Channel Assignment and User Association Game in Dense 802.11 Wireless Networks

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***Abstract*—In densely deployed IEEE 802.11 wireless networks, the transmission delay experienced by a user depends not only on the traffic load of the associated AP, but also the contention level from other APs operating on the same channel. However, due to the random distribution of users and inappropriate setting of AP channels, the traffic loads of different APs are often uneven, leading to unfair delay experience to different users. In this paper, we consider the problem of channel assignment and user association for balancing the traffic load of APs operating on different channels, which is modeled as a non-cooperative game. We prove the existence of Nash equilibrium (NE) for this game, and derive the price of anarchy and the fairness index at NE. Simulation results are provided to compare the performance of the proposed algorithm with the theoretical bounds.**

I. Introduction

In recent years, the deployment of IEEE 802.11 wireless networks has been growing rapidly, such as in office buildings, campus, airports and many other public areas. The increase of wireless network density has caused substantial performance degradation to users due to the limitation of default parameter settings recommended by the IEEE 802.11 standard. The reasons are twofold: (i) A user station (STA) can often detect multiple APs in its neighborhood in a dense wireless network environment. In this case, a STA is associated to the nearest AP(i.e., the AP with the strongest received signal strength indicator(RSSI)) following the 802.11 protocol. However, the RSSI does not carry any information about the congestion level of the AP, thus this tends to result in imbalanced traffic load to APs if the STAs are non-uniformly distributed. (ii) An AP also can find multiple APs within its contention range. However, since the number of orthogonal channels is limited in 802.11 wireless networks(e.g., 3 channels for 802.11b/g), these neighboring APs may be assigned with the same channel by the default out-of-the-box channel selection scheme in 802.11 protocol. This can lead to intensive co-channel contention between neighboring APs and their associated STAs.

As a result, in the dense wireless networking environment, the service received by a user depends not only on the traffic load of the associated AP, but also the contention level from other co-channel neighboring APs. To address this problem, many schemes have been proposed in literature from different perspectives. For example, the authors in [4] propose a scheme that attempts to provide max-min fair bandwidth allocation to STAs with user association. In [3], a cell breathing approach is proposed to control the association between STAs and APs by tuning the transmission power level of the beacon frame from APs. In [2], the *airtime cost* is adopted as a metric to measure the congestion level of the APs, with which a user association scheme is proposed to balance the traffic load between different APs. The same metric is used in [7] to develop a game theoretical model for analyzing the performance of user association scheme. In our previous work [12], we design both centralized and localized algorithms for the user association game based on the airtime metric, which are shown to provide better load balancing using global and local information respectively.

From the channel assignment perspective, some algorithms have been proposed to assign the channel to APs so that the interference between cells is minimized. In [6], the authors propose an algorithm to allocate orthogonal channels to a set of APs in a wireless network based on the real world measurements of interference. In [9], a game theoretic channel allocation scheme is proposed for the AP-level fairness problem in an uncoordinated deployed wireless network.

In [8], the authors present some algorithms that jointly solve the problem of channel assignment and user association based on the *Gibbs sampler* technique. It is demonstrated that a better load balancing to APs can be achieved by incorporating the channel allocation and user association. In a recent work [5], the authors explore the interdependencies between channel allocation, user association and power control, and provide guidelines for optimizing the performance of dense wireless network.

In this paper, we present a game theoretic approach for the joint channel assignment and user association problem in 802.11 wireless networks, with the objective of balancing the traffic load across different APs. To characterize the congestion level of a specific AP, we adopt the *airtime cost*, which is an approximate measure of the transmission delay experienced by the users associated with the AP. We formulate a non-cooperative game for the channel assignment and user association problem, whereby an AP(or a STA) is a player whose strategy is to select proper channel(or AP association) to maximize its payoff(i.e., to minimize its transmission delay). We propose an algorithm and prove the existence of Nash equilibrium for this game. The price of anarchy and the fairness index at the Nash equilibrium are analyzed. Simulation results show that the proposed algorithm provides good load balancing and fairness across different APs.

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The rest of paper is organized as follows. In Section II, we introduce the system models assumed in this paper. The channel allocation and user association game is formulated in Section III and an algorithm is designed accordingly. The existence of Nash equilibrium, price of anarchy, and fairness index are analyzed. In Section IV, we provide the simulation results to evaluate the performance of the proposed algorithm. Finally, we conclude this paper in Section V.

II. System Models

A. Network model

We consider a dense IEEE 802.11 wireless network that consists of a set of APs denoted by $\mathcal{A}$ and a set of STAs denoted by $\mathcal{U}$ respectively, which are randomly distributed in the network area. We assume that all APs and STAs are within the sensing range of each other so that every node can hear the transmissions of other nodes.

Each AP can operate on a set of orthogonal channels denoted by $\mathcal{Q}$. A STA operates on the same channel with its associated AP. We assume that APs and STAs can exchange information by broadcasting beacon frames. The achievable transmission rate between a STA and an AP is determined by the signal-to-noise ratio (SNR) of the link as specified by the IEEE 802.11 protocol.

B. Airtime cost

We adopt the *airtime cost* as a measure of the congestion level of a specific AP s, which was firstly proposed in [1] as a routing metric for 802.11 wireless mesh networks, and used for designing user association scheme in [7]. Specifically, let R_s^i denote the link transmission rate between STA i and its associated AP s , the airtime cost of STA i denoted by c_s^i is defined as follows[7]:

$$c_s^i = \left[O_{ca} + O_p + \frac{B_t}{R_s^i}\right]\frac{1}{1-e_{pt}}, i \in A_s. \tag{1}$$

where O_{ca} is the channel access overhead, O_p is the protocol overhead, B_t is the number of bits in the test frame. For the IEEE 802.11b networks, these parameters are constant and given by: $O_{ca} + O_p = 1.25\text{ms}$ and $B_t = 8224\text{bits}$. e_{pt} is the frame error rate for the test frame size. Since the error rate is low, we omit it in our analysis.

The airtime of an AP s is defined as the aggregate airtime of all associated STAs, that is,

$$C_s(A_s) = \sum_{i\in A_s} c_s^i = \sum_{i\in A_s}\left[O_{ca} + O_p + \frac{B_t}{R_s^i}\right], \tag{2}$$

where A_s denotes the set of STAs associated with AP s.

It is proven in [7] that the airtime cost $C_s(A_s)$ is a good approximation of the uplink transmission delay of AP s under the ideal saturation condition whereby all STAs always have packets for transmission, and hidden node problem is not considered. Under this condition, all STAs have equal chance to access the channel, so the airtime of AP s is equal to the sum of the airtime costs of all associated stations.

However, Eq. (2) is valid for characterizing the transmission delay of AP s only if it is not contending with any other APs(e.g., it is not in the contention domain of any other APs, or it is operating on a channel not used by any APs). However, in a dense wireless network, since the number of orthogonal channels is limited, some neighboring APs have to share the same channel, thus leading to co-channel contention between these APs. In this paper, we assume that the network is dense enough so that all APs operating on the same channel can always hear each other, and the 802.11 protocol can effectively reduce the collision probability and alleviate the hidden terminal problem for the APs within the same contention domain. In this case, the transmission delay experienced by an AP depends not only on the number of users associated with it, but also the traffic load of its co-channel neighboring APs since it has to defer its transmission if the channel is occupied by its co-channel neighbors. Since all APs operating on the same channel q can hear each other, their transmission delays are essentially the same. Therefore, let $A(q)$ denote the set of APs operating on channel q, we can formally define the airtime $F(q)$ for channel q as follows:

$$F(q) = \sum_{s\in A(q)} C_s(A_s) = \sum_{s\in A(q)}\sum_{i\in A_s}\left[O_{ca} + O_p + \frac{B_t}{R_s^i}\right]. \tag{3}$$

That is, all APs on the same channel have the same airtime cost, and the congestion level of an AP can be measured by the airtime cost of its operating channel. In next section, we will propose a game theoretical approach to solve the channel assignment and user association problem for balancing the airtime cost between different channels.

III. Channel Assignment and User Association Game

In this section, we first model the channel assignment and user association problem as a non-cooperative game, then propose an algorithm to solve the problem, and finally we provide some theoretical results for the game.

A. Problem formulation

As shown in Eq. (3), the transmission delay experienced by a STA can be approximated by the aggregated airtime of all APs operating in the same channel. Therefore, in order to minimize the transmission delay suffered by STAs, the APs should compete and interact with each other to find the least congested channel, while the STAs should compete for the association with the APs, which can be naturally modeled as a non-cooperative *channel assignment and user association(CAUA)* game.

This *CAUA* game consists of two types of players: one is the AP player whose strategy is to find the least congested channel so that its airtime is minimized, the other is the STA player whose strategy is to associate with the least congested AP. For each AP, it can switch its channel if it can find a less congested channel. Mathematically, for an AP s who is currently operating on channel q, it can switch to channel p if the following *channel switching* condition is satisfied:

$$F(q) > F(p) + C_s(A_s), \forall p, q \in \mathcal{Q}. \quad (4)$$

Similarly, for a STA i associated with AP s, it can switch to AP t if the following *re-association* condition is satisfied:

$$F(CH(s)) > F(CH(t)) + C_t(A_t \cup \{i\}) - C_t(A_t). \quad (5)$$

where $CH(s)$ and $CH(t)$ are the channels of AP s and t respectively.

B. CAUA algorithm

We can design an algorithm for the *CAUA* game based on the *channel switching* and *re-association* conditions given by (4) and (5) respectively. We assume all APs are initially assigned with the same channel, and each STA is associated with the nearest AP. In order to guarantee that a Nash equilibrium can be achieved, the operation order of STAs and APs needs to be scheduled carefully. To this end, we propose an algorithm proceeding in round as shown in Algorithm 1, which consists of two phases in each round: the channel switching phase that involves only the operations of APs, and the re-association phase that involves only the operations of STAs.

In the *channel switching* phase, each AP tries to switch to a less congested channel to reduce its airtime cost. The algorithm starts by finding the channel with the maximum airtime cost, and the APs operating on this channel are the most congested ones. From these APs, we find some ones satisfying the channel switch condition given by (4), which can be switched to the less congested channels. By doing so, the airtime cost of the most congested channels can be reduced. To avoid fluctuation, only one AP is allowed to perform the switching operation in each time. If none of the APs on this channel satisfies (4), that means there is no benefit for anyone of these APs to change their channel. In this case, this most congested channel is denoted as *fixed*, which means that all APs on this channel will no longer participate in the channel switching operation in the rest of this phase. Then the next most congested channels are selected and the same operation is performed. This procedure is repeated until all channels are *fixed* and no AP can reduce its airtime by switching its channel, which marks the end of this phase.

The algorithm proceeds to the *re-association* phase after all APs have settled down on their channels. In this phase, each STAs tries to re-associate to other less congested APs if it satisfies the *re-association* condition given by (5). The procedure is similar to the *channel switching* phase, i.e., the algorithm starts from the most congested channel, and switches the qualified STAs to the less congested APs, which proceeds until none of the STAs is qualified for a move, which then ends this round.

Note that the operations in the *re-association* phase may break the equilibrium established in the *channel switching* phase, so the algorithm needs to perform these two phases of operations iteratively until the Nash equilibrium is finally approached. We will prove in next section that our algorithm can achieve the Nash equilibrium with at most $|\mathcal{Q}|$ rounds.

Algorithm 1: CAUA algorithm

```
FLAG = true;
while FLAG do
    H = ∅; /* H is the set of fixed channels*/
    FLAG = false;
    while H ≠ Q do
        /* channel switching phase */
        q_m ← argmax_{q∈Q\H} F(q), F_max ← F(q_m).
        Find AP and channel pair (a, p) such that
        (a, p) ← argmax_{a∈A(q_m), p∈Q\H} F_max − F(p) − C_a;
        if F_max − F(p) − C_a < 0 or (a, p) == ∅ then
            H = H ∪ q_m;
        else
            FLAG = true; H = ∅;
            AP a switches to channel p ;
        end
    end
    H = ∅;
    while H ≠ Q do
        /* re-association phase */
        q_m ← argmax_{q∈Q\H} F(q), F_max ← F(q_m).
        Find AP and STA pair (a, i) such that
        (a, i) ← argmax_{a∈A(q_m), p∈Q\H} F_max − F(CH(a)) − c_i^a;
        if F_max − F(CH(a)) − c_i^a < 0 or (a, i) == ∅
        then
            H = H ∪ q_m;
        else
            FLAG = true; H = ∅;
            STA i switches to AP a;
        end
    end
end
```

C. Nash equilibrium

Without loss of generality, let us assume that by the end of the first phase in the first round, the airtime costs of all channels are ordered as follows,

$$F(1) \leq F(2) \cdots \leq F(Q). \quad (6)$$

Let $a_{\min}$ denote the AP with the minimum airtime on the most congested channel, i.e.,

$$a_{\min} = \arg\min_{a \in A(Q)} C_a$$

Let $C_{min} = C(a_{min})$, then according to the channel switch condition (4) and re-association condition (5), the following condition should be satisfied by all channels:

$$F(Q) - F(q) \leq C_{\min}, \forall q \in \mathcal{Q}. \quad (7)$$

Let $F^*(q)$ denote the airtime cost of channel q at the end of the second phase in this round, and $C^*_{\min}$ denote the minimum

AP airtime cost on channel Q. Then for any channel $q \in \mathcal{Q}$, we have:

$$\begin{aligned} F^*(Q) - F^*(q) &\leq F^*(Q) - F(1) && (8)\\ &= F^*(Q) - F(Q) + F(Q) - F(1) \\ &\leq F^*(Q) - F(Q) + C_{\min} && (9)\\ &= (C_{\min} - C^*_{\min}) - (F(Q) - F^*(Q)) + C^*_{\min} && (10)\\ &\leq C^*_{\min} && (11)\end{aligned}$$

Eq. (8) holds because at the end of second phase, the airtime cost of any channel q will be no less than the airtime cost of the least congested channel(i.e., $F(1)$). Eq. (9) is valid following (7). In (10), the difference between $F(Q)$ and $F^*(Q)$ is no less than the difference between $C_{\min}$ and $C^*_{\min}$, which leads to (11).

As a result, we can see that at the end of the second phase, the APs on the most congested channel will no longer satisfy the channel switch condition (4). Therefore, the most congested channel is already fixed by the end of the first round, then the APs on this channel will not participate in the channel switching in the next round. Similarly, the next most congested channels will be fixed by the end of the second round. In this way, at least one channel will be fixed in each round, so the channel assignment of all APs will be done within at most Q round. Once the channel allocation is fixed for all APs, the re-association phase can be performed one more time for all STAs, but after that no more STAs will satisfy the re-association condition (5), which marks the end of the algorithm. Therefore, the Nash equilibrium is achieved with at most Q rounds.

D. Price of anarchy

We define τ as the *social cost* of the network, i.e., the total airtime cost of all channels. That is,

$$\tau = \sum_{u \in \mathcal{U}} c_u = \sum_{q \in \mathcal{Q}} F(q). \tag{12}$$

Let $N_a(q)$ denote the number of APs on channel q at Nash equilibrium(NE), then we have

$$C_{\min} \leq \frac{F_{nash}(Q)}{N_a(Q)}. \tag{13}$$

From (7), at NE we have

$$F_{nash}(1) \geq F_{nash}(Q) - C_{\min} \geq F_{nash}(Q) \times \left(1 - \frac{1}{N_a(Q)}\right). \tag{14}$$

Note that the minimum social cost τ_{opt} is achieved at the initial stage since all STAs are associated with the nearest APs(thus with the minimum airtime). Therefore, according to (4) and (5), we have

$$\tau_{opt} \geq F_{nash}(1) \cdot Q. \tag{15}$$

It is easy to see that the social cost τ_{nash} at NE satisfies $\tau_{nash} \leq F_{nash}(Q) \cdot Q$, so the price of anarchy is bounded by

$$\frac{\tau_{nash}}{\tau_{opt}} \leq \frac{F_{nash}(Q)}{F_{nash}(1)} \leq \frac{N_a(Q)}{N_a(Q) - 1}. \tag{16}$$

For the special case that $N_a(Q) = 1$, because $\tau_{opt} \geq F_{nash}(Q)$ and $\tau_{nash} \leq F_{nash}(Q) \cdot Q$, the price of anarchy is less than Q. In the dense wireless networking environment, this case is rare because many APs may share the same channel.

E. Fairness Index

To quantify the load-balancing effects of the *CAUA* game, we adopt the fairness index as introduced in [10], that is, $FI = \frac{(\sum_{q \in \mathcal{Q}} F(q))^2}{Q \sum_{q \in \mathcal{Q}} F^2(q)}$, which is a value between 0 and 1, and the maximum value of 1 is achieved if all channels have the same airtime cost.

We now derive the lower bound for the fairness index at NE. For any specific channel q, we have

$$F(q) \leq F(p) + c_{max}, \forall p, q \in \mathcal{Q}, \tag{17}$$

where c_{max} is the maximum airtime cost of STAs.

Summing (17) for all $p \in \mathcal{Q}$, we have

$$QF(q) \leq \sum_q F(p) + Q \cdot c_{max}. \tag{18}$$

Taking square for both sides of (18) yields

$$Q^2 F^2(q) \leq \left(\sum_p F(p)\right)^2 + 2Q \cdot c_{max} \sum_p F(p) + Q^2 \cdot c^2_{max}, \forall q. \tag{19}$$

Summing (19) over all $q \in \mathcal{Q}$, we have

$$Q \sum_q F(q)^2 \leq \left(\sum_p F(p)\right)^2 + 2Q \cdot c_{max} \sum_p F(p) + Q^2 \cdot c^2_{max} \tag{20}$$

By the definition of fairness index FI, we have

$$\sum_q F(q))^2 = \frac{(\sum_{q \in \mathcal{Q}} F(q))^2}{FI \cdot Q} \tag{21}$$

Dividing both sides of (20) with $\sum_{q \in \mathcal{Q}} F^2(q)$ and using (21), we have

$$1 \leq FI + \frac{2c_{max} Q \cdot FI}{c_{min} N} + \frac{c^2_{max} Q^2 \cdot FI}{c^2_{min} N^2} \tag{22}$$

where N is the total number of STAs, and c_{min} is the minimum airtime cost of STAs. Let $t = \frac{c_{max} \cdot Q}{c_{min} \cdot N}$, we have

$$FI \geq \frac{1}{1 + 2t + t^2}. \tag{23}$$

We can see that the fairness index is an increasing function of the number of STAs, which means the more STAs, the better the load balancing effect by the algorithm.

IV. Performance Evaluation

A. Simulation setup

In this section, we evaluate the performance of the *CAUA* algorithm. We consider a dense wireless network in a 500 $\times$ 500m rectangular area, where APs and STAs are distributed in two ways: (i) uniform distribution whereby the STAs are located randomly in the whole area, (ii) non-uniform distribution whereby half of the STAs are located in the middle 250mx250m rectangular area, and the remaining STAs are

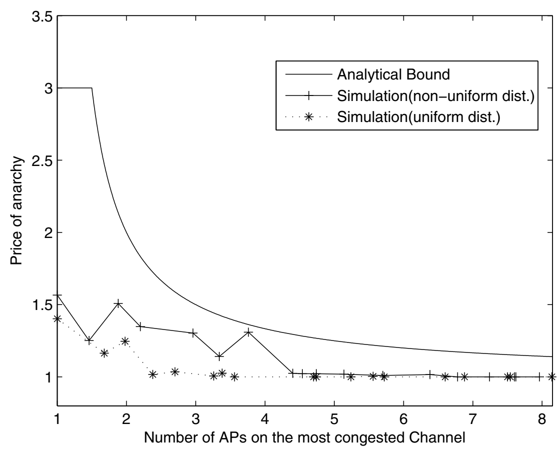

Fig. 1. Price of anarchy at NE

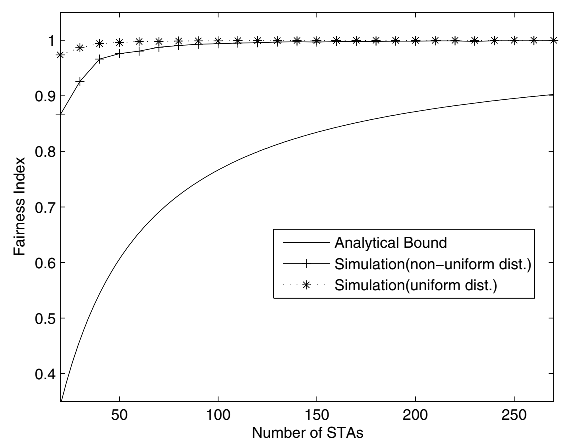

Fig. 2. Fairness Index at NE

randomly located in the whole area. We assume that there are 3 non-overlapping channels for APs. All APs are assumed to be able to sense the transmission of each other. The path loss exponent is set to 3.3 following [11]. The noise level is assumed to be constant and set to -94dBm. The transmission rate between an AP and a STA is a step function of the SNR of the link following the IEEE 802.11b protocol.

B. Simulation result

Fig. 1 shows the price of anarchy against the number of APs on the most congested channel for both the uniform and non-uniform distribution of STAs. The number of STAs is fixed to 100, while the number of APs varies from 3 to 20. The x-axes represents the average number of APs on the most congested channel in 50 simulation runs, while the y-axes is the maximum value of the price of anarchy in these 50 simulations. It can be seen that simulation results match well with the theoretical bound in general. The average value of price of anarchy is less than 1.2, which shows that the *CAUA* algorithm is very efficient.

Fig. 2 shows the fairness index against the number of the STAs. In this set of simulation, the number of APs is set to 10. The x-axes is the number of STAs, while the y-axes is the minimum fairness index in 50 simulation runs. We found that the fairness index obtained from the simulations is consistent with the analytical bound. Further more, it can be seen that when the number of STAs are more than 100, the fairness index obtained from the simulations is close to 1, which suggests that the *CAUA* algorithm has very good load balancing effect with more STAs.

V. CONCLUSION

In this paper, we propose a game theoretical approach for the channel assignment and user association problem in dense IEEE 802.11 wireless network. We prove the existence of Nash equilibrium of the game and show that the proposed algorithm can converge to the Nash equilibrium within a limited number of rounds. We also derive the theoretical bounds for the price of anarchy and fairness index at Nash equilibrium. Simulation results show that the proposed algorithm is efficient and provides good load balancing to different APs.

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