Cognitive Aware Interference Mitigation Scheme for LTE Femtocells

Ismail AlQerm(✉) and Basem Shihada

King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
{ismail.qerm,basem.shihada}@kaust.edu.sa

Abstract. Femto-cells deployment in today's cellular networks came into practice to fulfill the increasing demand for data services. However, interference to other femto and macro-cells users remains an unresolved challenge. In this paper, we propose an interference mitigation scheme to control the cross-tier interference caused by femto-cells to the macro users and the co-tier interference among femtocells. Cognitive radio spectrum sensing capability is utilized to determine the non-occupied channels or the ones that cause minimal interference to the macro users. An awareness based channel allocation scheme is developed with the assistance of the graph-coloring algorithm to assign channels to the femto-cells base stations with power optimization, minimal interference, maximum throughput, and maximum spectrum efficiency. In addition, the scheme exploits negotiation capability to match traffic load and QoS with the channel capacity, and to maintain efficient utilization of the available channels.

Keywords: Cognitive radio · Femtocells · Macro users · Radio channels · Cross-tier interference · Co-tier interference

1 Introduction

The lack of resources of the macro-cells networks makes them unable to fulfill the data services demand in the indoor areas. An efficient solution is to deploy femto-cells base stations (FBSs) which are capable of communicating users over a broadband wire-line connection [1]. FBSs are short-range, low-cost/low power and can be easily installed by the users in addition to the fact that they reduce the load of the Macro Base Stations (MBSs). However, interference is considered as a technical challenge that affects the femto-cells deployment [1]. There are two types of interference: cross-tier and co-tier. Cross tier is the interference to the macro users caused by the FBSs installed within the same sub-band (SB). Co-tier interference is the one among the deployed femto-cells contending for the same channel. These types of interference lead to service disruption, throughput degradation and connection droppings.

There are several proposed schemes for resource allocation in femto-cells deployments with interference consideration. For example, the schemes proposed

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in [2] and [3] aim to handle both types of interference using uncoordinated and coordinated resource assignment algorithms as in [2], and Q-learning based interference coordination as in [3]. However, the coordination between MBSs and FBSs is difficult due to the requirements of scalability, security, and the availability of backhaul bandwidth in addition to the fact that the number of the deployed FBSs is not fixed. The authors in [4] and [5] propose a scheme that assigns dedicated channels for the communication of FBSs over the up-link (UL) and the down-link (DL). This goes against the idea of improving spectrum utilization by accessing the macro-cells spectrum opportunistically. Femto-cells resource allocation mechanisms are investigated in [6] and [7] to mitigate interference. These mechanisms use cognitive radio and game theory to support their resource allocation methodologies. However, both schemes are limited to channel allocation without consideration of QoS requirements and the scheme in [7] considers cross-tier interference only. The work in [8] aims to maximize the weighted sum rate of the femto-macro network in a delay tolerant scenario. However, this requires high information overhead among MBSs and FBSs. Fractional Frequency Reuse (FFR) technique proposed in [9] shows capability to mitigate interference in multiple cells deployments. However, the cell edge users suffer from lower data rates because of the increase in path-loss and interference [10]. The FFR strategy has been widely used in multi-macrocell environments for suppressing interference as in [11]. The use of cognitive radio [12] in femto-macro deployment effectively contributes in solving the cross-tier interference problem by exploiting its spectrum sensing capability to allocate under-utilized channels. In addition, it is considered for spectrum assignment in order to increase the flexibility and the autonomy of the network in addition to interference mitigation [13].

In this paper, we propose an interference mitigation scheme that aims to mitigate cross-tier interference caused by FBSs to the macro users and the co-tier interference that affects the FBSs that contend to access the free sub-channels in the DL. The scheme enhances spectrum sensing and improves detection capability to find free sub-channels for FBSs to access in which the cross-tier interference is minimal. An adaptive power graph coloring spectrum assignment algorithm is used in conjunction with environment awareness to allocate sub-channels for FBSs that mitigate the co-tier interference. In addition to interference control, the scheme ensures that the selected sub-channel satisfies QoS requirements and matches with the traffic load. Other advantages of the proposed scheme include considering traffic priorities, and maintaining efficient utilization of the available sub-channels which enhances the spectrum efficiency.

The paper is organized as follows, section 2 presents the system model and the interference sources. The interference mitigation scheme and the femto-cells sub-channel allocation mechanism are described in Section 3, while section 4 presents the performance evaluation of our scheme compared to others. Finally, the paper is concluded in section 5.

2 System Model

We consider the interference problem of the DL in a network that consists of macro-cells and femto-cells where the priority of sub-channel access is for the macro-cell users. FBSs can access the sub-channel but with minimal interference to the macro-cell users. Spectrum sensing is employed to detect the available sub-channels that FBSs can access. Spectrum occupancy information is used to allocate the free sub-channels according to the awareness based algorithm to be discussed in the next section. The considered deployment employs Orthogonal Frequency Division Multiple Access (OFDMA) as a channel access technique for the DL with M hexagonal grid macro-cells and F femto-cells in range of each macro-cell. The bandwidth allocated for each MBS is divided into 6 SBs using FFR. Each SB is composed of N_c sub-channels. The MBS can access any of these sub-channels at any time instant. However, the sub-channels are not utilized most of the time.

The femto-cells considered deployment is depicted in Fig. 1 where they are distributed randomly and uniformly in each SB. Each femto-cell is assumed to have variable number of users active at any time instant. The sub-channels are assumed to be almost static with minor variations and follow Rayleigh multi-path fading distribution. Femto-cells deal with two types of connections which are the link between femto-cells and macro-cells and the link between FBSs and their associated users. There are three types of gains considered in the signal propagation model and they contribute to the total channel gain calculated in (1). These gains include antenna's gain (A), shadowing gain (S) and path loss gain (G).

$$H = A + S + G \tag{1}$$

The received signal to interference and noise ratio (SINR) of a macro-cell user k over sub-channel n is calculate as,

$$SINR_{k,n} = \frac{P_{k,n} H_{k,n}}{I_1 + I_2 + N_{n,k}} \tag{2}$$

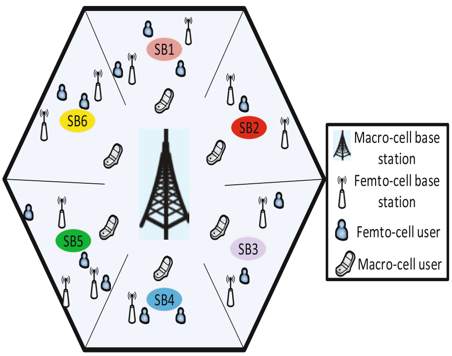

Fig. 1. Femto-cells network

where $P_{k,n}$ is the received power of the macro-user k over sub-channel n, I_1 and I_2 are the two interference imposed by the other MBSs and FBSs respectively and $N_{n,k}$ is the additive white Gaussian noise (AWGN) power. The two types of experienced interference by the macro user I_1 and I_2 are calculated according to (3) and (4) respectively.

$$I_1 = \sum_{l=1}^{M} P_{l,n} H_{k,l,n} \tag{3}$$

$$I_2 = \sum_{j=1}^{F} z^* P_{j,n} H_{k,j,n} \tag{4}$$

where $P_{l,n}$ and $P_{j,n}$ are the transmission powers of the other MBS and FBS over the nth sub-channel respectively and z^* is the factor that indicates if the sub-channel is assigned to a certain femto-cell. It takes a value of 1 if the sub-channel is assigned and 0 otherwise. l and j are the indexes of the MBSs and FBSs respectively. The achievable throughput by the macro user k over sub-channel n is given by,

$$T_{k,n} = B \log(1 + SINR_{k,n}) \tag{5}$$

where B is the sub-channel bandwidth.

Following a similar process, the SINR for a femto user i served over sub-channel n is calculated as,

$$SINR_{i,n} = \frac{P_{i,n} H_{i,n}}{I_1 + I_2 + N_{n,i}} \tag{6}$$

The interference imposed by MBS I_1 and the other FBSs interference I_2 are calculated according to (7) and (8) respectively.

$$I_1 = \sum_{l=1}^{M} P_{l,n} H_{i,l,n} \tag{7}$$

$$I_2 = \sum_{j=1, j \neq i}^{F} z^* P_{j,n} H_{i,j,n} \tag{8}$$

The achievable throughput of the femto user i over sub-channel n is given by,

$$T_{i,n} = B \log(1 + SINR_{i,n}) \tag{9}$$

The cross-tier interference that impacts the performance of the macro-cell users is caused by either miss detection during spectrum sensing or hidden macro users problem. Due to the limitation on the software and/or the hardware sensing capability, interference is caused to the macro users as a result of an incorrect detection. Note that the probability of miss detection depends on the sensing methods, (e.g., the energy detector, the cyclostationarity-feature sensing, and the matched-filtering sensing). Matched-filtering is known as the best approach for spectrum sensing as it maximizes the received SINR [14]. However, it is difficult since it requires dedicated receiver for each signal. The performance of energy detector is limited by the energy threshold and the types of signals. Besides, it fails when the noise becomes non-stationary because of the presence of the cross-tier interference. However, energy detector is the easiest to implement in actual systems. The hidden macro-cell users problem is similar to the hidden node problem in carrier sense multiple access (CSMA). It is caused by many factors including severe multi-path fading, shadowing, and high penetration loss in the areas sensed by femto-cells.

Contending between FBSs for channel access especially in the dense femtocells deployment is the main reason to encounter co-tier interference that affects the performance of the femto users. Other problems like hidden terminal and exposed terminal problems also contribute to this interference as the femto-cells network is similar to other wireless network once free channels are detected. Adjacent channel interference is another type of interference that affects the macro users on the edge of cell. It is caused if different but adjacent channels are occupied by the macro users and FBSs respectively. However, this interference can be leased by reasonable layout of base stations deployment.

3 The Interference Mitigation Scheme

In this section, we describe the interference mitigation scheme to control both cross-tier and co-tier interference that impact femto-cells operate under the coverage of macro-cells. The scheme also aims to maximize throughput, allocate sub-channels that satisfy QoS requirements by assigning priorities for different types of traffic, and ensure efficient spectrum utilization. Spectrum sensing is exploited to support this scheme in order to mitigate cross-tier interference. Both interference mitigation mechanisms are detailed in the following sections.

3.1 Cognitive Based Cross-tier Interference Mitigation

Cognitive spectrum sensing is employed by the FBSs to determine whether certain SB include free sub-channels. This forces the FBSs to cease their channel access if the sub-channel is busy with macro user transmission. If all SBs are busy, the FBS tries to access the SB with the minimal interference to macro users. The presence of MBS transmissions is detected in the DL signal.

Our scheme implements an enhanced energy detection based spectrum sensing that effectively explores the interference range and maximizes the detection sensitivity. According to the energy detection approach, the signal observed by the FBS is expressed as,

$$y(x) = h(x)s(x) + w(x) \tag{10}$$

where $s(x)$ is the signal transmitted by the MBS, $h(x)$ is the channels gain from the MBS to FBS, $w(x)$ is the AWGN sample, and x is the sample index. The average received energy is given by,

$$Y(X) = \frac{1}{X} \sum_{x=0}^{X-1} |y(x)|^2 \tag{11}$$

where X is the total number of samples. Spectrum sensing aims to distinguish between the following two hypotheses,

$$H_0 : y(x) = w(x) \tag{12}$$

$$H_1 : y(x) = h(x)s(x) + w(x) \tag{13}$$

The hypothesis H_0 is for miss-detection and $H1$ is for correct detection. Energy detection is defined by two probabilities, the probability of detection P_D and the probability of false alarm P_F. The occupancy of sub-channels by macro-cell users can be determined by comparing the metric Y against a threshold λ. Therefore, the P_D is calculated as follows,

$$P_D = Pr(Y > \lambda | H_1) = Q_m(\sqrt{2 * SINR}, \sqrt{\lambda}) \tag{14}$$

where m is the product of time and bandwidth and $Q_m(.,.)$ is the generalized Marcum Q-function [15]. The P_F is calculated as follows,

$$P_F = Pr(Y > \lambda | H_0) = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{15}$$

where $\Gamma(.)$ and $\Gamma(.,.)$ are the complete and incomplete gamma functions, respectively [16]. Both probabilities are calculated for each SB as the product function of all sub-channels contained in each SB.

We enhance the normal energy detection procedure to improve the detection capability. The decision regrading channel access by FBS is determined by quantifying how harmful is the interference caused to the macro receivers if the FBS uses the sub-channel. The interference to the macro users is deemed to be harmful if it causes the signal-to-interference ratio (SIR) at the macro receiver to fall below a threshold SIR^*. This threshold depends on the macro receiver robustness toward interference and varies from one service to another. In addition, it may depend on the characteristics of the interfering signal (*e.g.,* signal waveform, continuous versus intermittent interference, etc.) [17]. From the above definitions, we define the interference range of the FBS as the maximum distance from a macro receiver at which the incurred interference is still considered harmful. Consequently, the interference range depends on the macro user interference tolerance not just the FBS transmission power. Let P_m and P_f denote the transmission power of the MBS and the FBS respectively. The distance between the macro-cell transmitter and receiver is denoted as R. The interference range of the FBS (D) is determined according to,

$$\frac{P_m R^{-\alpha}}{P_f D^{-\alpha}} = SIR^* \tag{16}$$

where α is the path loss factor. We deduce from (16) that the macro receiver can tolerate the interference caused by FBS as long as the distance between them is greater than D. As a result, we can define the detection sensitivity (DS) as the minimum SNR of the MBS at which an FBS should be still capable of detecting the macro signal. The FBS should be able to detect active macro transmission within a radius of $R+D$ according to (16). Therefore, the sensitivity is calculated as follows,

$$DS = \frac{P_m(D+R)^{-\alpha}}{N_0} \tag{17}$$

The spectrum sensing is conducted periodically to stay aware of any MBS starts to transmit. During the sensing period, the QoS degradation incurred by the macro users in accessing the band is determined. The choice of the sensing period depends on the type of the service running on the macro user terminal and has to be set for each SB. For example, the sensing period is less for services that vary over a much larger time scale.

3.2 Awareness Based Co-tier Interference Mitigation

In this section, we develop an awareness based algorithm to mitigate co-tier interference between femto-cells that are using the same SB. The algorithm aims to maximize system throughput, improve spectrum efficiency, and adapt transmission power according to FBS SINR requirements. It is assumed that each group of FBSs are assigned to certain SB and able to access its sub-channels. Each FBS is aware of its interference profile which is characterized by certain interference weight W_i. This weight is exploited to label the interference over the link between any two FBSs and is calculated as,

$$W_i = \sum_{e_i} 10^{I_i/10} \tag{18}$$

where I_i is I_2 that is calculated using (4). Due to the relatively low distance between the FBS and its femto-cell associated user, the throughput maximization problem for a femtocell can be written as follows,

$$max \sum_{i \in V} \sum_{j \in V} \sum_{n \in N_c} z_i^* z_j^* Blog(1 + \frac{P_i}{\sum_{j \neq i} P_j H_{ji} + N}) \tag{19}$$

where V is the group of FBSs that share the same SB and $z*$ is the assignment indicator of the sub-channel, P_i is the transmission power of the FBS, H_{ji} is the total gain between FBS j and FBS i, and N is the corresponding noise power. Note that i and j are the indexes of the interfering FBSs.

The FBSs channel allocation problem can be modeled as a graph coloring problem with support of an awareness based mechanism between the FBSs sharing the same SB. The awareness mechanism aims to share the interference weight, data rate requirement, traffic type and traffic load information for each FBS among other FBSs sharing the same SB. Consequently, each FBS is aware of its network environment. Interference weight is the basic metric for the graph coloring channel assignment while data rate requirement, traffic type and traffic load are exploited to ensure QoS, assign traffic priority, and improve spectrum utilization. The sub-channel assignment process as in Algorithm 1 starts by mapping the network into a bidirectional graph $GR = (V, E, W)$ with a group of vertices $V = \{v1, v2...\}$ where each vertex v represents an FBS and a group of edges $E = \{e1, e2...\}$ where an edge e is the link connecting two vertices with interference weight w. A larger weight implies having a larger sum of the path loss and shadowing values. The problem is equivalent to coloring each vertex with one color from $C = \{c1, c2...\}$ and assign proper power level to the respective vertex in order to maximize the throughput and mitigate interference. The color of the vertices represents the available sub-channel, and a color pool of the interference graph relies on which particular SBs can be used by that graph. Once the graph is established, we label each FBS with the total interference

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Algorithm 1.. Co-tier Channel Assignment

Require: $GR = (V, E, W)$, $C = \{c1, c2...\}$, FBS data rate, traffic load and traffic type
Ensure: Sub-channel assignment with maximum throughput T , maximum spectral efficiency and minimum interference I
  BEGIN
  Define V_0 as the number of vertices in GR
  Define i as the index for the FBS
  for $(a = 1$ to $a = V_0)$ **do**
    Calculate W_i, Tp_i, $\forall V \in GR$
    if $(W_i = W_{max})$ **then**
      Select FBSs with maximum W
    end if
    if FBS with W_{max} is not unique **then**
      find FBS with $(Tp_i = Tp_{max})$
    end if
    Color the vertex v with color c (Assign the sub-channel to the FBS)
    Adapt transmission power as in (21)
  end for
  while (1) **do**
    Check U for each FBS
    if $(U < Th_{min})$ **then**
      Switch the users associated the FBS to other FBSs with condition that $(U \leq Th_{max})$ for the target FBSs
    end if
  end while
  END

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weight calculated in (18). At this moment, the vertex with the highest interference weight is colored with an appropriate color with condition that the selected sub-channel satisfies application QoS. If there are more than one FBS with the same interference weight, we check the traffic priority. For example, if one FBS has real-time traffic or it is loaded more than others, it will have the priority to access the sub-channel. Traffic load and application data rate are used to quantify the traffic priority. An indicator Tp is assigned to the FBS to refer to the priority of its traffic. The indicator is ordered in ascending order as the traffic priority increases. The coloring process to maximize throughput can be characterized as follows,

$$argmax \sum_{i \in V} \sum_{n \in N_c} z^* Blog(1 + SINR_{i,n}) \tag{20}$$

$$s.t. \quad \sum_{n \in N_c} z^* \leq 1, \forall i \in V$$

where N_c denotes the specific set of sub-channels, which are used by the vertices involved, $SINR_{i,n}$ is the SINR of femtocell i over the sub-channel n and V is a set of vertices in the graph. Then, the power is adapted for the FBS according to $SINR_{target}$ and the current transmission power as follows,

$$P_i^* = P_i \; SINR_{target} \frac{I_2 + N(i)}{H_{i,n}} \tag{21}$$

where P_i is the current transmission power, $H_{i,n}$ is the channel gain experienced by FBS i while accessing sub-channel n and $N(i)$ is the corresponding noise power. Finally, the FBS is removed from the graph GR and the process repeated again until the set V is empty. In addition, the awareness mechanism manages to improve spectrum utilization by sharing the number of users associated with each FBS (U). If this number falls below certain threshold Th_{min}, all the users associated with this FBS are switched into another FBSs in the same domain with a condition that U for these FBSs is not exceeding certain threshold Th_{max} and QoS of the switched users is guaranteed. Consequently, the sub-channel is released for other FBSs and this improves spectrum utilization and reduces contention of other FBSs.

4 Performance Evaluation

In this section, the performance of our proposed cognitive aware interference mitigation scheme is evaluated through simulation. The simulation environment parameters are presented in Table 1. Note that d is the distance between the user and the base station.

We compare our scheme with the two schemes proposed in [18] and [19] for interference mitigation in femto-cell macro-cell deployment. In addition, we compare it with the standard scheme that does not implement any interference mitigation mechanism. The scheme proposed in [18] is cognitive based (CR-based) and aims to allocate resources in femto-cell networks to maximize the throughput while minimizing interference to macro-cell users nearby only. However, the scheme (femto-macro) proposed in [19] considers mitigating the

Table 1. Simulation environment parameters

Parameter	Value
Carrier frequency	2 GHz
Cellular layout	Hexagonal grid
Macro-cell radius	500 m
Femto-cell radius	10 m
Path loss MBS user	$L = 15.3 + 37.6log(d)$
Path loss FBS user	$L = 38.46 + 20log(d) + 0.7(d)$
Lognormal shadowing	0 mean, 8 dB standard deviation
MBS transmission power	45 dBm
FBS transmission power	20 dBm
White noise power density	- 174 (dBm.Hz^{-1})
Number of SBs	6
Number of sub-channels per SB	10
Macro-user per macro-cell	30
The penetration loss of walls Lw	10 dB

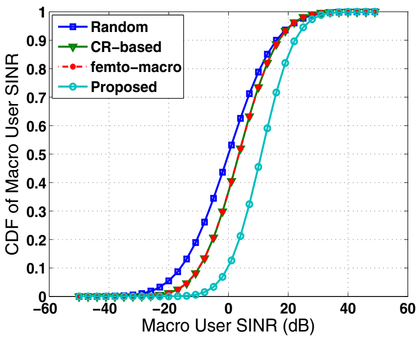

Fig. 2. CDF of macro-cell user's SINR

interference among femto-cells in addition to macro users interference control. The Cumulative Distribution Function (CDF) of the macro user's SINR is presented in Fig. 2. The proposed scheme achieves the highest macro-user's SINR in contrast to the standard random resource allocation, the CR-based and the femto-macro schemes. The reason is that both the CR scheme and the femto-macro scheme employ simple energy detectors to detect the vacant sub-channel. However, our scheme considers accurate detection by better evaluating the interference range and improving the detection sensitivity.

The CDF of the femto-user's SINR is shown in Fig. 3. The proposed scheme achieves significantly better performance than all the other schemes owing to the interference coordination between FBSs with the awareness based spectrum allocation mechanism. The CR-based scheme has no capability to mitigate interference between FBSs while the femto-macro scheme is based on clustering which limits each cluster of femto-cells to access only one sub-channel. This increases the probability of collisions between the contending FBSs. On the other hand, the proposed scheme is not limited to one sub-channel and it comprises awareness and information exchange between the FBSs for channels allocation which does not only mitigate interference but also improves spectrum utilization and maximizes throughput.

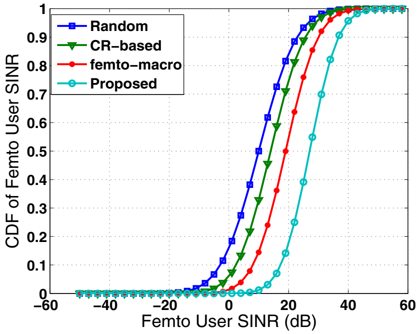

Fig. 3. CDF of femto-cell user's SINR

Fig. 4 presents the spectrum efficiency achieved by all the schemes. It can be noticed that the proposed scheme recorded the highest spectrum efficiency as it considers efficient spectrum utilization by switching users from under-utilized FBSs and free more sub-channels. Fig. 5 presents the throughput achieved by

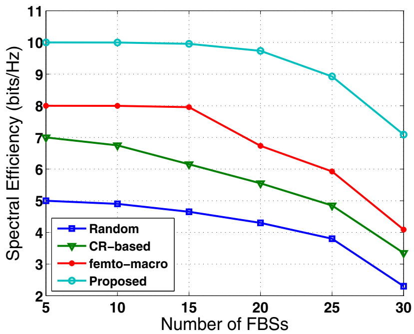

Fig. 4. Spectral efficiency comparison for all schemes

the femto-cell as a function of various number of FBSs. The transmitted traffic considered here is real-time traffic. Our proposed scheme achieved the highest throughput compared to other schemes as it employs adaptive power allocation, considers users QoS requirements and traffic priority which enhances the throughput. Moreover, we notice that the throughput decreases as the number of FBSs increases. It is mainly due to the increase in the probability of collision as the number of FBSs grows.

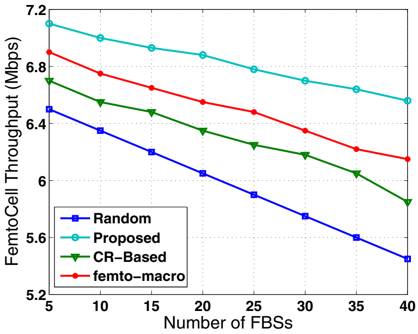

Fig. 5. Femto-cell throughput as a function of the number of FBSs

5 Conclusion

In this paper, we proposed a novel interference mitigation scheme for both cross-tier and co-tier interference in LTE femto-cell and macro-cell deployment. An improved version of cognitive radio spectrum sensing with better detection capability was exploited to mitigate the cross-tier interference. Moreover, an awareness based co-tier interference mitigation mechanism with the aid of graph coloring algorithm was proposed. The mechanism also ensures QoS requirements, supports traffic priority, and improves spectral efficiency by using smart user-FBS association. The adaptive power allocation used by the interference mitigation mechanism improves SINR CDF for both macro and femto users. In addition, the proposed scheme shows ultimate performance in terms of throughput and spectral efficiency.

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