ABSTRACT

Interference in unlicensed band is a severe problem due to sharing of the limited spectrum resource and uncoordinated power transmission of wireless access points. To solve this problem, we aim for minimizing interference among Access Points’ coverage while preserving throughput fairness. We investigate this problem by modelling the spectrum sharing WLAN networks as a cooperative game. A bargaining game model is desirable in this frequently changing WLAN networking environment. Our solution is developed based on Nash Bargaining Solution, which can derive desirable properties such as Pareto Efficiency and proportional fairness. In this paper, we first derive the Nash Bargaining Solution for a 2-AP case and a 3-AP case. Then we provide a general solution for scenario with arbitrary number of APs. Simulation results show that the total networking throughput in maximum in the proposed scheme, compared with all other possible transmission power strategies. The interference between WLAN APs is minimal. Our work can lead to a cooperative spectrum sharing WLAN networking design with allocation fairness and optimal throughput performance.

I. INTRODUCTION

Recently, IEEE 802.11-based WiFi Access Points (APs) are widely deployed throughout the world. There are several citywide WiFi access deployment for municipal wireless access [3]. Using unlicensed wireless spectrum helps the fast-growing WiFi deployment. Nevertheless, un-coordinated WiFi access point deployment creates interference in the shared wireless spectrum. Interference between WiFi access points leads to inefficient network resource utilization and network QoS degradation.

In shared-spectrum wireless local area (WLAN) networks, the shared unlicensed wireless spectrum is the limiting factor of the network performance. Since all WLAN clients share the common spectral resource without paying, selfish WLAN clients might overly use this common resource [1]. This leads to the famous “the tragedy of the commons” phenomenon. We will apply bargaining solution in the context of cooperative game theory to resolve this resource sharing problem.

Cooperative communications [9] and cooperative networking design [10] could enhance overall network performance and increase communication efficiency. In this work, we investigate the cooperative networking techniques in the context of unlicensed WLAN networks using a shared wireless spectrum. The cooperative WLAN networking design is aimed for creating efficient power control and coverage control mechanisms between uncoordinated yet cooperative WLAN access points. We will apply bargaining theory [7] to model the behaviors between distributed wireless access points.

The wireless shared-spectrum problem has been investigated by Felegyhazi and Hubaux [2]. The power control problem between spectrum sharing wireless access points is formulated by a non-cooperative game. The Nash Equilibrium of the spectrum sharing game is studied. In certain Nash Equilibrium, wireless access points might be ‘knocked out’ (overpowered by neighboring access points), which leads to undesirable network operation scenarios.

The goal of our research work is to create a mechanism for access points to share the same spectrum with proportional fairness. To deal with this kind of multi-users problem, cooperative game theory is a good choice such that all access points (AP) can be treated as players, and the problem can be formulate into a game [4][5]. To reach a solution with desire properties, we will apply Nash Bargaining Solution (NBS) to solve this problem. Bargaining model is suitable for this problem because the spectrum resources is limited and wireless network changes frequently. APs should communicate to each other and get a new solution to reflect the scenario changes. In addition, NBS can achieve some fairness properties with proper bargaining rule design.
II. PROBLEM OVERVIEW

A. Overview

We consider a wireless network with multiple Access Points (APs) and Mobile Wireless Users (Users). We assume that each user can attach to any AP they like. To preserve a stable and faster link, user will attach to the AP with strongest signals. We also assume all APs use the same spectrum for communication. APs could transmit signals with power that is equal or less than the maximum allowable transmission power. When multiple APs locate in a geographical area, APs might interfere with each other. The interference degrades the performance of the spectrum-sharing wireless network. To enhance the network performance, APs will transmit at certain power level to extend the network coverage while limiting the interference.

B. System Model

To analyze our problem, we first consider an one-dimension space $S$. There is a total of $n$ APs, which are denoted as $A_1, A_2, ..., A_n$, with separation distances $l_1, l_2, l_3, ..., l(n-1)$ as shown in Figure 2. AP $A_i$ transmits with power $P_i$ to users within the transmission range of $r_i$. We also assume that wireless users are uniformly distributed over the space $S$. The users will choose to be served by the AP with the strongest radio signal. To make this model realistic, the following two constraints hold:

1. There is no uncovered area in $S$, all area is covered by at least one AP.
2. An AP’s transmission ranges is not greater than the distance to its nearest neighboring AP.

The first constraint is to guarantee that users can attach to at least one AP. If there are some users can’t attach to any AP, their neighbor APs will increase their power to reach the AP. The second constraint holds because APs do not increase transmission power when no extra users will be served by the AP. Assume we have two APs $A_i, A_j$ and an user $u$. $A_j$ is located between $A_i$ and $u$. It is almost impossible for $A_i$ to reach $u$ because $A_j$ can always provide stronger radio signal for $u$. Thus, we have the second constraint to avoid this scenario. These two constraints lead to the following equations:

$$
\frac{1}{2}(r_1 + r_u) + \sum_{k=2}^{n-1} r_k \geq \sum_{h=1}^{n-1} l_h \tag{1}
$$

$$
r_i \leq l_i, r_i \leq l_{i-1} \tag{2}
$$

As shown in Figure 3, an AP’s coverage area could be categorized as Non-Interference Area (NA) and and Interference Area (IA). In NA, users’ transmission won’t be interfered by neighbor APs, but not in IA. To define the utility function, we first define an interference coverage constant $\alpha$. We define $\alpha$ as the discount factor of interfered coverage to the non-interfered coverage. $\alpha$ value will be measured as the ratio of the expected user throughput in IA over the expected throughput in NA. We will use the overall coverage $c_i = NA_i + \alpha IA_i$ as the utility in our problem formulation.

III. NASH BARGAINING SOLUTION

Bargaining is an important concept in cooperative game theory. It involves dynamic bargaining procedure and discuss if there is a final deal or a breakdown. When a deal is made in the end, it means this game has a cooperative deal, and the problem it formulate has a cooperative solution. However, if it comes out with a breakdown, this problem won’t lead to cooperation. We will use Nash Axiomatic Bargaining Model[8] to derive the bargaining solution with desirable properties.

We denote the set of players in the bargaining game as $S = \{1, 2, ..., N\}$. Set $X$ represents all possible deals that the players in $S$ can make cooperatively. On the contrary, disagreement $D$ represents the breakdown point when players in $S$ don’t cooperate. An output set $U$ includes all possible outcome of players’ payoffs by utility function $u_1, u_2, ..., u_N$. We define $U$ as:

$$
U = \{(v_1, v_2, ..., v_N) | u_i(x) = v_i, i = 1 \sim N \forall x \in X \}
$$

For the disagreement D’s outcome, we set $d = (u_1(D), u_2(D), ..., u_N(D)) = (d_1, d_2, ..., d_N)$. Then we can define a bargaining problem $P(U, d)$. To apply Nash Bargaining Solution, this problem should have 4 properties:

1. $d \in U$
2. $\exists u = (v_1, v_2, ..., v_N) \in U, v_1 > d_1, v_2 > d_2, etc.$
3. $U$ is convex.
4. $U$ is bounded and closed.

The first and second properties are to make sure there is a deal $x \in X$ with payoff $u \in U$ larger than $d$. So this bargaining won’t breakdown. The third and fourth properties offers a Pareto Efficiency property for the bargaining solution. If above conditions are satisfied, it can be shown that there exists an unique NBS $x_n \in X$ for $P(U, d)$:

$$
u = (u_1(x_n), u_2(x_n), ..., u_N(x_n))
\max_{u_1, u_2, ..., u_N} \prod_{i=1}^{N} (u_i - d_i)
$$

$$
\tag{3}
$$
It has been proved that NBS satisfied 4 axioms:

1. Pareto efficiency (PAR)
2. Symmetry (SYM)
3. Invariance to equivalent payoff representations (INV)
4. Independence of irrelevant alternatives (IIA)

The first axiom PAR is the property we want to derive, and NBS guarantee this property. Our model can easily transform into Bargaining Model because the total coverage is less than a constant $\frac{1}{2} \sum_{k=1}^{n-1} l_k$. Each linear space $l_k$ is shared by $A_k$ and $A_{k+1}$. By using wireless signal, it is easy to design algorithm for them to bargain to each others and derive a deal. We can transform Nash axiomatic model into extensive game form to derive the procedure of bargaining. As a result, this model reduces the difficulties for implementation.

IV. Problem Formulation

Now let’s go back to our problem. In our model, the space is linear and is limited by APs’ distribution. We only consider the space between APs. For those APs, their main goal is to reach as many neighbor users as possible. But the transmission quality is in their concerns, too. Because users are uniformly distributed in the linear space, the larger their coverage, the more users they can connect. To maximize their coverage, AP will increase their radio range. But this also increase IA and will decrease their and overall wireless network throughput. So our goal is to find a optimal solution of each AP’s radio range in concerns of maximize coverage and decrease interference. Now we formulate the problem with our system model and Nash Axiomatic Bargaining Model. In this paper, we show a complete-information game. That means all information can be known by any players. First we define the n APs in our model as players in the bargaining game $P(U, d)$. For every player $A_i$, it has all information about all other players in the game and the distance $l_i, i = 1 \sim n - 1$. These information can be gathered by broadcast signals and stored a “database table” in the memory. The players’ bargaining methods is changing their radio range $r$. So we define deal space $X$:

$$X = \{ (r_1, r_2, ..., r_n) | 0 < r_i < max(l_i, l_{i-1}), r_i + r_{i+1} > l_i \}$$

If they can’t make a deal, the game goes breakdown. Every player will use their maximal power to transmit signal. We assume their signal power goes infinite, so we define $D = (\infty, \infty, \ldots, \infty)$. According to S and D, we define the players’ utility function $u_i$ for $A_i$:

$$u_i = c_i = NA_i + \alpha IA_i, i = 1, ..., n$$

Now we show how to calculate NA and IA between $A_1$ and $A_2$ with radio range $r_1$ and $r_2$ and distance $l$. Where $NA_1$ and $NA_2$ can directly derive from definition. To calculate IA, we first define the deciding point. For users on the left of the deciding point belongs to $A_1$, while on the right belongs to $A_2$. We place the deciding point by the ratio of radio ranges. So we divide the distance into two portion by ratio of $r_1$ and $r_2$. Our equations shows as follows.

$$u_1 = NA_1 + IA_1 = l - r_2 + \frac{r_1 + r_2 - l}{r_1 + r_2} r_2$$

$$u_2 = NA_2 + IA_2 = l - r_1 + \frac{r_1 + r_2 - l}{r_1 + r_2} r_1$$

We set the utility function $u_i$ as the coverage of $A_i$. The definition of coverage has concerns with the interference problem. We can see if NA transform into IA due to other player’s interference or the change of radio range, the outcome will decrease by a factor $\alpha$. This will move all players to increase NA while decrease IA. If all players use the same definition of utility function from above, it can be shown that this game has a Nash Bargaining Solution, which is Pareto Efficiency and with no Interference Area.

V. NBS for Spectrum Sharing WLAN Network

To solve this problem, we first discuss $n = 2$ and $n = 3$ cases. After these cases are fully solved and proved, we can move to general solution for arbitrary $n$ values.

A. Two-AP case

Assume there are only two APs $A_1$ and $A_2$. The distance between them is $l$. So their utility functions are:

$$u_1 = l - r_1 + \alpha \left( \frac{r_1 + r_2 - l}{r_1 + r_2} \right) r_2$$

$$u_2 = l - r_2 + \alpha \left( \frac{r_1 + r_2 - l}{r_1 + r_2} \right) r_1$$

Now we try to find out the relation between $r_1, r_2$ and $u_2$.

$$\Rightarrow r_2 = \frac{-\alpha r_1 l}{u_2 - l + r_1 - \alpha r_1} - r_1$$

$$l - u_2 < r_1 < \frac{l - u_2}{1 - \alpha} (r_2 \rightarrow \infty)$$

Then we can compute $u_i$’s maximum value.

$$u_1 = l - \alpha l + (l - u_2) + \frac{\alpha r_1 l}{r_1 (\alpha - 1) + l - u_2 (\alpha - 1)}$$

$$\frac{du_1}{dr_1} = \frac{(\alpha - 1) \alpha (l - u_2) (r_1 (\alpha - 1) + l - u_2 - \alpha r_1 l (\alpha - 1))}{(r_1 (\alpha - 1) + l - u_2)^2}$$

$$= \frac{(\alpha - 1) \alpha (l - u_2) (r_1 (\alpha - 1) + l - u_2)^2}{(r_1 (\alpha - 1) + l - u_2)^2} < 0$$

According to our model, we know that in the possible value range of $r_1$, $\frac{du_1}{dr_1} < 0 \Rightarrow u_1$ is maximum when $r_1$ is minimum $= l - u_2$. Thus, the solution space is bounded by $r_1 = l - u_2 = u_2 \Rightarrow u_1 + u_2 = l$, which is a straight negative slope. And according to our model, when the game goes breakdown, $D = (\infty, \infty)$. We can get the breaking point $d = (u_1(\infty), u_2(\infty)) = (\frac{\alpha l}{2}, \frac{\alpha l}{2})$, which is in the solution
space. So this problem fits Nash Bargaining Solution’s 4 properties, and there is a unique NBS:

\[(u_1 - \frac{\alpha_1}{2})(u_2 - \frac{\alpha_1}{2}) = C, u_1 + u_2 = 1\]

\[\Rightarrow u_2 = \frac{1}{2}, u_1 = \frac{1}{2}\] (10)

We can see that this solutions is Pareto Efficient and that no IA occurs.

**B. Three-AP case**

Now we assume there are 3 APs, 1, A_2, A_3 with distance l_1 and l_2 between them.

\[u_1 = l_1 - r_2 + \alpha\left(\frac{r_1 + r_2}{r_1 + r_2} - l\right)\] (11)

\[u_2 = l_1 - r_1 + \alpha\left(\frac{r_1 + r_2 - l}{r_1 + r_2}\right)\]

\[+ l_2 - r_3 + \alpha\left(\frac{r_3 + r_2 - l}{r_3 + r_2}\right)\] (12)

\[u_3 = l_2 - r_2 + \alpha\left(\frac{r_3 + r_2 - l}{r_3 + r_2}\right)\] (13)

We assume u_1 and u_3 are constant to derive the relation between r_1, r_2, r_3 and u_2:

\[u_2 = (l_1 + l_2)(2 - \alpha) + 2r_2(\alpha - 1) - u_1 + u_3\]

\[+ (\alpha - 1)\left(\frac{2r_2}{r_2(\alpha - 1) + l_1 - u_1} - r_2\right)\]

\[+ (\frac{2r_2}{r_2(\alpha - 1) + l_2 - u_3} - r_2)\] (14)

Now we try to find r_2 to maximize u_2:

\[\frac{du_2}{dr_2} = 4(\alpha - 1)^2(l_1 - u_1)(l_2 - u_3)(l_1 + l_2)\]

\[(-l_1(l_1 - u_1)^2 - l_2(l_2 - u_3)^2) < 0\] (15)

Thus, u_2 is maximum when r_2 is minimum based. It can be shown from 2 APs case that when r_1, r_3 are minimum, their utility will reach maximum value. So we can get a solution space bounded by u_1 + u_2 = l_1 and u_2 + u_3 = l_2. This is a flat plane in U. We calculate the breaking point \(d = \left(\frac{\alpha_1}{2}, \frac{\alpha_1 + \alpha_2}{2}, \frac{\alpha_2}{2}\right)\), which is in the solution space, so this case has a Nash Bargaining Solution:

\[C = (u_1 - \frac{l_1}{2})(u_2 - \frac{l_1 + l_2}{2})(u_3 - \frac{l_2}{2})\]

\[l_1 = r_1 + r_2 = u_1 + \frac{u_2}{2}\]

\[l_2 = r_2 + r_3 = u_3 + \frac{u_2}{2}\]

\[\Rightarrow u_2 = \frac{1}{3}(l_1 + l_2)(2 - \frac{\alpha}{2})\]

\[-\sqrt{(l_1 + l_2)^2(\frac{\alpha_1}{4} - 5\alpha + 4) + 2l_1l_2(1 - \frac{\alpha}{2})^2}\] (16)

\[u_1 = l_1 - \frac{u_2}{2}\] (17)

\[u_3 = l_2 - \frac{u_2}{2}\] (18)

**C. General Case**

According to 2-AP and 3-AP solutions, we can derive a general solution for \(n > 3\) case:

\[r_i + r_{i+1} = l_i, i = 1 \sim n - 1\] (19)

\[u_i = \left\{\begin{array}{ll}
2r_i, & 1 < i < n \\
r_i, & i = 1 \text{ or } n
\end{array}\right.\] (20)

\[d_i = \left\{\begin{array}{ll}
\frac{2}{3}(l_i + l_{i-1}), & 1 < i < n \\
\frac{2}{3}(l_i), & i = 1 \text{ or } i = n
\end{array}\right.\] (21)

\[C = \prod_{i=1}^{n}(u_i - d_i)\] (22)

Similar to the previous cases, we could readily derive the NBS for general cases by solving these equations.

**VI. PERFORMANCE EVALUATION**

**A. Simulation Setting**

We use NS-2.29[6] for performance evaluation. In our simulation topology, there are three APs which locate at 10, 250, 450. WLAN users are uniformly distributed between APs. There are 22 WLAN users receiving data from APs, which locate at 20, 40, 60, 80, ..., 420, and 440. For every WLAN user, we decide which AP a user attaches to based on the receiving signal power strength. If there exist more than one signal in MS’ position, it choose the AP with stronger received signal power. In our simulation, each AP sends constant-bit-rate UDP traffic with 500-byte packet every 0.02 second to each MS. IEEE 802.11 is used for wireless MAC. Two-ray-ground model is used for radio propagation. Except the AP transmission power values, NS-2 default parameters are used throughout the simulations. After the simulation, we will analyze and compute the total throughput of three APs from trace files. The total throughput represents the performance of this wireless network.

**B. Simulation Results**

To examine the network performance in the proposed NBS solution point, we fix r_2 as the NBS value and adjust r_1 and r_3 to measure the total throughput as shown in Figure 4. The result
Although the proposed Nash Bargaining Solution computation is based on the abstract mathematical formulation, the simulation results show that our solution indeed enhances overall network performance with IEEE 802.11 APs with practical network parameter settings.

VII. CONCLUSION

In this paper, we investigated the cooperative shared-spectrum WLAN networks with cooperative game theory. We built a bargaining model by Nash Axiomatic Model for selfish WLAN APs. To reach a solution with Pareto Efficiency, we apply Nash Bargaining Solution to find the solution with desirable properties. WLAN APs control their respective transmission range for maximal service coverage. We derived a general bargaining solution to maximize the WLAN AP coverage while limiting the interference. Although all APs try to maximize their own coverage, we proved that our solution makes the WLAN network with no interference area between APs. And our solution had Pareto Efficiency and Proportional Fairness. These property could enhance the overall network performance in theory. We also demonstrated that the solution can achieve the maximum overall throughput. 

REFERENCES