
Energy Efficient Spectrum Access in Cognitive Wireless Access Networks

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Abstract

It is estimated that by 2020 the traffic in wireless access networks will increase drastically as compared to the 2010 level. To meet this challenge, it needs the huge increase of spectrum, very high spectrum efficiency, dense deployment of small cells, and highly energy efficient solutions. Combining these together, we believe that the cognitive wireless access network would be a promising solution. In this paper, we study the energy efficient spectrum access problem in dynamic spectrum access (DSA) based wireless access networks, in which densely deployed access points (AP) provide open access to mobile terminals (MT) by spectrum opportunities enabled by primary users (PU). The question is how the spectrum is allocated to MT via AP so that the bit/energy to deliver the data is maximized. We separate the problem into the channel selection problem of AP and the AP association problem of MT, and propose the distributed AP channel selection algorithm and MT association algorithm, which are run on the AP and MT separately, with a joint goal to improve the bit/energy delivery by the efficient use of spectrum. The proposed algorithms only rely on local information exchange to estimate inter-cell interference, and are therefore scalable to large networks. The per-

formance of the proposed algorithms are evaluated by simulation. It shows in average around 10% bit/energy improvement over the algorithms which randomly allocate channels and associate MTs.

Keywords: cognitive radio system, wireless access network, channel assignment, energy efficiency, interference control.

1 Introduction

Wireless communication services have become an integral part of people's everyday life. According to a collection of recent forecasts of the global mobile data traffic by the International Telecommunication Union Radiocommunication (ITU-R) in [4], there is an increasing data rate demand for the next decade (2012-2022). In fact, there has been a rapid uptake of smart phones, tablets and innovative mobile applications created by users which will lead to a significant increase in the mobile data traffic in [4], which was not predicted earlier in [1]. In light of the increasing data rates and growing numbers of new devices, the efficient use of the basic resources in wireless communications in terms of energy and spectrum become increasingly important design criteria.

In fact, a major challenge facing the mobile communication industry is to develop means to respond to the growing data rate demand while keeping the energy consumption at a reasonable level. The energy efficiency (EE) can be defined in different levels such as system level and component level as shown in [6]. Improvements in the energy efficiency of wireless networks can be obtained via interference control by dynamically switching to connections that can better optimize the resource usage. Cognitive radio systems (CRS) as defined by the International Telecommunication Union Radiocommunication sector (ITU-R), employ "technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained" [2]. The CRS techniques can be used in future wireless networks to improve the energy efficiency through interference control by assigning the frequency channels for operations by considering the interconnections of the throughput and the energy consumption.

We believe that the wireless access network based on dynamic spectrum access (DSA) in a densely deployed environment would be a promising solution to meet the future mobile traffic challenge with CRS capabilities. In such

a network, not only the capacity improvement, but also EE are critical problems. The trade-off between capacity and EE in cellular networks has been shown in [8]. It is reported that in a multi-cell scenario the interference from neighboring cells will degrade both EE and spectrum efficiency (SE). Interference management becomes an important means to improve EE in DSA based wireless access networks. The challenges and solutions to achieve an energy efficient wireless communications are summarized in [11, 13]. In [11], the cognitive radio (CR) approaches applied to the green cellular network are mentioned. However, less research has been done on the application of CR to energy efficient wireless networks.

In this paper we study the energy efficient resource allocation in a DSA based wireless access network. In such a network access points (AP) are densely deployed to provide open access to mobile terminals (MT). Spectrum of the network is opportunistically shared from primary users (PU). In multiple channels divided from available spectrum, an AP selects one working channel and all MTs attached to the AP use the same channel to communicate with the AP. In the previous work [7], the spectrum access problem in the targeted network has been studied, with the objective to improve the spectrum efficiency. We extend the work in [7] by taking into account EE in the channel allocation and MT association. The main contributions of the paper include: designing a local information exchange method to estimate inter-cell interference, proposing a local energy efficient metric used for distributed energy efficient algorithms, and developing the distributed energy efficient algorithms for AP channel selection and MT association, respectively.

The rest of this paper is organized as follows. The system model including the considered wireless access network and the EE metric is presented in Section 2. Section 3 describes the problem formulation for the selection of channels and access points (AP). The way to calculate the throughput of an AP based on given neighboring topology and traffic load of MTs is given in Section 4. Section 5 presents the proposed algorithm for the selection of channels for the APs. Section 6 presents the proposed algorithm for MTs to select the best AP. The performance of proposed algorithms is studied in Section 7. Some remarks regarding the proposed approach are given in Section 8. Finally, conclusions are drawn in Section 9.

2 System Model

We study wireless access networks under the DSA scheme, in which N APs provide Internet access to M MTs through spectrum chances opportunist-

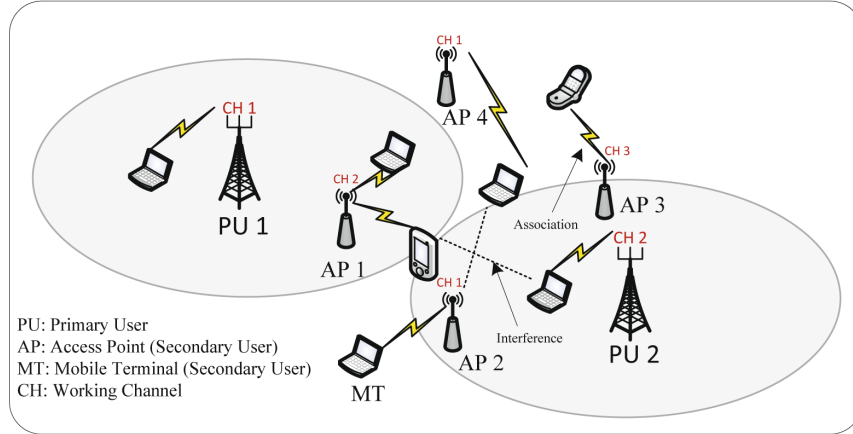


Figure 1 A DSA based wireless access network.

ically availed by P PU of spectrum. The studied network is illustrated in Figure 1. It can be applied to the scenarios where femtocells and Wi-Fi hot-spots are densely deployed with macrocells.

We use a simple spectrum coexistence model, which defines a reach range for each active PU. SUs out of the reach range of a PU are permitted to use the PU's licensed spectrum. The spectrum of the network is divided into C channels. For simplicity, we assume each channel has equal bandwidth W . Each SU i maintains an available channel list c_i , obtained from spectrum sensing, spectrum database, or other approaches defined for specific spectrum bands in question [14, 15]. We assume that an SU is able to update the available channel list timely according to activities of PUs.

An AP selects one channel out of c_i as its working channel. All MTs with the AP use the same working channel. The AP n and all its MTs form a cell n . In the following, depending on the context, the AP n may refer to the AP node or the cell n . An AP is allowed to shift its working channel according to its observation from the surrounding, e.g. if a PU is activated on its working channel, or if the AP finds another working channel that suffers from less interference from neighbors.

The time division multiple access (TDMA) is used by an AP. The channel access of an AP is structured into contiguous time frames, and each frame has L time slots. We assume APs are synchronized by time frames, which

could be achieved by beacon or backhaul connections of APs. The detailed synchronization techniques are out of the scope of the paper.

An MT can associate with any AP, but only one AP at one time. Each MT m has its own downlink and uplink data rate preference, which are the up-limits of rates achieved by interference-free transmission. The MT can change its association if it finds another AP that can provide more energy efficient transmission to support its preferred data rate. Given the preferred rate R_m^D and R_m^U for the downlink and uplink of the MT m , the AP n assigns time slots according to the interference-free link rate, i.e. $r_m^D(n)$ to and $r_m^U(n)$ from the MT. The allocated slots are

$$l_m^D(n) = \left\lceil \frac{R_m^D}{r_m^D(n)} \cdot L \right\rceil \quad (1)$$

$$l_m^U(n) = \left\lceil \frac{R_m^U}{r_m^U(n)} \cdot L \right\rceil \quad (2)$$

where $\lceil \cdot \rceil$ is the ceil operator. We assume a node always has transmission in the allocated slots.

The following admission control rule is applied to the AP: if the unallocated time slots are not sufficient to support the preferred data rate of an MT, the AP will not admit the MT. As a result, not every MT can access to the network even it is in the reach range of an AP.

The interference-free link rate between the AP n and the MT m is computed by

$$r_m(n) = W \log_2 \left(1 + \frac{\gamma}{10^{\theta_{\text{dB}}/10}} \right) \quad (3)$$

where W is the bandwidth, γ is the signal to noise ratio, and θ means an operation θ dB from Shannon the capacity limit [10]. We set $\theta = 3$ dB. Additive white Gaussian noise (AWGN) channel is assumed to calculate $r_m(n)$.

The actual link rate is affected by interference from neighboring nodes on the same channel, and therefore makes the actual data rate less than the preferred data rate. We use the following way to estimate the actual data rate of an MT. For each AP and MT we define a reach range according to their transmission power. If a node is in the reach range of the other, the other node is its one-hop neighbor. A node fails to receive if any of its one-hop neighbors transmits simultaneously in the same channel. We assume the neighbors of a node which are two or more hops away will not affect the reception of the node. Consequently, we are able to use a collision model to take into account the interference. For each time slot, a collision probability is calculated based

on the topology of local nodes and the scheduling on the time slot. The actual link rate as well as the downlink and uplink data rates of the MT are obtained thereafter.

To estimate the actual data rate, a node needs to discover its neighbors, and know the traffic load and scheduling of the neighbors. We assume that an effective neighbor discovery mechanism is used in the network, which allows MT and AP to know its local neighbors and their traffic load in the form of $l_m^D(n)$ and $l_m^U(n)$. By the local neighbor it means a neighbor two hops away. To simplify the analysis, we assume the AP randomly schedule the time slot to its MTs. That is, if the MT m is allocated $l_m^U(n)$ slots for uplink, the probability of the MT m to transmit at any slot is $p_m^U = l_m^U(n)/L$.

The activities of PUs as well as the mobility of SUs are assumed to be semi-stationary.

2.1 Power Consumption Model of AP and MT

We study the EE of the whole network, in which not only the energy consumed by radio parts, but also the energy used to support the network function of the node is taken into account. Since an AP is dedicated for the network access, the total energy of the AP is included in the study. For an MT we only consider the energy for the radio front-end as the significant portion of energy on MT is used to run applications.

The power consumption of an AP by building blocks is shown in Figure 2. As can be seen from this figure, the power consumption of the AP is insensitive to the transmission power. Hence, we define the power consumption model of an AP as follows:

$$P_A = P_0 + P_r \quad (4)$$

where P_A is the total power of an AP, P_0 is the power other than the radio power, and P_r is the radio power. Referring to Figure 2, we assume P_0 consumes 2/3 of P_A , and P_r uses 1/3 of P_A .

The power consumed by the radio front-end of an MT for transmission and reception are defined as P_T^M and P_R^M , respectively. The suggested values for P_T^M and P_R^M are referred to Chapter 20 of [12]. In this study, we set $P_T^M = 0.151$ W and $P_R^M = 0.148$ W.

The transmission power of an AP is set to P_t^A W for its MTs. The transmission power of an MT is set to P_t^M W.

In each downlink time slot, an AP transmits using the power of P_t^A , and consumes the total power of P_A . In the receiving and idle mode, the AP

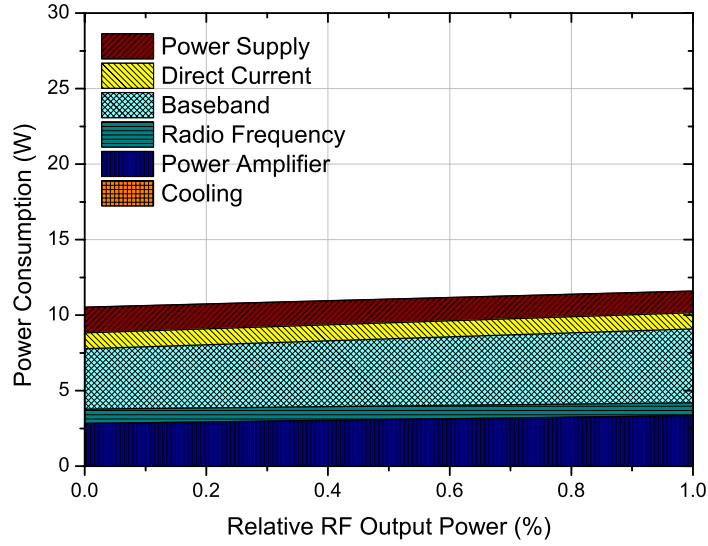


Figure 2 Power consumption of AP by building blocks as function of output power, redrawn from [5].

consumes the power of P_0 . An MT consumes P_R^M in its downlink slots, P_T^M in its uplink slots, and 0 when it is idle. Note that we only consider the radio energy of an MT in this study.

2.2 EE Metric

EE of the whole network is measured by the ratio of the throughput of the whole network and the total energy consumption of the network, which is defined as:

$$EE = \frac{\sum_{n \in N} R(n)}{\sum_{n \in N} P(n)} \text{ bit/Joule} \quad (5)$$

where EE is the network EE metric, $R(n)$ is the throughput of an AP n , and $P(n)$ is the average power consumed by the cell n . $R(n)$ is the sum of downlink and uplink throughput, and $P(n)$ includes the power of AP and its MTs.

In our proposed algorithm, an MT uses an EE metric to associate with an AP which offers the best bit/energy gain. As an MT can only obtain local

information of its neighbors, it is not feasible to use EE from (5) in the algorithm. Instead, we use the local EE metric, which is defined as

$$ee(S_A) = \frac{\sum_{i \in S_A} R(i)}{\sum_{i \in S_A} P(i)} \text{ bit/Joule} \quad (6)$$

where $ee(S_A)$ is the local EE metric which takes into account the bit/energy cost of the cell set S_A . According to different energy efficient MT association algorithms, S_A may include the cell n of the MT m , and neighboring cells of the cell n , denoted as $N_A(n)$, or some neighboring cells or $N_A(n)$. We define $N_A(i)$ is the local neighboring cells of the node i . For the MT m on the AP n , we have $N_A(m) = N_A(n)$.

3 Problem Formulation

Let $R^D(n)$ and $R^U(n)$ be the actual downlink and uplink data rates of the AP n , $R(n)$ be the actual data rate of the AP n , $R_m^D(n)$ and $R_m^U(n)$ be the actual downlink and uplink data rate of the MT m on the AP n , $N_{PU}(i)$ be the neighboring PUs of the node i , $N(i)$ be the one-hop neighbors of the node i , and $c(n)$ be the available channels of the cell n . The problem of energy efficient spectrum access of the network is formulated as follows:

$$\max_N \quad EE = \frac{\sum_{n \in N} R(n)}{\sum_{n \in N} P(n)} \quad (7)$$

$$\text{subject to} \quad c(n) = \bigcap_{m \in n} c_m \cap c_n \text{ for } \forall n \in N \quad (8)$$

$$l_m^D(n) = \lfloor \frac{R_m^D}{r_m^D(n)} \cdot L \rfloor \text{ for } m \in \text{AP } n \quad (9)$$

$$l_m^U(n) = \lfloor \frac{R_m^U}{r_m^U(n)} \cdot L \rfloor \text{ for } m \in \text{AP } n \quad (10)$$

$$\sum_{m \in n} (l_m^D(n) + l_m^U(n)) \leq L \text{ for } \forall n \in N \quad (11)$$

$$R(n) = R^D(n) + R^U(n) \text{ for } \forall n \in N \quad (12)$$

$$R^D(n) = f(R_m^D, R_m^U | m \in A(i | i \in N_A(n))) \quad (13)$$

$$R^U(n) = g(R_m^U, R_m^D | m \in A(i | i \in N_A(n))) \quad (14)$$

where $A(n)$ is the MTs of the AP n , $f(R_m^D, R_m^U | m \in A(i | i \in N_A(n)))$ and $g(R_m^U, R_m^D | m \in A(i | i \in N_A(n)))$ are the functions to compute the actual

downlink and uplink data rate of the AP n in term of the traffic load and the topology of neighboring MTs and APs surrounding the AP n .

In the problem (7), (8) is the channel constraint of SUs, (9), (10) are the data rate constraints of an MT, (11) is the admission control of an AP, and (12), (13), (14) are the actual data rates of an AP affected by interference.

It is difficult to solve (7). We separate it into two sub-problems and use distributed iterative algorithms to approach the optimized result. One is the AP channel selection problem and the other is the MT association problem. Two problems are dealt with independently, and only local neighboring information is required to solve them.

In the AP channel selection problem, each AP estimates on different available channels the actual data rate that can be achieved under the current MT association and traffic load. The best channel provides maximum network throughput.

Since there is a network throughput gain to swift to the best channel and the power consumption of the network is not changed, the EE of the network is maximized. Instead of calculating $ee(S_A)$ metric of an AP, we use the throughput to get the most energy efficient channel. In this way the complexity of the problem is significantly reduced.

The problem is modeled as follows:

$$\underset{c \in c(n)}{\operatorname{argmax}} \quad \sum_{i \in N_A(n)} (R(i)|_c = R^D(i)|_c + R^U(i)|_c) \text{ for each AP } n \quad (15)$$

$$\text{subject to} \quad c(n) = \bigcap_{m \in n} c_m \cap c_n \text{ for } \forall n \in N \quad (16)$$

$$\sum_{m \in n} (l_m^D(n) + l_m^U(n)) \leq L \text{ for } \forall n \in N \quad (17)$$

$$R^D(n) = f(R_m^D, R_m^U | m \in A(i) | i \in N_A(n)) \quad (18)$$

$$R^U(n) = g(R_m^U, R_m^U | m \in A(i) | i \in N_A(n)) \quad (19)$$

where $x|_c$ denotes the value of x on the channel c . Note that $\cdot|_c$ is omitted in (17), (18), (19). In the problem (15), (16) is the channel constraint of the AP, (17) is the admission control of the AP, and (18), (19) are the constraints to achieve actual data rates.

In the MT association problem, each MT evaluates the change of bit/energy of the local area when it attaches to different neighboring APs. The local area includes the cell of the MT and its neighboring cells. The AP with best bit/energy becomes the choice of the MT and the EE of the network

is improved. The problem is modeled as the follows:

$$\operatorname{argmax}_{n \in N_A(m)} \sum_{n \in S_A} ee(S_A) \text{ for each MT } m \quad (20)$$

$$\text{subject to } S_A = N_A(m) \cap a(m) \quad (21)$$

$$\sum_{i \in n} (l_i^D(n) + l_i^U(n)) \leq L \text{ for } \forall n \in N \quad (22)$$

$$R(n) = R^D(n) + R^U(n) \text{ for } \forall n \in N \quad (23)$$

$$R^D(n) = f(R_i^D, R_i^U | i \in A(j) | j \in N_A(n)) \quad (24)$$

$$R^U(n) = g(R_i^U, R_i^D | i \in A(j) | j \in N_A(n)) \quad (25)$$

In the problem (20), (22) is the admission control of the AP, and (23), (24), (25) are the constraints to achieve actual data rates.

4 Throughput of AP

Given the interference-free link rate of $r_m^D(n)$ and $r_m^U(n)$, the allocated time slots of $l_m^D(n)$ and $l_m^U(n)$, the topology of neighboring nodes, and the random scheduling of time slots in each AP, we are able to calculate the collision probability on transmission at each time slot. With the collision probability, the throughput of an AP is obtained.

As shown in Figure 3, the collisions between two APs are divided into four basic cases:

- Case I: On the downlink of an MT, MTs of another AP collide the MT from their uplinks but the neighboring AP can not reach the MT;
- Case II: On the downlink of an MT, MTs of another AP collide the MT from their uplinks and the neighboring AP collides the MT from the downlink;
- Case III: On the uplink of an AP, MTs of another AP collide the AP from their uplinks but the neighboring AP can not reach the AP;
- Case IV: On the uplink of an AP, MTs of another AP collide the AP from their uplinks and the neighboring AP collides the AP from the downlink.

We first analyze the throughput of an AP, denoted as the AP a , on the channel c . The AP a has K MTs, and its neighboring AP b on the same channel has M MTs. In Case I of Figure 3, assuming an MT m of the AP a detects k one-hop neighboring MTs from the AP b , the probability that the AP b will

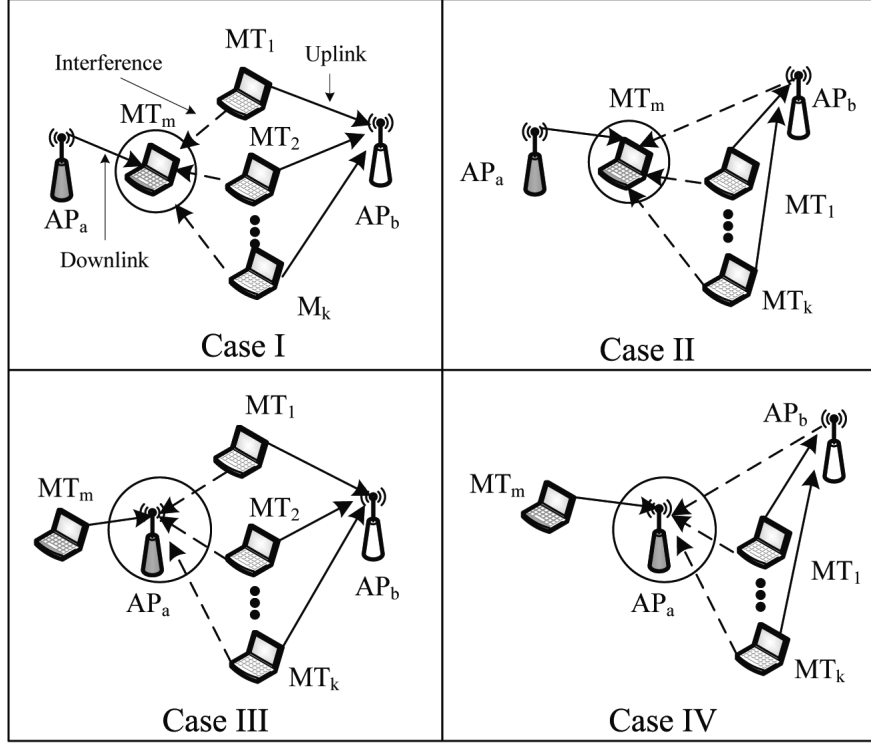


Figure 3 Interference in different topologies.

collide with the downlink transmission of the MT m on a time slot is

$$p_m^c(b) = \frac{l_m^D(a)}{L} \cdot \frac{\sum_{i \in N_k} l_i^U(b)}{L} \quad (26)$$

where N_k is k one-hop neighboring MTs from the AP b .

In Case II, the downlink of the MT m contends with the downlink of the AP b and the uplink of its k MTs. The collision probability of the MT m with the downlink of the AP b is

$$\frac{l_m^D(a)}{L} \cdot \frac{\sum_{i \in A(b)} l_i^D(b)}{L}$$

and with k MTs is

$$\frac{l_m^D(a)}{L} \cdot \frac{\sum_{i \in N_k} l_i^U(b)}{L}$$

with the uplink of m MTs in AP b 's cell. The collision probability of the MT i in this case is

$$p_m^c(b) = \frac{l_m^D(a)}{L} \cdot \frac{\sum_{i \in A(b)} l_i^D(b) + \sum_{i \in N_k} l_i^U(b)}{L} \quad (27)$$

In the same way we can get the collision probabilities of the AP a in Cases III and IV as

$$p_a^c(b) = \frac{\sum_{i \in A(a)} l_i^U(a)}{L} \cdot \frac{\sum_{i \in N_k} l_i^U(b)}{L} \quad (28)$$

$$p_a^c(b) = \frac{\sum_{i \in A(a)} l_i^U(a)}{L} \cdot \frac{\sum_{i \in A(b)} l_i^D(b) + \sum_{i \in N_k} l_i^U(b)}{L} \quad (29)$$

respectively.

The collision probability of the node i with all neighboring cells on the channel c is

$$p_i^c = \bigcup_{b \in N_A(i)^c} p_i^c(b) \quad (30)$$

where $N_A(i)^c$ is the neighboring AP list of the node i on the channel c , and the node i can be AP or MT.

The throughput of the AP a on the channel c is then

$$R^c(a) = \sum_{m \in A(a)} \frac{r_m^D(a) \cdot l_m^D(a) \cdot p_m^c + r_m^U(a) \cdot l_m^U(a) \cdot p_a^c}{L} \quad (31)$$

where the MTs of the AP a are on channel c .

5 Energy Efficient Channel Selection of AP

In this section we describe the distributed channel selection algorithm. In the algorithm the AP n calculates its throughput on all available channels and gets a channel list $C'(n)$ on which its throughput is larger than that on the current working channel. For each channel in $C'(n)$, it calculates the throughput changes on all affected neighboring cells after the channel shift. The AP gets the throughput of its neighbor APs by information exchange through wireless links connected by MTs or wired links.

Note that we only calculate the throughput gain received by the AP n plus the throughput lost of all neighboring cells on the new channel, as the throughput gains of the neighboring APs on the current working channel of the AP have no impact on the channel selection.

From the channels in $C'(n)$, the AP n selects the one that can achieve the maximum throughput to shift, or in other word, it shifts to the channel:

$$c' = \operatorname{argmax}_{c' \in C'(n)} (\Delta R^{c'}(n) + \sum_{b \in N_A^{c'}(n)} \Delta \tilde{R}^{c'}(b)) \quad (32)$$

where $\Delta R^{c'}(n)$ is the throughput gain of the AP n moving to the new channel c' , and $\Delta \tilde{R}^{c'}(b)$ is the throughput lost by the neighboring AP $b \in N_A^{c'}(n)$. $N_A^{c'}(n)$ are the neighboring APs on the channel c' .

To avoid the ping-pong effect, each time an AP n starts the algorithm with a probability of

$$p_A(n) = 1 - \beta \frac{R(n)}{\sum_{m \in A(n)} \frac{r_m^U(n) \cdot l_m^U(a) + r_m^D(n) \cdot l_m^D(a)}{L}} \quad (33)$$

over its working channel, where $\beta \in [0, 1]$ is a weight to control the sensitivity of the algorithm, and $p_A(n)$ is a simulated annealing factor to reduce the exploration when the current throughput is close to the interference-free throughput.

To reduce the complexity to calculate (32), the simplified version of the algorithm chooses the new channel based on

$$c = \operatorname{argmax}_{c' \in C'(n)} \Delta R^{c'}(a) \quad (34)$$

That is, an AP selects a new working channel without considering the throughput impact to the neighboring cells.

6 Energy Efficient MT Association

In this section we present the distributed MT association algorithm. An MT associates with an AP that can offer better bit/energy gain. The bit/energy is affected by the link rate between the MT and the AP as well as the topology of the neighboring nodes of the cell.

The energy efficient MT association algorithm is proposed as follows. An MT joins the first discovered AP. Once detecting a new AP, the MT will get by information exchange the MTs and the throughput of the AP. Moreover, we assume an MT will be informed by its AP when the neighboring cells have changes on the working channel or associated MTs. The MT will then gradually learn adjacent APs on its available channels. Assume that an MT m

initially joins the AP n , and later knows all neighboring APs and stores them in the list $N_A(m)$. Knowing the throughput of each AP in $N_A(m)$, the MT m calculates the bit/energy metric when accessing an neighboring AP. Since a re-association will only affect the bit/energy gain of neighboring cells, the affected cells when the MT m shifts from the AP n to the AP $b \in N_A(m)$ is $S_A(n, b) = n \cup b \cup N_A^{c(n)}(n) \cup N_A^{c(b)}(b)$. The MT m can get an AP list $S(m)$ satisfying

$$\delta_{ee}(n, b) = ee(S_A(n, b)) - ee'(S_A(n, b)) > 0 \quad (35)$$

for $b \in S(m)$, where $\delta_{ee}(n, b)$ is the bit/energy gain for the re-association from the AP n to b , and $ee(S_A(n, b))$ and $ee'(S_A(n, b))$ are the bit/energy metric of S_A before and after the re-association of the MT m . Equation (35) ensures that the re-association does reduce the EE of the whole network.

The MT m selects the AP n where

$$n = \operatorname{argmax}_{b \in S(m)} \delta_{ee}(n, b) \quad (36)$$

to re-associate with the probability:

$$p_M(m) = 1 - \alpha \frac{r_m^D(n) + r_m^U(n)}{\max_{b \in S(m)} (r_m^D(b) + r_m^U(b))} \quad (37)$$

where $\alpha \in [0, 1]$.

Like in Section 5, the probability $p_M(m)$ acts as a simulated annealing factor to reduce the re-association frequency when the current link rate of the MT m is close to the highest.

To reduce the complexity of the algorithm, two simplified versions are proposed. The first one only has the AP n and b in S_A of (35). The second one is based on the first one but is even simple: it only uses the link rate to calculate the bit/energy metric $ee(n, b)$. The results from simplified version are suboptimal. However, the complexity of the algorithm is significantly reduced.

7 Simulation Study

The simulation is used to evaluate the performance of the proposed algorithms. The simulation setup is the following. A given number of PUs, APs and MTs are randomly placed on a 600 m × 600 m playground. The maximum reach range of PUs are set to 200 m, and APs as well MTs are set to 100 m.

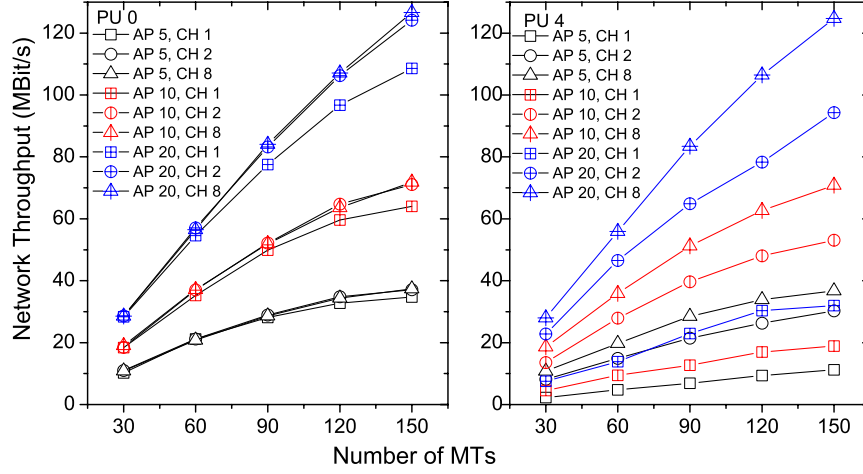


Figure 4 Network throughput under proposed algorithms.

The number of channels in the network are set to 1, 2, 4 or 8. Each channel has a bandwidth of 1 MHz. A PU randomly picks up one channel as its working channel. APs and MTs in the reach range of a PU avoid using its channel.

The power of an AP is set to 10 W, in which the radio power is 3.5 W and other parts consumes 6.5 W. The transmission power of an AP and an MT is set to 32 dBm. No power control is applied. The reciprocity of the downlink and uplink channel is assumed. Hence, the downlink and uplink interference-free link rates are identical.

Each MT has the downlink and uplink data rate preference of 500 kbit/s, respectively. The interference-free link rate between AP and MT is calculated by Equation (3) and the requested time slots are obtained thereafter. The path loss model from [9] is used:

$$l(\text{dB}) = 37 + 32 \log_{10}(r) \quad (38)$$

where r is the distance in meter. The noise in γ is calculated by

$$N = k \cdot T \cdot \text{NF} \cdot W \quad (39)$$

where $k = 1.3804 \cdot 10^{-23} \text{ J/K}$ is the Boltzmann constant, $T = 290\text{K}$ is the temperature, $\text{NF} = 7 \text{ dB}$ is the noise figure, and W is the channel bandwidth.

The parameter α and β in Equations (37) and (33) are set to 0.8.

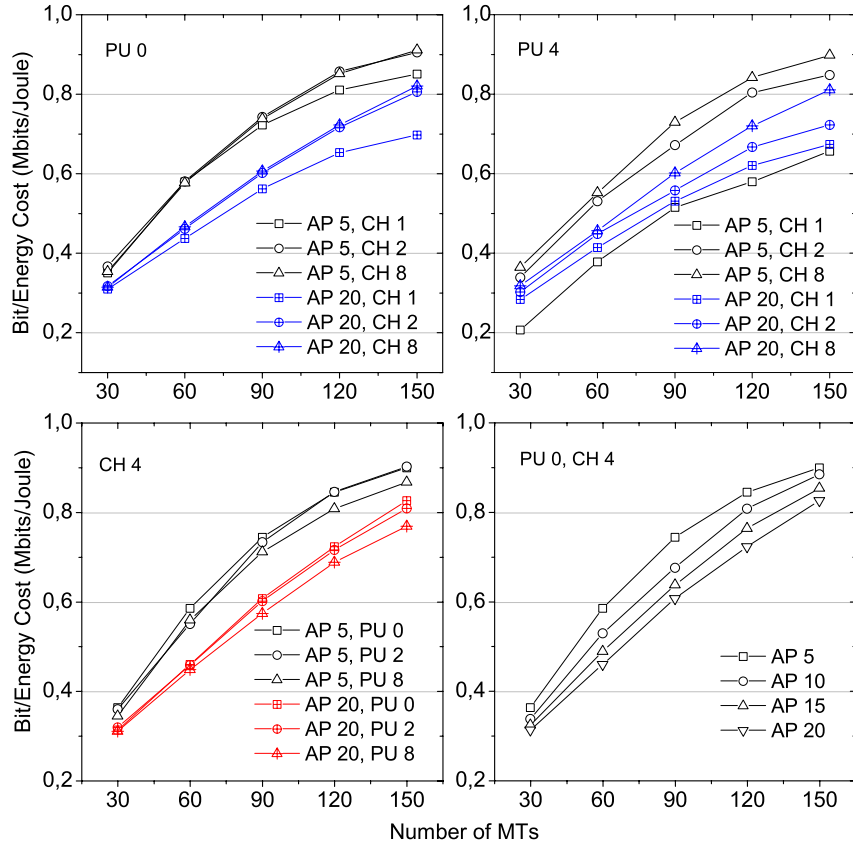


Figure 5 Bit/energy cost of network under proposed algorithms.

For each setup the simulation runs multiple times and the results are averaged.

Figure 4 shows the network throughput under different network setups. It can be seen from the figure, that the network throughput increases as more APs are deployed, because more APs increase the capacity of the network, and also get more MTs served. Figure 4 also shows the influence of available channels to the network throughput. More channels provide better throughput as the channel selection algorithm mitigates interference between neighbor cells. However, when there is no PU in the network, the throughput gain is not significant, especially when the available channels are more than one.

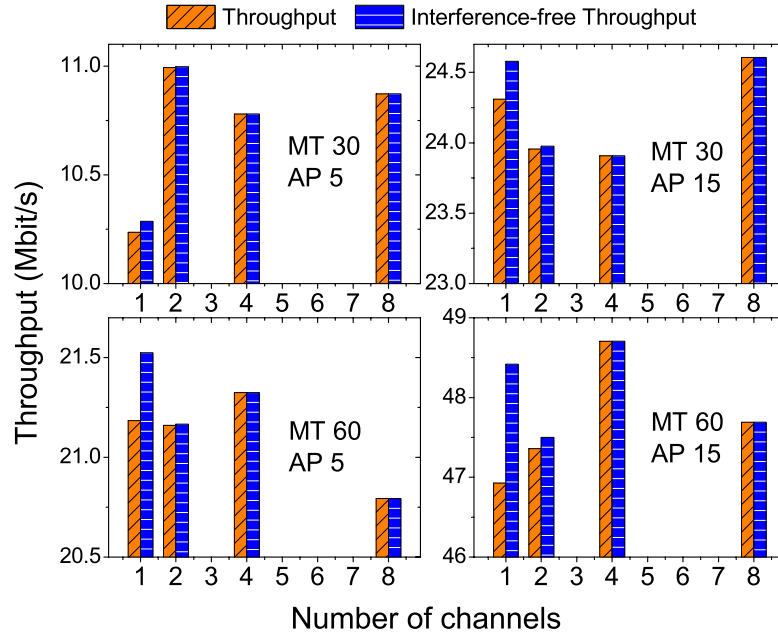


Figure 6 Network throughput and interference-free throughput under different available channels, no PU in network.

When there are 4 PUs in the network, more channels provide APs significant throughput improvements.

The bit/energy cost of the network is shown in Figure 5. Similar to the results in Figure 4, more MTs and more channels provide better bit/energy results. It is because the network is able to accommodate more throughput. We can see from this figure, especially from the right-bottom figure, that less APs provide higher EE. The reason is that each AP has significant power overhead compared to the MT. For the same available channels, the impact of the number of PUs is shown in the left-bottom graph of Figure 4. The number of PUs has less impact on EE of the network when there are less MTs, but the impact increases as MTs increase. It also shows 2 PUs and 8 PUs have similar effect on network EE.

It is interesting to see how the proposed algorithm exploits channel opportunities to avoid interference and then improves the throughput and EE. We use the interference-free throughput, which assumes that each AP has its own

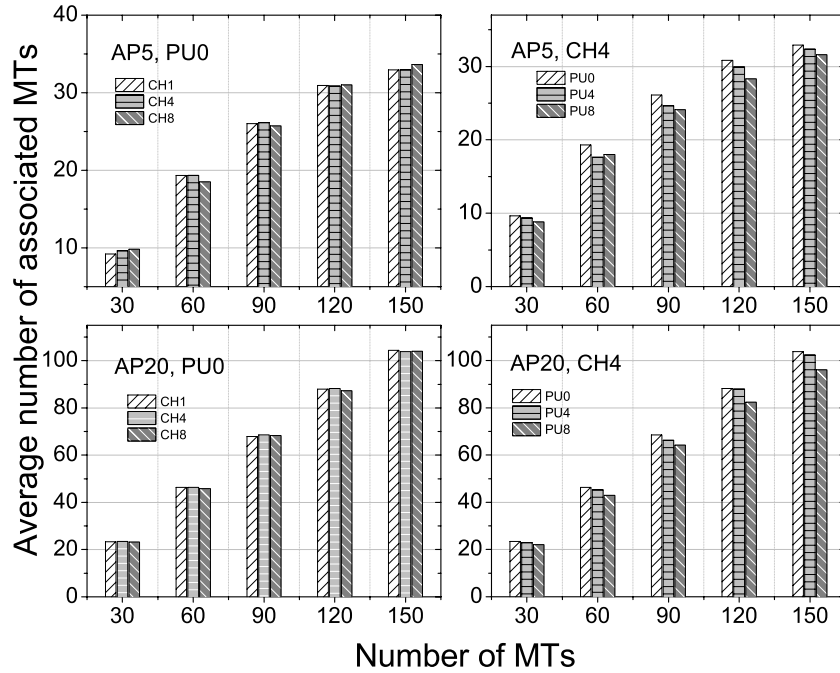


Figure 7 Average number of associated MTs in network.

channel and therefore no interference from other cells, as the reference for comparison. Shown in Figure 6, in the cases of 4 and 8 channels, those two throughput are the same, meaning that APs select channels in a way to avoid interference from other cells. When there is only one channel in the network, inter-cell interference is inevitable and it reduces the throughput. It is also shown in the figure that more MTs and more APs generate more interference.

Due to the reach range of an AP, as well as the capacity limit of an AP, not every MT can access an AP. Figure 7 shows the average number of associated MTs in the network. In the case of 5 APs, less than 30% of MTs gain access to APs. When there are 20 APs, around 70% of MTs gain access to APs. The reason is straightforward as more APs provide more coverage. But we can see that even if the number of APs is large, there is a significant number of MTs that can not access the network. The number of PUs affects the number of associated MTs. The more PUs are in the network, the less MTs can access the network. However, the impact of PUs on associated MTs is not severe.

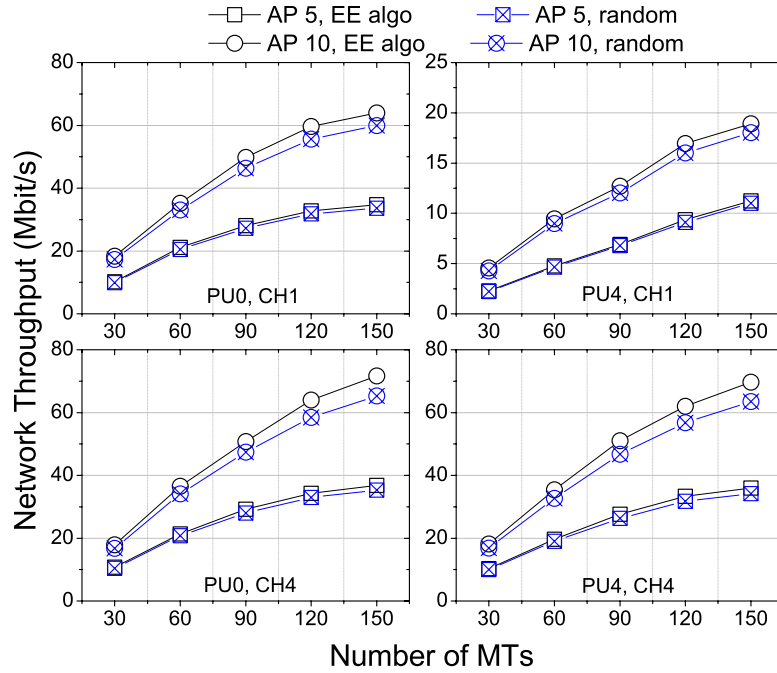


Figure 8 Comparison of network throughput between proposed algorithm and random association algorithm.

Finally, Figures 8 and 9 compare the throughput and EE of the network between proposed algorithm and a reference algorithm, which randomly associates MTs with nearby APs. The proposed algorithm improves the throughput and EE of the network as compared to the random algorithm. The gain of throughput over the random algorithm increases as the number of MTs, and/or the number of APs increase. For EE of the network, the gain of EE increases slower than throughput when the number of MTs increases. In average, 10% of EE gain can be achieved by proposed algorithm compared to the random algorithm.

8 Discussion

In this paper, MT association and AP channel selection algorithms are performed separately, but they affect each other. The re-association of an MT may change the load of the new AP, and in turn the interference to neigh-

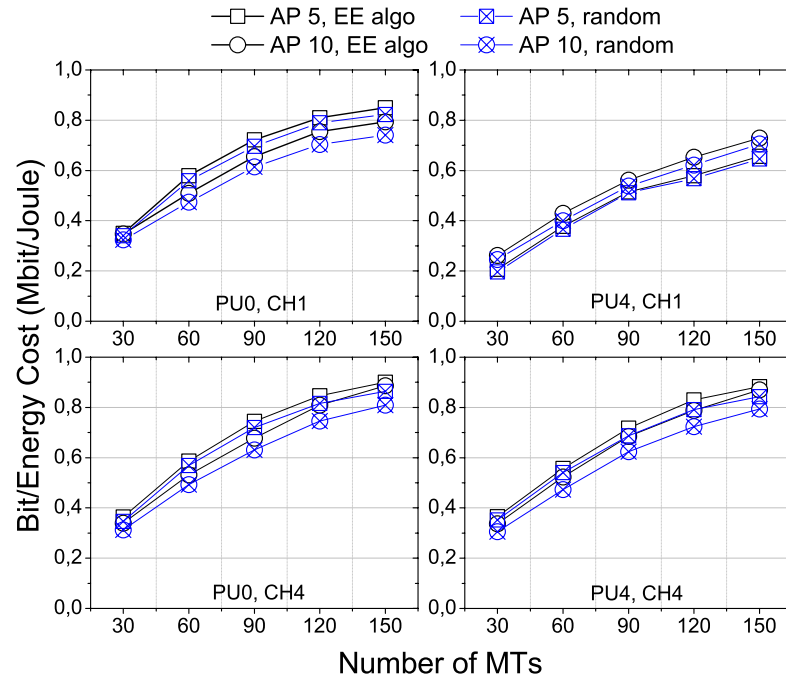


Figure 9 Comparison of bit/energy cost between proposed algorithm and random association algorithm.

boring cells. The channel change of an AP will change the neighbors of its MTs, and in turn let MTs to initialize re-association processes. The interaction between two algorithms move the network topology towards an optimal configuration.

We do not show the impact of dynamic behaviors of PUs on the performance of the algorithms. However, as the algorithms run in a distributed way, the changes of channel will be adapted by the network and in a long run the network will return to an optimal setup.

Strong assumptions on channel access and scheduling are applied in this paper. The reason is to simplify the analysis and provide insights on the problem. In practice, the collision probability between cells may be obtained from measurement. In this case the algorithms can be applied in practical wireless access systems.

Note that the inter-AP coordination will further improve throughput and EE of the network. Proper coordination among neighboring APs may sig-

nificantly reduce the inter-cell interference. For instance, IEEE 802.16h uses joint scheduling among BSs to improve the spectrum reuse in the overlapping area of cells [3]. Future work could study efficient inter-AP communications for interference coordination and energy saving.

9 Conclusion

We study in a DSA based wireless access network the energy efficient spectrum access problem with the goal to maximize the bit/energy gain. The original problem is divided into two sub-problems, i.e. the channel selection problem of AP and the AP association problem of MT. We proposed distributed approaches to solve those two problems, which only rely on the local information exchange of inter-cell interference. The distributed AP channel selection algorithm and MT association algorithm are developed, which allow an AP to explore spectrum with less interference, and an MT to connect to an AP with the most bit/energy gain. Two algorithms are interactive in a way that allows an MT to access spectrum resource with less interference and more energy efficiently. Our approach is flexible and provides scalability to large networks. It can be applied to small cell environment where femtocells and Wi-Fi APs are densely deployed with macrocells.

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Biography

Tao Chen received his B.E. degree from Beijing University of Posts and Telecommunications, China in 1996, and Ph.D. degree from University of Trento, Italy in 2007, both in telecommunications engineering. Since 2008, he has been with VTT Technical Research Center of Finland, now working as senior researcher and project manager. From 2003 to 2007 he worked as a researcher in CREATE-NET, Italy. From 1996 to 2003, he was an engineer in a national research institute at China. His research interests include dynamic spectrum access, energy efficiency of heterogeneous wireless networks, cooperative communications, and wireless networking.

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