Spectrum Self-coexistence in Cognitive Wireless Access Networks

Tao Chen*, Honggang Zhang†, Marko Höyhtyä*, Marcos D. Katz*

* VTT Technical Research Centre of Finland, P.O. Box 1100, FI-90571 Oulu, Finland
† Zhejiang University, Zheda Road 38, 310027 Hangzhou, China

Abstract—Future wireless access networks, characterized by a large number of small cells densely distributed in metropolitan area, are likely to be the dominating form of future wireless communications. It is expected that the dynamic spectrum access (DSA) enabled by cognitive radio (CR) technologies will act as a key for their success. Considering the high cell density and the large size of network, the spectrum coexistence will be a prominent problem in future wireless access networks. In this paper we study the spectrum self-coexistence of DSA based wireless access networks. The objective is to improve the spectrum utilization among densely distributed cells. To achieve this, topology-aware distributed algorithms are proposed for mobile terminal (MT) association and access point (AP) channel selection. The proposed algorithms enable self-coordination of spectrum in studied networks. The simulation study shows the efficiency of distributed solutions to solve the spectrum coexistence problem in proposed networks.

I. INTRODUCTION

The extreme success of hotspot networks makes us believe cognitive wireless access networks will be the next big thing in wireless communications. According to the evolution path of wireless networks, next generation wireless access networks will be featured by a large number of femto-cells densely distributed in metropolitan area, capable of providing high bandwidth services to mobile users. The DSA [1] backed by CR [2] technologies is expected as the key for the success of such a network.

Considering the high cell density and the large size of the network, the spectrum coexistence becomes the most prominent problem in future wireless access networks. It requires spectrum being efficiently and intelligently utilized among small cells, most likely by distributed approaches for scalability and reliability reasons. Current studies on DSA and CR are, however, mainly focused on the spectrum coexistence problem between primary users (PU) and secondary users (SU) [2]. Less attention has been paid on the spectrum coexistence inside DSA based wireless access networks. It is thus the focus of this paper to study the spectrum allocation problem in DSA based multi-cell access networks.

The similar problem has been intensively investigated in cellular networks, in which the base station (BS) assigns a frequency band to a mobile phone for each call [3]. Centralized coordination schemes are normally employed by them to optimize frequency reuse problem. Although centralized solutions are also found in small scale wireless data networks [4], considering the high cell density and randomly distributed nature of access points (AP) in future wireless access networks, distributed or hybrid approaches are better choices to manage the complexity.

A good example of distributed spectrum coordination is provided by Kauffmann et al [5], who proposed a measurement based approach that adapts MT association and AP channel selection with sampled channel conditions. The limitation of [5] is that in order to facilitate the channel measurement it assumes that APs always send traffic to MTs. Jing et al [6] studied the spectrum coexistence problem using the common spectrum coordination channel (CSCC) approach. Although showing significant gain in spectrum utilization, the problem of this approach is that in a DSA scenario a common control channel may not always exist. The recent development of IEEE 802.11h enables transmission power control (TPC) and dynamic frequency selection (DFS) functions to facilitate dynamic association and channel selection procedure in IEEE 802.11 networks [7]. Based on IEEE 802.11h, Korakis et al. proposed an adaptive approach jointly considering the uplink and downlink quality for MT association with an aim to maximize the network capacity [8].

![Fig. 1. DSA based wireless access networks.](image)

Aforementioned approaches assume that either a single channel is used by the whole network or multiple channels are always available to the network. This may not hold in a DSA based network, where available channels of the network change along with the fluctuation of spectrum holes. This means the assumption of a common control channel [9] may not hold here. Without a common control channel, it is difficult...
to apply centralized spectrum coordination. Sengupta et al [10] studied the distributed spectrum coexistence problem in IEEE 802.22 networks using minority game theory, in which each cell of the network uses a binary strategy set to select or not select a spectrum band independently. It assumes the fixed configuration of each cell. The reassociation of MTs among neighboring APs with an aim to reduce the inter-cell interference is not taken into account. With a more practical model, we propose distributed algorithms to coordinate spectrum among multiple cells of a wireless access network. We call it the spectrum self-coexistence problem since all cells are assumed to use the same access technology. The main contributions of this paper are following:

- The use of topology information to estimate the compromise for spectrum coexistence in multi-cell wireless access networks,
- Development of distributed MT association algorithms with a goal to improve network capacity,
- Development of distributed AP channel selection algorithms with a goal to improve spectrum coexistence.

The remainder of the paper is structured as follows. In section II we describe the system model and give the assumptions. The metric to estimate the potential capacity of cells is proposed in section III. The following two sections develop the algorithms for MT association and AP channel selection, respectively. Then the performance of the proposed algorithms is studied by simulation in section VI. After a brief discussion on the properties of the algorithms in section VII, the conclusion is drawn in section VIII.

II. CONCEPT, SYSTEM MODEL AND ASSUMPTIONS

The DSA scenario shown in Fig. 1 is studied, in which the cells of a DSA based wireless access network are densely distributed and coexist with PUs. Each cell is constituted by an AP and several MTs, where the AP determines the working frequency band of the cell, which can be any frequency band not occupied by proximate PUs. MTs can associate with any adjacent AP and change their association according to needs. It models a typical case of future wireless access networks, in which enormous femto-cells coexisting with PUs.

The focus of this paper is to study the spectrum coexistence problem of SUs, or more specifically, how MTs associate with APs and APs select working frequency bands so that the use of spectrum is optimized. The essential idea is to have adjacent cells separated their frequency bands as much as possible so as to reduce inter-cell interference. To achieve this, MTs will continuously observe surrounding and associate an AP that can provide better throughput. Meanwhile, APs will make frequency band selection periodically according to the setup of their cell and radio environment. All those processes are done distributively.

To simplify the analysis, a specific wireless access system is used in this paper. However, it should be pointed out that the principles developed in this paper can be easily extended to other DSA based wireless access systems. The system model is described as follows.

The channel access of the proposed system is illustrated in Fig. 2, in which the time of each cell is structured into frames. Each frame starts with a beacon followed by time slots. Beacons are used for synchronization and AP discovery; time slots are used for data transmission. Cells are assumed being synchronized by a given mechanism, e.g. by distributed consensus algorithms or wired links among APs.

In a frame, an AP instructs its MTs to sense PUs and discover neighboring APs and MTs on different frequency bands regularly. An adaptive sensing algorithm is needed to balance monitoring overhead and accuracy in a specific scenario. The study of the algorithm is not the scope of this paper. By collecting neighbor information, an AP is able generate the neighbor topology graph of the cell and use it for frequency band selection.

MTs access channels based on fixed-length time slots. Although the channel and the frequency band are different concepts, without losing generality, in the rest of this paper, two terms are exchangeable. We assume that MTs always have downlink and uplink traffic to receive/send. For simplicity, we assume that MTs in a cell have the equal chance to share the channel. Moreover, the downlink and uplink of an MT have the same priority to access an assigned time slot. As a result, for each time slot in a cell the AP has the half of the chance to transmit downlink traffic, and the MTs of the cell equally share the other half for their uplink traffic.

The achievable data rate between an AP and an MT is the function of signal to noise ratio (SNR) measured at the receiver of the MT. The symmetric link is assumed so that the downlink and uplink achieve the same data rate. Based on the achievable data rates of the MTs in a cell, the AP is able to calculate the interference-free capacity of the cell, which is the average data rate of the cell without inter-cell interference. However, as shown in Fig. 2, collisions may happens among adjacent cells. Taking into account inter-cell interference, the potential capacity of a cell is the actual data rate attained.
by the cell. The concepts of interference-free capacity and potential capacity are illustrated in Fig. 2 and will be precisely defined in Section III.

### III. POTENTIAL CAPACITY

![Fig. 3. Neighborhood of cells.](image)

Given an MT, denoted as the MT \( i \), and its associated AP \( a \), the achievable data rate of the MT \( i \) on the channel \( c_j \) is obtained by:

\[
r_{ij}^{c_j}(a) = f(\text{SNR}_{ij}^{c_j}(a))
\]

where \( r_{ij}^{c_j}(a) \) is the achievable data rate, \( f(\cdot) \) is the auto-rate function, and \( \text{SNR}_{ij}^{c_j}(a) \) is the SNR measured by the MT \( i \) for the signal from the AP \( a \) on the channel \( c_j \). For simplicity, we use \( r_{ij}(a) \) to represent the capacity of the MT \( i \) on the working channel of the AP \( a \). The interference-free capacity of the AP \( a \) on the channel \( c_j \) is then:

\[
RA_{ia}^{c_j} = \frac{1}{|U_a|} \sum_{i \in U_a} r_{ij}^{c_j}(a)
\]

where \( U_a \) is the set of MTs associated with the AP \( a \), and \( |\cdot| \) is the size of the set.

To estimate the potential capacity of a cell on a given channel, we need to know the potential collisions caused by the neighboring cells. As shown in Fig. 3, the potential collisions between two cells can be divided into four cases: MTs of one cell are one-hop neighbors of MTs of the other cell; MTs of one cell are one-hop neighbors of the other AP; one AP are one-hop neighbors of MTs of the other cell; two APs are one-hop neighbors.

Assume we analyze the potential capacity of an AP, denoted as the AP \( a \), on the channel \( c_j \). The AP \( a \) has \( K \) MTs, and its neighboring AP \( b \) on the same channel has \( M \) MTs. Since the MTs of an AP equally share the channel, the probability that an MT gets a time slot in the AP \( a \) is \( 1/K \), and is \( 1/M \) in the AP \( b \). Note the downlink and the uplink of the MT equally share that time slot. In the case I of Fig. 3, assuming an MT \( i \) of the AP \( a \) detects \( m \) one-hop neighboring MTs from the AP \( b \), the probability that the AP \( b \) will collide the data transmission of the MT \( i \) on a time slot is:

\[
p_i^{c_j}(b) = \frac{1}{2K} \times \frac{m}{2M}
\]

In the case II, the downlink of the MT \( i \) contends with the downlink of the AP \( b \) and the uplink of its \( m \) MTs. The collision probability of the MT \( i \) with the downlink of the AP \( b \) is \((1/2K) \times (1/2)\) and is \((1/2K) \times (m/2M)\) with the uplink of \( m \) MTs in AP \( b \)'s cell. The collision probability of the MT \( i \) in this case is:

\[
p_i^{c_j}(b) = \frac{1}{2K} \times (\frac{1}{2} + \frac{m}{2M})
\]

Similarly, we can get the collision probabilities of the AP \( a \) in the case III and IV as:

\[
p_a^{c_j}(b) = \frac{1}{2} \times (\frac{m}{2M})
\]

\[
p_a^{c_j}(b) = \frac{1}{2} \times (\frac{1}{2} + \frac{m}{2M})
\]

respectively.

The collision probability of the node \( i \) with all neighboring cells on the channel \( c_j \) is:

\[
P_i^{c_j} = \bigcup_{b \in N_i^{c_j}} p_i^{c_j}(b)
\]

where \( N_i^{c_j} \) is the neighboring AP list of the node \( i \) on the channel \( c_j \). Note that a node may represent either an AP or an MT. Further, we denote the neighboring AP list of the node \( i \) on the working channel of its cell as \( U_i \).

The potential capacity of the AP \( a \) on the channel \( c_j \) is then:

\[
RP_a^{c_j} = \frac{1}{2|U_a|} \sum_{i \in U_a} r_{ij}^{c_j}(a) \times (2 - P_i^{c_j} - P_a^{c_j})
\]

when all MTs of the AP \( a \) work on the channel \( c_j \).

In the following, we describe the MT association and channel selection algorithms separately.

### IV. MT ASSOCIATION

An MT associates with an AP that can offer better throughput. The throughput is determined by the channel quality between the MT and the AP as well as the configuration of the cell. Obviously, the offered throughput will be low if the cell has already been crowded. The potential capacity of an AP reflects the throughput it can provide to the MTs in its cell, and is used as the metric for the MT association.

We propose as follows a distributed heuristic algorithm for the MT association. An MT joins the first discovered AP. Once detecting a new AP, the MT will know by information exchanging the configuration of the AP, which includes the cell size and the potential capacity of the cell. Moreover, we assume the MT will be informed by its AP once the configuration changes of the neighboring cells are detected and collected by the AP. The MT will gradually learn adjacent
APs on its available channels. Assume an MT \( i \) initially joins the AP \( a \), and later it detects all neighboring APs and stores them in the list \( A(i) \). Knowing the potential capacity of each AP in \( A(i) \), the MT \( i \) is able to calculate the capacity gain when changing its association to each neighboring AP. Since a reassociation will only affect the potential capacity of immediate neighboring cells, the affected cells when the MT \( i \) shifting from the AP \( a \) to the AP \( b \in A(i) \) is \( S(a,b) = a \cup b \cup \bar{N}_a \cup \bar{N}_b \). The MT \( i \) can get an AP list \( B(i) \) satisfying:

\[
\delta_{\tilde{R}P}(a,b) = \frac{\sum_{d \in S(a,b)} (\tilde{R}P'(d) - \tilde{R}P(d))}{\tilde{R}P'(d)} > 0 \quad (9)
\]

for \( b \in B(i) \), where \( \delta_{\tilde{R}P}(a,b) \) is the potential capacity gain of the reassociation from the AP \( a \) to \( b \), and \( \tilde{R}P'(d) \) and \( \tilde{R}P(d) \) are the potential capacity of the AP \( d \) before and after the reassociation of the MT \( i \). The Eqn. 9 guarantees that the reassociation does not reduce the potential capacity of the whole network.

The MT \( i \) selects the AP:

\[
e = \arg \max_{b \in B(i)} \delta_{\tilde{R}P}(a,b) \quad (10)
\]

to shift with the probability:

\[
PM(i) = 1 - \alpha \frac{\tilde{r}_i(a)}{\max_{b \in B(i)} \tilde{r}_i(b)} \quad (11)
\]

at the beginning of the next frame. The probability \( PM(i) \) acts as a simulated annealing factor to reduce the reassociation frequency when the current data rate of the MT \( i \) is already close to the highest. The parameter \( \alpha \) is a weight between 0 and 1. It gives an MT a chance to explore when \( \tilde{r}_i(a) \) approaches \( \max_{b \in B(i)} \tilde{r}_i(b) \). In a dynamically changed system it is good to have a big \( \alpha \) while in a less changed system a small \( \alpha \) is a better choice. In the simulation study of this paper, we use a fixed value for \( \alpha \).

The aforementioned algorithm needs significant overhead to compute the potential capacity. A simplified version is proposed, which only uses the interference-free capacity to determine the reassociation gain. In this algorithm, an MT changes the association to the neighboring AP providing maximin positive reassociation gain. Since this algorithm does not take into account the cell-cell interference, the result is a suboptimal result. However, the simulation shows the simplified algorithm achieves similar performance as the first one.

V. CHANNEL SELECTION OF ACCESS POINT

The distributed channel selection algorithm is presented in this section. It takes the similar approach as the MT association algorithm.

Frequently, an AP \( a \) starts the algorithm with the probability:

\[
PA(a) = 1 - \beta \frac{\Delta RPa_j^c}{RAa_j^c} \quad (12)
\]

where \( \beta \) is a weight to control the sensitivity of the algorithm to current potential capacity, and \( PA(a) \) is a simulated annealing factor to reduce the exploration when the current potential capacity has already approached the interference-free capacity. \( \beta \) has a similar meaning as \( \alpha \). It takes a value between 0 and 1. In the simulation study we also use a fixed value for \( \beta \).

In the algorithm the AP calculates its potential capacity on all available channels and gets a channel list \( C'(a) \) on which its potential capacity is larger than that on the current working channel. For each channel in \( C'(a) \), it calculates the sum of the capacity gain on all affected neighboring cells after the frequency band shifting. The AP knows the potential capacity of its neighbor APs by information exchange with its neighbor APs through wireless links connected by MTs or wired links. Note that since the sum of the capacity gain all neighboring APs on the current working channel receiving is always the same and thus has no influence on new channel selection, we only calculate the gain received by the AP \( a \) plus the sum of the gain lost by the neighboring cells on the new channel. From the channels in \( C'(a) \), the AP \( a \) selects the one that can achieve the maximin capacity gain to shift, or in other word, it shifts to the channel:

\[
eck = \arg \max_{c' \in C'(a)} \{ \Delta RPa_j^c + \sum_{b \in Na_j^c} \Delta RPa_j' b \} \quad (13)
\]

where \( \Delta RPa_j^c \) is the gain obtained by the AP \( a \) when moving to the new channel \( c_j' \), and \( \Delta RPa_j' b \) is the gain lost by the neighboring AP \( b \in Na_j^c \).

Like in Section IV, to reduce the overhead to calculate Eqn. 13, the simplified version of the algorithm chooses the new channel based on

\[
eck = \arg \max_{c' \in C'(a)} \{ \Delta RPa_j^c \} \quad (14)
\]

It means an AP select a new working channel without considering the impact to the neighboring cells.

Note that since MTs and APs change their spectrum related configurations only when potential capacity can be improved, the algorithm can be modeled as a potential game. An extra signaling mechanism among adjacent APs is needed to ensure the iterative process of channel section required by the game. Since APs in our network are roughly synchronized, it is not a big challenge to design such a mechanism. The detail of the mechanism is not included in this paper.

VI. SIMULATION STUDY

The performance of the algorithms is studied by simulation. We have the following simulation setup. A set of PUs, APs and MTs are randomly placed on a 600m\( \times \)600m playground. The maximum reach range of them are set to 200m. A number of channels are available in the network. A PU picks up one of them as its working channel. APs and MTs in the reach range of a PU vacate the working channel of the PU.

The achievable data rate of an MT to an AP is calculated by:

\[
r = A \log(1 + B/d^2),
\]

where \( d \) is the distance between the
MT and the AP, and $A, B$ are constants. Note that this formula is just used to catch the essential of the path loss model and Shannon equation and has no meaning to any real system. We set $A$ and $B$ to 20. Moreover, we set both $\alpha$ and $\beta$ in Eqn. 11 and Eqn. 12 to 0.8.

Fig. 4. Potential capacity of network under proposed algorithms. (AP $n$: $n$ APs; CH $n$: $n$ available channels; PU $n$: $n$ PUs)

Combining with the accumulation effect of the AP number on the potential capacity, it explains in Fig. 4 why the case with larger AP number and larger available channels has much higher potential capacity than others.

From Fig. 4 and Fig. 5, we find the presence of PUs reduces the potential capacity of the system.

Fig. 5. Average potential capacity of AP under proposed algorithms.

The difference between the potential capacity and the interference-free capacity of the system is shown in Fig. 6. As the available channels increase, APs have more choices to stay on different channels so as to avoid inter-cell interference, therefore improving their potential capacity. It is shown in the figure that the potential and interference-free capacity are almost the same in the eight-channel case. When there is only one channel exists, since no channel diversity gain can
be exploited by APs, the difference between potential and interference-free capacity is significant. The figure also shows the difference on the potential and interference-free capacity is larger when the number of APs is larger. This is because the potential capacity of the system is the sum of all APs.

To compare the performance with other algorithms, we simulate the potential capacity in the random association and max rate association algorithms. In the former an MT randomly associates with a neighboring AP, while in the latter an MT associates with the AP that can achieve the maximum data rate. Fig. 7 shows the performance of the proposed algorithms are better than others. The max rate association algorithm outperforms the random association algorithm. However, the max rate association does not mean the potential capacity will be maximized. Fig. 7 also shows more available channels give the proposed algorithms more space to outperform other two algorithms.

VII. FURTHER DISCUSSION

This paper does not consider the use of the inter-cell coordination to further improve the capacity. Proper coordination among neighboring cells may significantly reduce collisions. Various approaches have been proposed in different systems. For instance, IEEE 802.11 uses the request to send (RTS)/clear to send (CTS) mechanism to avoid hidden terminal problems; IEEE 802.16h uses joint scheduling among BSs to improve the spectrum reuse in the overlapping area of cells. The combination of distributed approach with the inter-cell coordination will be one of our future study topics.

In order to precisely show the meaning of potential capacity, specific channel access assumptions are applied in this paper. In practice, the collision probability between cells can be obtained from measurement. In this case the algorithms can be generalized and applied in practical wireless access systems.

Although the MT association and AP channel selection algorithms are performed independently, they are actually coupled. The MT association has an impact on the potential capacity of neighboring cells, which may trigger the channel shifting processes. The interaction between two algorithms pushes the network topology towards an optimal configuration.

The fact that the algorithms continuously optimize the use of the spectrum in a distributed way makes them reliable and scalable in opportunistic DSA scenarios. When PUs are detected, SUs in the affected area simply leave the network and start the network joining process independently. The algorithms will gradually bring them back to the optimized configuration. When PUs release their spectrum, the algorithms will automatically regain the empty bands.

VIII. CONCLUSION

In this paper, we study the spectrum coexistence problem in DSA based wireless access networks. The studied scenario is featured by a large number of cells densely distributed in a given area. To improve the spectrum coexistence, topology-aware distributed algorithms are proposed for MT association and AP frequency band selection. The idea is to separate cells on different frequency bands as much as possible while providing MTs better throughput. The simulation results show the proposed algorithms are able to adapt to radio environments and utilize spectrum efficiently. Although the proposed algorithms are designed for a specific wireless access system, by replacing the inter-cell interference estimation method with a measurement based approach, they can easily be applied in other DSA based wireless access systems. The future work will be the extension of the proposed algorithms into DSA based multi-hop wireless networks where the networks are managed by clusters. Moreover we will study the combination of proposed algorithms with proper inter-cell coordination to further improve the spectrum coexistence in the studied network.

REFERENCES