(c)), their utilizations also become higher along with AP_2 and AP_4, and hence (1-*utilization*) becomes low.

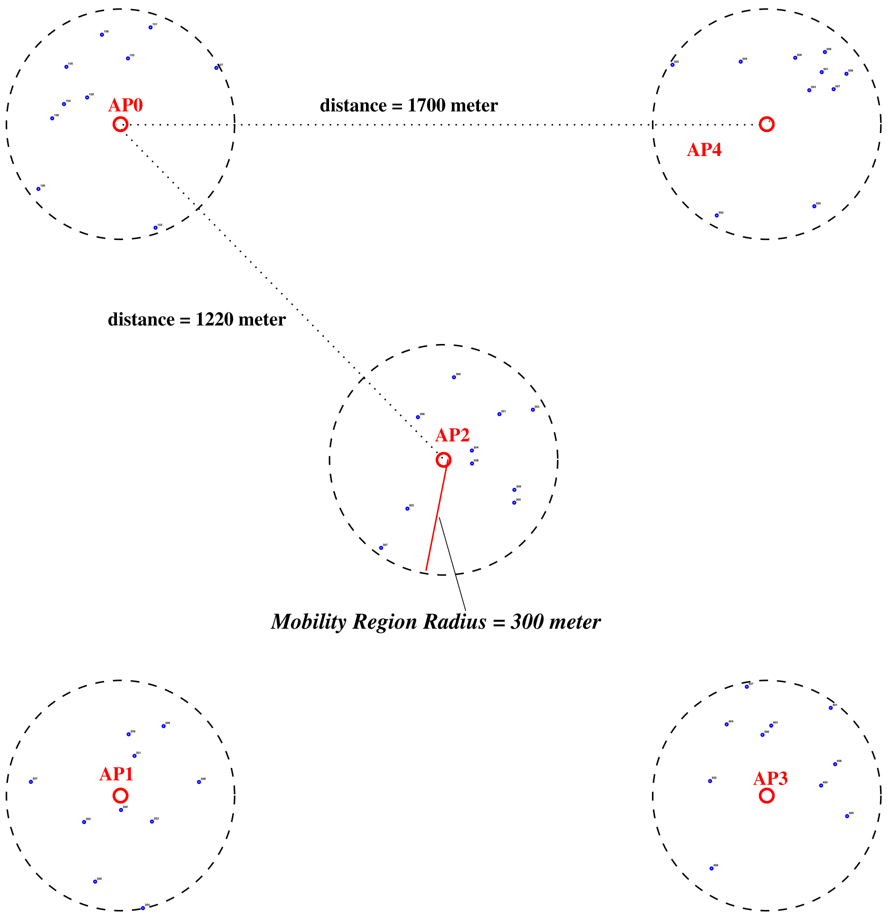


Fig. 15 Five cell scenario with scaling value two

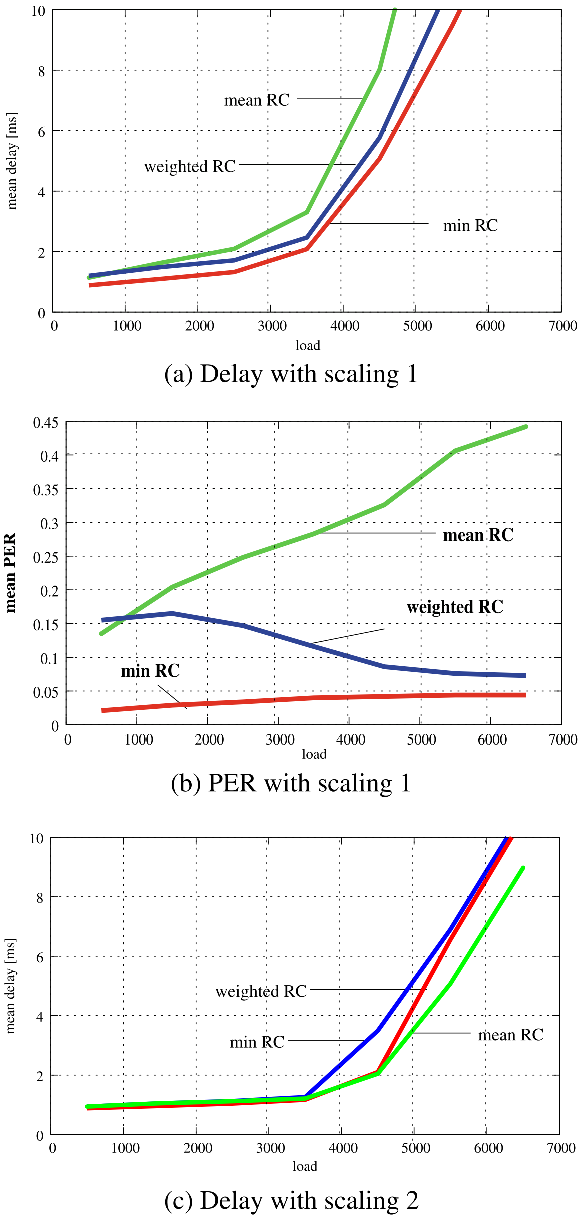
8.4 Finding optimal FRP for a five cell scenario

In order to compare the newly developed DCA scheme with the fixed FCA scheme, we have investigated the optimal FRP for the scenario shown in Fig. 13. In this case, we have used 16 OFDMA subchannels, 10 MTs per cell and 9 time slots per sub-channel and both *mean on* and *mean off* time are 0.1 in traffic load generation. We have obtained the optimal FRP for this scenario by investigating three feasible FRPs that are as follows:

$$cosetA = \{AP_0, AP_1, AP_3, AP_4\}; \{AP_2\},$$
$$cosetB = \{AP_0, AP_3\}; \{AP_2\}; \{AP_1, AP_4\},$$
$$cosetC = \{AP_0\}; \{AP_1\}; \{AP_2\}; \{AP_3\}; \{AP_4\}.$$

In *cosetA*, the average number of subchannels assigned to each set is 8, in *cosetB* is 5.33 and in *cosetC* is 3.2. Here different simulations have been performed by varying

Fig. 16 Mean delay and PER for three RCs using scaling values one and two



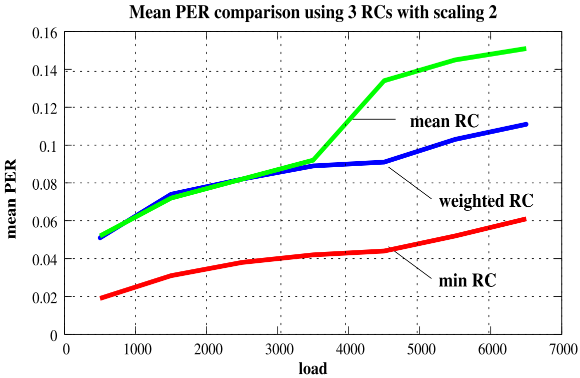
(a) Delay with scaling 1

(b) PER with scaling 1

(c) Delay with scaling 2

the loads of AP_2 and AP_4 while keeping fixed the loads of AP_0, AP_1, and AP_3. In the corresponding curves, *cosetA* will be termed as 2-cochannel cells set because it has two clusters. Similarly, *cosetB* will be 3-cochannel cells set and *cosetC* will be 5-cochannel cells set. Finally, by simulating the same scenario with these three reuse partitioning, we have found that *cosetB* is the optimal reuse partitioning in terms of mean delay.

Fig. 16 (*Continued*)



(d) PER with scaling 2

Figure 18(a) shows that the mean delay of *cosetB* is less than that of *cosetA* and *cosetC*, because in *cosetA*, the cochannel interference increases by allowing AP_0, AP_1, AP_3, and AP_4 to reuse their subchannels. Therefore, the Packet Error Rate (PER) increases (Fig. 18(b)) which shows that the PER for the *cosetA* is greater than the maximum allowable PER 0.01 in the considered system. For *cosetC*, the mean PER is less than 0.01 since each cell uses orthogonal subchannels, and consequently, there is less cochannel interference.

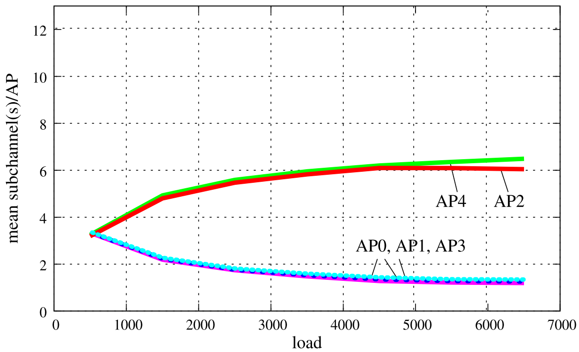
Although in case of *cosetB* mean PER is higher (there is reuse of subchannels) than *cosetC*, mean delay decreases on the higher traffic loads for the better utilization of the resources than the *cosetC*. In case of *cosetC*, delay increases on the higher traffic loads due to the higher resource requirement of AP_2 and AP_4. As they do not get more subchannels on increasing load, the packets are queued, and, therefore, the mean delay increases. The mean utilization curve is shown in Fig. 18(c).

The mean utilization is around 50% because different simulations have been performed only increasing the load for two APs (AP_2 and AP_4) by keeping others fixed. Here the utilization of the APs whose loads were fixed is too low, and thereby, the mean utilization decreases to 50%. The curve shows that the utilization for *cosetC* is the highest, and with the increasing traffic load it becomes saturated due to the limited queue length. But in case of *cosetA*, the mean utilization is upward at the high load as in this case packets retransmission is higher for the co-channel interference.

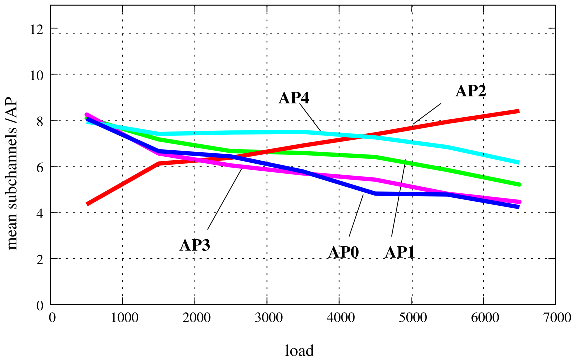
8.5 Comparison between developed DCA scheme and FCA scheme

In this subsection, we compare the performance of the newly developed Dynamic subChannel Allocation (DCA) scheme with Fixed subChannel Allocation scheme (FCA) using the same scenario (Fig. 13) discussed in the previous subsections. Here, for the FCA scheme, the optimal cell FRP *cosetB* (discussed in the above subsection) has been used. In this partitioning, cochannel set $\{AP_0, AP_3\}$ gets 6 subchannels while the remaining two cochannel cells set, $\{AP_1, AP_4\}$ and $\{AP_2\}$ get 5 subchannels each. As DCA scheme always performs better than FCA scheme in an uneven traffic situation, we have done different simulations with increasing traffic load for AP_2 and AP_4 while keeping fixed the traffic loads of AP_0, AP_1, and AP_3 at 500 kbps.

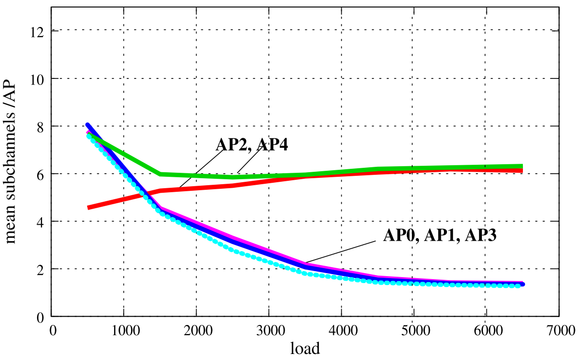
Fig. 17 Mean subchannels for three RCs with scaling value one



(a) Subchannels/AP with min RC



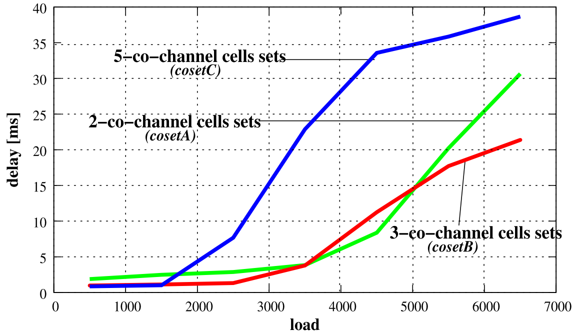
(b) Subchannels/AP with mean RC



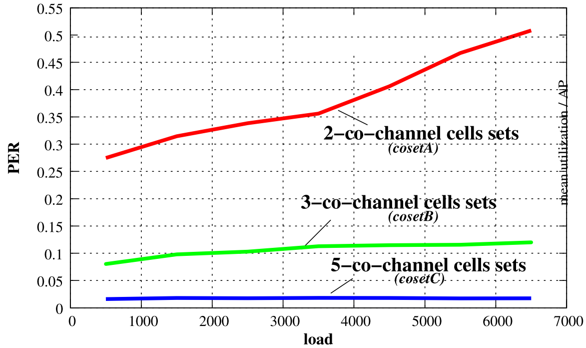
(c) Subchannels/AP with weighted RC

As a result, different resource requirement behaviors were prevailed in the APs. The mean utilization of resources for each of the APs is shown in Fig. 19(a). In case of the FCA, in the mean utilization curves, AP_0, AP_1, and AP_3 have always a lower utilization as their traffic load is fixed at 500 kbps. Their average utilization is around 10%. On the other hand, AP_2 and AP_4 are overloaded in case of higher traffic load.

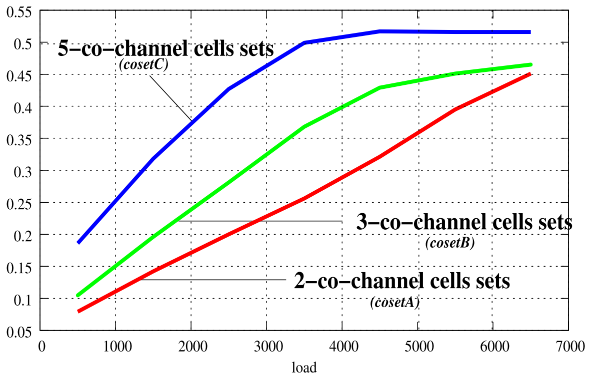
Fig. 18 Comparison of mean utilization, PER and delay among 3 FRPs



(a) Mean delay



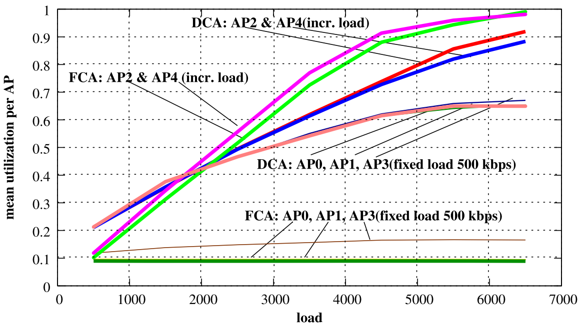
(b) Mean PER



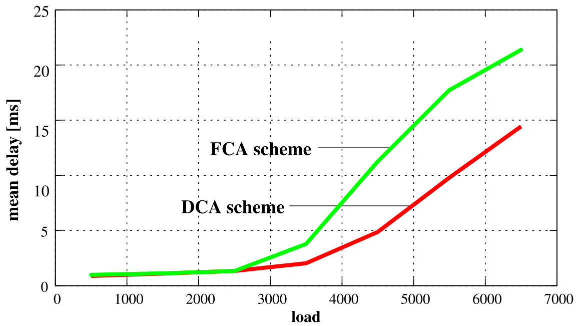
(c) Mean utilization

Their utilization is greater than 80% after the load 3500 kbps. Whereas in the DCA, AP_0, AP_1, and AP_3 utilize 50% of the assigned resources on average and AP_2 and AP_4 utilize 70% of the assigned resources on average. The mean delay for the FCA scheme is greater than that of the DCA scheme (shown in Fig. 19(b)) as the FCA

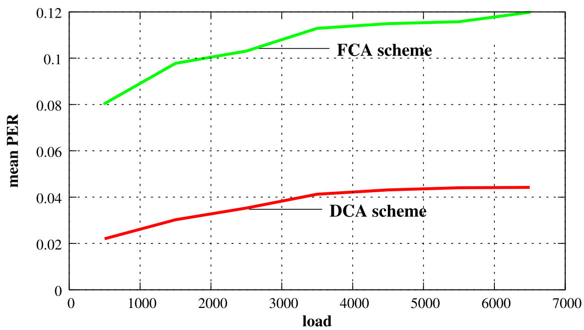
Fig. 19 Mean delay comparison between DCA and FCA schemes on increasing load of AP_2 and AP_4 and fixed load of AP_0, AP_1 and AP_3



(a) Mean utilization



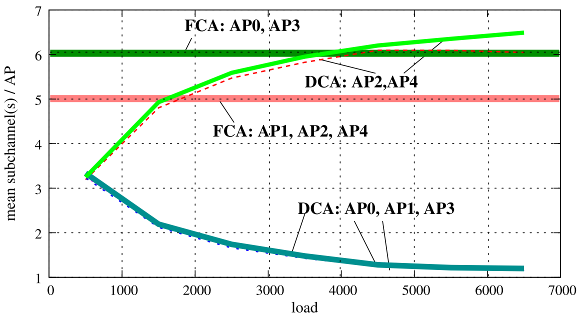
(b) Mean delay



(c) Mean PER

scheme is not assigning sufficient subchannels to AP_2 and AP_4 on increasing load. Another reason is that the PER increases as the FRP of cells is used by the FCA scheme which is shown in Fig. 19(c). But in case of the DCA scheme, as adaptive cell reuse partitioning is used, the mean PER is much lower than the FCA. The mean number of assigned subchannels for each the AP is shown in Fig. 19(d). As in the used scenario the APs are not sufficiently far apart to reuse resources and the loads of AP_2 and AP_4 are varying, both are getting higher number of subchannels on increasing load. On the other hand, as the loads of the remaining three APs (AP_0, AP_1 and AP_3)

Fig. 19 (*Continued*)



(d) Mean subchannels/AP

are fixed, they are getting lower number of subchannels with increasing loads of AP_2 and AP_4.

9 Conclusion and future work

In this paper, we have developed a framework to provide radio resources to the APs in a centralized manner. Using the framework, the APC can allocate either time slots or subchannels as resources to the APs using different allocation schemes, such as dynamic, fixed, hybrid, and random. However, in this paper, the APC assigns subchannels to the APs using an interference aware DCA scheme. This work shows that an intelligently interference aware DCA scheme has a great benefit compare to FCA schemes in case of uneven traffic situation. This is due to the fact that in the uneven resource requirements, the DCA scheme attains more utilization of resources by assigning resources to the APs which actually need resources. In general, there is a tradeoff between the QoS, the implementation complexity of the channel allocation algorithms, and the spectrum utilization efficiency [7]. Therefore, the FCA scheme becomes superior at high offered traffic load, especially in case of uniform traffic situation and DCA scheme performs better in case of uneven traffic loads. Most previously developed DCA schemes have involved PER and SINR for taking the channel allocation decision. As a result, the computational complexities of those algorithms were either exponential or too high. Whereas by considering the utilization as a decision factor, the computational complexity of the developed algorithm has been reduced to $O(n^2m) + O(k.n^2)$ and it works much better than the FCA scheme with the optimal fixed reuse partitioning.

Using the developed framework, this paper also shows that frequency reuse has a great impact on the performance of a multicell OFDMA system. If the frequency reuse can be done avoiding/mitigating the cochannel interference, the transmission delay decreases and efficiency of the AP increases. We have shown that exploitation of the appropriate reuse constraint (RC) can mitigate the cochannel interference remarkably. We have investigated three RCs: *min RC*, *mean RC*, and *weighted RC*, and evaluated and compared their performance, assigning various traffic loads to the APs, and using different spatial distances between the APs. However, in the developed framework, the APC can only employ a single RC for generating the cochannel cells at a time. As each RC has advantages and disadvantages, it might not be wise to use a single RC at a time. Therefore, as a future extension of the framework, the APC should employ different RCs at a time, depending on the position of the MTs. For example, when the MTs are closer to the interferer AP, the APC can use *min RC*, whereas when they are far apart from interferer AP, the APC can use *mean RC*.

A further improvement of this algorithm can be done by prioritized traffic. In this regard, the APs will provide individual information of utilization of resources for high priority traffic and for low priority traffic. After gaining the full knowledge about the traffic priorities of the individual APs, the APC will assign subchannels according to that knowledge. Another improvement can be done by using adaptive reuse threshold for the decision concerning the reuse of resources. In this regard, the APC can trace the modulation schemes that the APs use in data transmission and can set the reuse threshold according to the modulation schemes or PHY mode.

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