Energy Efficient Topology Control for WLANS

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Abstract – Wireless LANs employing the IEEE 802.11a/b/g/n standard operate in the unlicensed frequency bands. Their deployment has seen an exponential growth since their introduction. It is very common to find a wireless LAN in most buildings and houses around the world. These infrastructure-based WLANs are deployed to meet certain connectivity requirements and are usually deployed randomly. This random deployment has made the networks to be collectively unmanaged leading to the existence of larger interference areas. Power is lost because the access points usually operate with their factory default configurations that use the maximum authorized power level. This leads the access points to cover an area beyond required leading to the formation of larger interference areas that affects the performance of the networks. In this paper we study the power control problem in these networks using computation geometry and coalition formation game theory. We first analyze a coalition formation game between two neighboring access points for transmit power optimization. Then we set the requirements for other access points to join the coalition and investigate if a stable coalition can be formed. We finally show that by forming a coalition of up to five access points an optimal radio range assignment scheme exists that minimizes the total transmit power in the network substantially while meeting the requirements of network coverage.

Keywords – coalitional game, power control, core, utility, payoff, Voronoi diagram

I. INTRODUCTION

Mobile nodes in infrastructure-based WLANs communicate with network resources on wired LANs via wireless access points that serve a given service area and are connected to the wired LAN using Ethernet or similar technology. It is very common to find these networks in most buildings and homes around the world. Some of these networks are designed carefully to cover a given service area and to minimize the interference area. But most of the networks are deployed randomly and use the factory default configuration with the maximum authorized transmission power level. This random deployment forces the access point to cover a service area than required creating larger interference areas that affects the performance of the networks negatively. The cross-layer design in WLAN systems is discussed in [16]

One of the major components of a wireless network design is the assignment of coverage areas and hence radio ranges to the access points. These assignments signify the transmit power level usage of the access points. In this paper we focus on the assignment of coverage areas and radio ranges (and hence the transmit power levels) for access point devices in an infrastructure-based wireless LANs. We employ the coalition formation game from economics to analyze our power control problem.

Game theory is used to study power control of user devices in wireless networks, notably in cellular systems as studied in [4], [5], [7] and [14]. Game theory is also used to study cooperation in wireless ad-hoc networks, for example in [6], [8] and [12]. The authors in [13] have used computational geometry and linear programming to address the problem of power control in spontaneously deployed wireless networks. In [3] the authors have studied the power control by base stations in a cellular network in a shared media using computational geometry and competitive game theory framework.

In this paper we are proposing that a significant amount of transmit power can be saved if access points in a WLAN employ different (rather than the same) radio ranges. We show that the reduction in transmit power does not affect the coverage of the service area. We use computational geometry and coalition formation game theory to analyze the power control problem in these networks. We also demonstrate the efficiency of our radio range assignment scheme using simulation work.

This paper is organized in the following manner. In Section II we describe the system model. In Section III we outline the corresponding coalition formation power control game and solve this game for first two and then for N randomly deployed access points. Section III also presents fairness considerations for the coalition formed. Section IV concludes our paper.

II. SYSTEM MODEL

We consider a wireless network where the access points, hereafter called base stations (BS-s), are deployed randomly in a two dimensional plane. We further assume that the BS-s are operated by different operators that are willing to cooperate for the purpose of power saving. We call the operator operating BS b_i O_i. We denote the union of all BS-s by B. There exists no BS-s that belongs to different operators located at the same location. We also assume several users

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equipped with WLAN access devices to access the communication network.

Base stations and mobile devices operate in the same unlicensed frequency band. Each of these devices might perform power control but in our paper we focus on the downlink power control of the transmit signal of the BS-s, i.e., BS to mobile devices.

According to the physical model of signal propagation [10], the transmit power of a base station $b_i \in B$ can be received by a user device u if its signal-to-interference-noise ratio (SINR) exceeds a reception threshold β:

$$\frac{P_i g_{iu}}{N_0 + \sum_{j\in B, j\neq i} P_j g_{ju}} \geq \beta \qquad (1)$$

Where P_i is the transmission power of BS b_i, g_{iu} is the channel gain between the BS b_i and the user device u and N_0 is the Gaussian thermal noise. We assume the channel gain depends only on the distance of the transmitter and the receiver and we normalize the effect of the antenna characteristics, thus we have $g_{iu} = d_{iu}^{-\alpha}$ between the BS b_i and user device u, where $2 \leq \alpha \leq 5$ is the path loss exponent that characterizes the radio signal propagation properties of the environment. Equation (1) captures how the reception power depends on the most important factors, namely on the transmission power and the distance between transmitter and receiver. Note that we considered the local average of the received signal but in reality, on a small time scale, the transmit power signals have a time-varying property due to fading.

We assume that (1) holds for every point in the service area for at least one base station and that the user device u attaches to the base station b_i with the best SINR. Thus, we can write, for any other base station b_l, that:

$$\frac{P_i d_{iu}^{-\propto}}{N_0 + \sum_{j\in B, j\neq i} P_j d_{iu}^{-\propto}} \geq \frac{P_l d_{lu}^{-\propto}}{N_0 + \sum_{m\in B, m\neq l} P_m d_{mu}^{-\propto}} \qquad (2)$$

We abstract away the end users and assume that their expected position is uniformly distributed over the service area. Note that this also means a balanced load on the base stations (i.e., no users have to switch base stations due to the lack of available bandwidth). This is an ideal assumption and we leave the unbalanced scenarios for future research.

Let us assume that the transmit signals propagate in an almost open area, meaning α = 2. Then (2) defines a multiplicatively weighted power diagram [9], which determines the set of points in the service area (potential places of user devices) that are attached to a given base station. The Voronoi diagram with multiplicatively weighted distances has a complex shape and is generally difficult to derive analytical solution for the power control problem. Hence, we apply a radio range model that is simpler and widely used in the literature. An example of this approach can be found in [3].

Let us derive from (1) the radio range of the transmit signal of the BS b_i as the Euclidian distance within the users are able to attach to this base station if there is no interference from other devices. This is usually the case when the network employs the Distributed Coordination Function (DCF).

$$r_i = \sqrt[\propto]{\frac{P_i}{\beta N_0}} \qquad (3)$$

According to this radio range model, we can define the additively weighted power distance as:

$$\mathrm{pow}(u, b_i : w_i) = d_{iu}^2 - w_i \qquad (4)$$

Where d_{iu} is the Euclidian distance between the points u and b_i and w_i is a weight assigned to point b_i.

We can now define the Voronoi region $V(b_i)$ around a base station $b_i \in B$ as the set of points u that are "closer" to point b_i than to any other point b_j (i.e., $i \neq j$). Hence, we can write $V(b_i)$ as:

$$V(b_i) = \{u | \mathrm{pow}(u, b_i : w_i) \leq \mathrm{pow}(u, b_j : w_j) \text{ for } i \neq j\} \qquad (5)$$

We can write the Voronoi diagram V(B) of all BS-s in B as:

$$V(B) = \cup V(b_i) \qquad (6)$$

In this paper, we substitute $w_i = r_i^2$ and hence we obtain a Voronoi diagram in the Laguerre geometry [9]. This model corresponds to a Voronoi diagram, where the distance is defined as a tangential Euclidean distance to circles centered at the base stations' locations and radii corresponding to their radio ranges.

In the analyses of the power control problem the following assumptions are used in order to simplify our model.

- No place should remain uncovered in the service area (full coverage).
- There exists a limitation on the maximum transmission power of any base station which is defined by the standards of the wireless LAN technology. We call the radio range associated with this maximum power R_{max}. This also goes for the minimum power with radio range R_{min}.
- The base stations and the user devices have omni-directional antennae.

Note that the assumptions and constraints of the signal and channel model are idealized. however for typical LAN settings with line-of-sight, they capture the most important physical parameters.

III. COALITION FORMATION POWER CONTROL GAME

Consider a number of BS-s in a two-dimensional plane. Assume that there exists a BS at the middle of all the other BS-s. This BS is the one that has the minimum sum distance to the others. Let us call the middle BS b_0. And let us call this BS with the shortest distance from b_0 with distance d_1 BS b_1. We construct our coordinate system with the x-axis along the line segment $\overline{b_0 b_1}$ and the y-axis perpendicular to this line. BS b_0 is assigned the coordinates (0,0) and b_1 is assigned the coordinates $(d_1,0)$ as shown in Figure 1.

We model the power control problem as a coalition formation game between the BS-s in the plane as players. The strategy of the coalition is to assign coverage areas and hence radio ranges to the BS-s that minimizes the total transmit power in the network while covering the required service area. The coalition should also divide the value of the coalition fairly such that a stable coalition is formed. It can achieve this by assigning the same or different coverage areas (and radio ranges) to its members.

In this paper we assume the general case where the coalition chooses to assign different radio ranges for its members. We first analyze the case of two BS-s, b_0 and b_1, with the minimum separation distance d_1 forming a coalition. We then analyze the situation where other BS-s, with greater distance from b_0, join the coalition and investigate if a stable and fair coalition can be forced that minimizes the total transmit power in the network.

A. TWO BASE STATIONS CASE

Consider two BS-s b_0 and b_1 with radio ranges r_0 and $r_1 > r_0$. Figure 1 shows the coverage areas and the radio range assignment of the two BS-s. The parameters p_1 and q_1 are given by:

$$q_1 = \frac{d_1}{2} - \frac{r_1^2 - r_0^2}{2d_1} = \frac{r_0}{\sqrt{2}} \ \ and \ p_1 + q_1 = d_1 \qquad (7)$$

The coverage areas of the BS-s are given as:

$$A_0 = 4q_1^2 = 2r_0^2 = \frac{[d_1^2 - (r_1^2 - r_0^2)]^2}{d_1^2} \qquad (8)$$

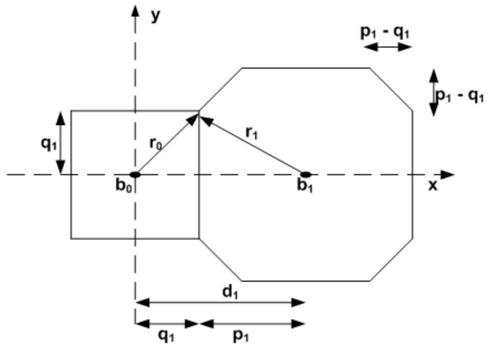

Fig. 1. Coverage areas of the two base stations

$$A_1 = 2(p_1 + q_1)^2 - 4q_1^2 = 2d_1^2 - 2r_0^2 = \frac{d^4 + 2d^2(r_1^2 - r_0^2) - (r_1^2 - r_0^2)^2}{d^2} \qquad (9)$$

Note that the total area covered by the two base stations is equal to $2d_1^2$.

From the geometry of Figure 1, we note that

$$r_1^2 - r_0^2 = d_1^2 - \sqrt{2} d_1 r_0 \qquad (10)$$

Maximizing the coverage area of BS b_1 minimizes the coverage area of BS b_0. But the coalition should ensure that b_0 is assigned a fair allocation of the coalition value. In this paper we particularly use the game in characteristic form with transferable utility (TU) theory from economics. Please refer to [17] and reference therein.

Definition 1: - A *coalitional game with TU*, (N, v) consists of

- A finite set N (the set of players)
- A characteristic function v that associates with every non empty subset B of N (a coalition) a real number v(B) – the worth of B.

For each coalition B the number v(B) is the payoff that is available for division among the members of B. Due to the TU assumption v(B) can be divided among the members of the coalition. Fairness in allocation is required to maintain the coalition.

The core of a coalition game is analogous to the Nash equilibrium of a non-cooperative game: an outcome is stable if no deviation is profitable. In the case of the core, an outcome is stable if no coalition can deviate and obtain an outcome better for all its members. Players will join a coalition only if they obtain better utility than staying alone (see individual rationality defined below).

Definition 2: - A coalition game (N, v) with TU is said to be *superadditive* if for any two disjoint coalitions B_1, $B_2 \subset N$

$$v(B_1 \cup B_2) \geq v(B_1) + v(B_2) \quad (11)$$

If the superadditivity property holds for all the coalitions, then we say that the Grand coalition, the coalition that contains all the players, can form. i.e., a split of values of the grand coalition can be found such that all players get larger utility than in any other coalition including the single player coalition.

Definition 3: - A payoff vector $y=[y_1,\ldots,y_N]$ is said to be *group rational* or *efficient* if $\sum_{i=1}^{N} y_i = v(N)$. A payoff vector y is said to be *individually rational* if the player can obtain the benefit no less than acting alone, i.e., $y_i \geq v(\{i\})$. A group rational or efficient payoff vector is also referred to as a feasible payoff profile. An *imputation* is a payoff vector satisfying the above two conditions.

The set S of stable imputations is called the Core, i.e.,

$$S = \{y: \sum_{i \in N} y_i = v(N) \text{ and } \sum_{i \in B} y_i \geq v(B)\ \forall B \subset N\} \quad (12)$$

A non-empty core means that the players have an incentive to form the Grand coalition for all payoff vectors in the core.

In coalition formation games network structure and cost for cooperation play a major role [11]. An important characteristic, which classifies a game as a coalition formation game, is the presence of a cost for forming coalitions. In this paper, we propose a coalition formation game with TU with a payoff for each BS defined as a function of the coverage area, A_i, as

$$y_i = h(A_i) - C(A_i), \qquad i = 1,2 \quad (13)$$

Where $h(A_i)$ is the sigmoid function. The sigmoid function used in this paper, see Figure 2, is defined as

$$h(A_i) = \frac{1}{1 + e^{-a(A_i - b)}} \quad (14)$$

Which has been widely used in the analysis of neural networks. Clearly h(b)=1/2, so we call b the center of h(A). The parameter *a* defines the steepness of h(A). The derivative of h(A) satisfies

$$h'(A) = a h(A)[1 - h(A)] \quad (15)$$

The sigmoid function has a convex and concave part and it captures the allocation of the coverage areas quite naturally. Therefore, we use the sigmoid function as the utility covering an area A.

$C(A_i)$ is the cost associated with covering an area of A_i. There are at least two requirements for the cost function: C(0) = 0 and C(A) should increase in the coverage area. In this paper we will use a linear function defined as:

$$C(A_i) = \frac{cA_i}{d_1^2} \quad (16)$$

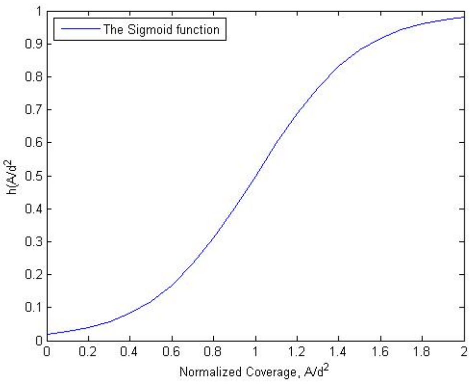

Fig. 2 – The Sigmoid Function

where c is the price coefficient and d_1 is the Euclidean distance between the two BS-s.

In this paper we use the value $\frac{a}{d_1^2}$ instead for the steepness parameter of the sigmoid function. If both base stations are to cover equal areas then they will cover an area of d_1^2 each. This was also shown in [3] as a Nash equilibrium for BS in a cellular network. Hence we will use the value of $b = d_1^2$ for the center parameter of the sigmoid function.

The values of *a* and c are constants and are set by the coalition. The constants are strictly non-zero positive real numbers.

The goal of forming the coalition is to minimize the total transmit power by the base stations while covering the entire service area. In order to achieve its goal, the coalition might assign BS b_1 coverage area in the concave part of the sigmoid function while that of BS b_0 will be assigned a coverage area in the convex part. In doing so the coalition should assign a payoff for both base stations efficiently. That means the allocation of the coalition value should be fair.

Taking the derivative of the payoff with respect to the coverage area yields

$$h(A_i) = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{c}{a}} \quad (17)$$

One necessary condition is that $a \geq 4c$. Based on their coverage areas, we assign the higher value for BS b_1 while the lower value will be assigned to BS b_0. Note that the higher value of equation (18) is in the concave part of the sigmoid function while the lower value is in the convex part. Hence, we assign the following values for the two BS-s:

$$h(A_1) = \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{c}{a}} = K \quad (18)$$

$$h(A_0) = \frac{1}{2} - \sqrt{\frac{1}{4} - \frac{c}{a}} = 1 - K \quad (19)$$

Note that $h(A_1) + h(A_0) = 1$. Also note that $½ \leq K \leq 1$ and $K \to 1$ as $a \to \infty$. Using any of the two equations (18) or (19) lead to the same result. Hence let us take equation (18) of the BS b_1. We can easily show that

$$A_1 = d_1^2 + \frac{d_1^2}{a} \ln\left(\frac{K}{1-K}\right) = d_1^2 + d_1^2 z \quad (20)$$

where

$$z = \frac{\ln\left(\frac{K}{1-K}\right)}{a}. \quad (21)$$

Note that $0 \leq z \leq 1$ and $z \to 1$ as $a \to \infty$. Since z is a function of c and a, it is also a coalition parameter.

Solving for r_0 and r_1 using (9) and (10), we find that

$$r_0^2 = \frac{d_1^2}{2}(1 - z) \quad (22)$$

And

$$r_1^2 = \frac{d_1^2}{2}\left(1 + \left(1 - \sqrt{1 - z}\right)^2\right) \quad (23)$$

We will determine the value of the coalition parameter z so that the total transmit power in the network is minimized. This will be determined in the next section.

B. N Base Stations Case

Consider a number of BS-s including b_0 and b_1 deployed randomly in the two-dimensional plane as shown in figure 3. We assume that the beacon signal of each BS can be received by BS b_0. Given the received power level of the beacon signal and the transmit power BS b_0 is able to measure the distance of each BS from itself. The angles can be measured using the cosine law once the distances between successive BS-s is available to BS b_0. Such a coordinate system can be constructed according to [15]. We assume that all angles are positive. We require that $d_i > d_1$, for all i, for any BS b_i to join the coalition. In order to make sure that the minimum distance between any two BS-s is greater that d1, we require that the angles and distances between BS-s satisfy the following inequalities.

$$d_{ij}^2 = d_i^2 + d_j^2 - 2d_i d_j \cos(\beta_{ij}) \geq Max(d_i^2, d_j^2) \quad (24)$$

Where d_{ij} is the distance between any two neighboring BS-s b_i and b_j and $d_i(d_j)$ is the distance of BS b_i (b_j) from BS b_0.

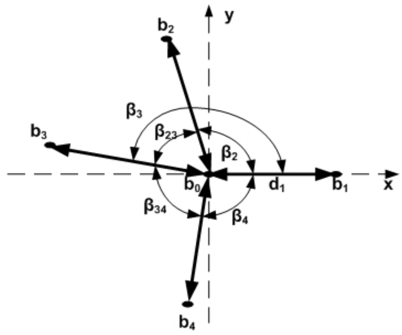

Fig. 3 – Randomly Deployed BS-s

Assuming that $d_j > d_i$, for d_1 to be the minimum distance in the network we require that the angle β_{ij} should satisfy

$$cos(\beta_{ij}) \leq \frac{d_i}{2d_j} \quad (25)$$

If all BS-s have equal distance from BS b_0 (i.e., $d_i = d_1$, for all i) then $\beta_{ij} \geq 60^0$. Taking equality suggests that we can have up to 6 BS-s around BS b_0 and the BS-s are found on a circle of radius d_1 with an angle of 60^0 between two successive BS-s. This is not usually the case in practice since one of the distances deviate from equality with a high probability.

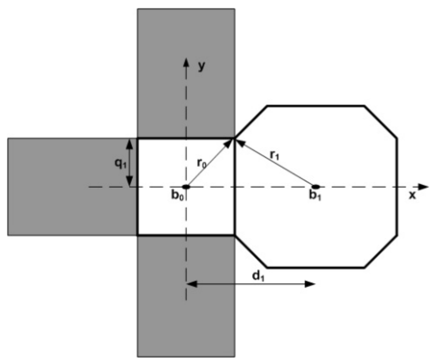

Fig. 4 – Region BS-s are to be deployed

We further require that only BS-s located in the shaded region of Figure 4 can join the coalition. This restricts the maximum BS-s in the network to five. In Figure 3, $\beta_i = angle(b_i b_0 b_1)$ can be calculated if BS b_i's beacon signal can be received by BS-s b_0 and b_1 as

$$\cos(\beta_i) = \frac{d_{i1}^2 - d_i^2 - d_1^2}{2 d_i d_1} \qquad (26)$$

Note that $d_{i1} \geq d_i \geq d_1$. If the beacon signal of bi cannot be received by b_1 then it must be received another neighboring BS b_j so that the angle can be calculated by BS b_0 as $\beta_j = \beta_{ij} + \beta_j$. If the beacon signal of BS b_i cannot be received by any other BS (except b_0) then BS b_i will not be a member of the coalition.

A BS that does not meet the requirements will not be a member of this coalition but can form another coalition with other similar BS-s or can operate independently using a different frequency channel to avoid interference with the coalition members. Note that the wireless LAN standards define a number of non-overlapping frequency channels in the unlicensed frequency band. For example IEEE 802.11 b/g defines three non-overlapping frequency channels [2].

We put the requirement that only BS-s found in the shaded region with distances from BS b_0 equal to $d_i > d_1$ join the coalition formed in the previous section so that we can have a well defined coverage areas for the BS-s in the wireless network. With the requirements met, we assign coverage areas for the BS-s in the coalition as shown in Figure 5. In Figure 5 the parameters necessary to define the coverage areas of the BS-s are given as (for i=2, …, N-1).

$$M_i = Max\{|\sin(\beta_i)|, |\cos(\beta_i)|\}$$

$$L_i = Min\{|\sin(\beta_i)|, |\cos(\beta_i)|\} \qquad (27)$$

In Figure 5, the parameters p_i and q_i are defined as

$$p_i = d_i M_i - {r_0}/{\sqrt{2}}$$

$$q_i = d_i L_i + {r_0}/{\sqrt{2}} \qquad (28)$$

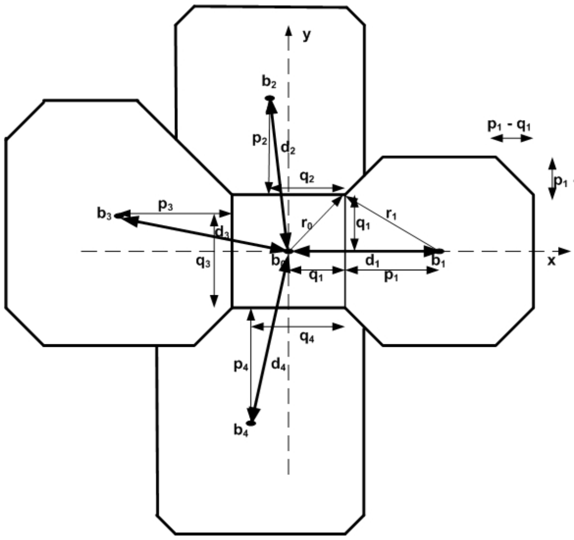

Fig. 5 –Coverage areas of the BS-s

Note that M_1=1 and L_1=0 for BS b_1 so that the values of p_1 and q_1 in the previous section (for BS-s b_0 and b_1) are intact. With these parameters defined the minimum coverage areas of the BS-s are given by (the coverage areas of BS-s b_0 and b_1 are just like in the previous section)

$$A_i = 2(p_i + q_i)^2 - 4q_i^2 - \frac{1}{2}[(p_i + q_i - \sqrt{2}r_0)^2 - (p_i - q_i)^2]$$

$$= 2d_i^2 - 2r_0^2 - 2d_i L_i[\sqrt{2}r_0 - d_i(M_i - 2L_i)] \qquad (29)$$

Note that when $L_i = 0$ and $M_i = 1$, i.e., when all the BS-s are along the coordinate axis, the coverage area will reduce to $A_i = 2d_i^2 - 2r_0^2$. In general it holds $A_i \leq 2d_i^2 - 2r_0^2 = 2d_i^2 - A_0$.

For the BS-s joining the coalition to remain in the shaded region of figure 4, we require that $q_i \leq \sqrt{2}r_0$. That is

$$d_i L_i \leq \frac{r_0}{\sqrt{2}} \qquad (30)$$

For the BS-s to have a coverage area greater than that of BS b_0's, we require that $p_i > q_i$, i.e., (note that $M_i - L_i \leq 1$)

$$\frac{\sqrt{2}r_0}{d_i} < M_i - L_i \leq 1 \qquad (31)$$

Note that $d_i > \sqrt{2}r_0$, for all i is implied in (31).

From the geometry of Figure 5, the minimum radio range required to enclose the coverage area of BS b_i is given by

$$r_i^2 = p_i^2 + q_i^2 = d_i^2 + r_0^2 - \sqrt{2}d_i r_0(M_i - L_i) \qquad (32)$$

BS b_0 has the minimum radio range and coverage area. If there are less than 5 BS-s some mobile nodes that were associated with BS b_0 might not be covered. To solve this situation BS b_0 could put a minimum required radio range that enables the uncovered nodes to be covered.

The radio ranges defined in (32) are given in terms of the coalition parameter z defined in the previous section as, see (22)

$$r_i^2 = d_i^2 + \frac{d_1^2}{2} - d_1^2\left[{}^{z}/_{2} + ({}^{d_i}/_{d_1})(M_i - L_i)\sqrt{1-z}\right] \quad (33)$$

In accordance with our system model, transmit power is proportional to the square of the radio range. Hence the total transmit power by the N BS-s in the network can be expressed as (normalizing the effects of antenna gains and frequency parameters):

$$P_T = r_0^2 + \sum_{i=1}^{N-1} r_i^2$$

$$P_T = \sum_{i=1}^{N-1} d_i^2 + \frac{Nd_1^2}{2} - d_1^2 f(z) \qquad (34)$$

where

$$f(z) = \frac{Nz}{2} + \sqrt{1-z}\sum_{i=1}^{N-1}\frac{d_i}{d_1}(M_i - L_i) \qquad (35)$$

Maximizing f(z) minimizes the total transmit power P_T. The value of z that minimizes f(z) is obtained by setting $\frac{df(z)}{dz} = 0$. It is easy to show that the optimum value of z is given by

$$z_{opt} = 1 - \left[\frac{\sum_{i=1}^{N-1} d_i(M_i - L_i)}{Nd_1}\right]^2 \qquad (36)$$

The associated minimum total transmit power is give by

$$P_{min} = \sum_{i=1}^{N-1} d_i^2 - \frac{1}{2N}\left[\sum_{i=1}^{N-1} d_i(M_i - L_i)\right]^2 \qquad (37)$$

Since $0 \le z \le 1$, we require that the minimum distance d_1 should satisfy the inequality given by

$$d_1 \ge \frac{1}{N-1}\sum_{i=2}^{N-1} d_i\,(M_i - L_i) \qquad (38a)$$

From $d_i > \sqrt{2}r_0$ (see (31)), we generally require that

$$d_i \ge \frac{1}{N-1}\sum_{j=1, j\ne i}^{N-1} d_j\,(M_j - L_j) \qquad (38b)$$

If all BS-s transmit use the maximum authorized power level that corresponds to a radio range of R_{max} ($R_{max} \ge d_i$, for all i), the total transmit power in the network will be NR_{max}^2which is significantly greater than the P_{min} in (37). Hence our proposed radio range assignment offers a substantial power saving while ensuring that the coverage area in figure 5 remains intact. For example if all BS-s use a radio range equal to Max{d_i}, a power greater than $d_1^2 + \frac{1}{2N}[\sum_{i=1}^{N-1} d_i(M_i - L_i)]^2$ is saved.

Fairness Considerations

In order for the coalition formation game to have a stable core, each member of the coalition should get a payoff that is individually rational (See Definition 3). That is each member should get a payoff at least equal to the one it gets if it operates alone. The payoff of each member of the coalition is given by:

$$y_0 = \frac{1}{1 + e^{\frac{-a}{d_1^2}(A_0 - d_1^2)}} - \frac{c}{d_1^2}A_0 \qquad (39)$$

For $i = 1, \dots, N-1$

$$y_i = \frac{1}{1+e^{\frac{-a}{d_i^2}(A_0 - d_i^2)}} - \frac{c}{d_i^2}A_i \qquad (40)$$

Where A_i is the optimum coverage area of BS b_i and d_i is its distance from BS b_0. Note that for BS b_0, d_1 is taken as the distance.

If the BS-s operate independently and simultaneously using the maximum authorized radio range, their coverage area is roughly equal to d_i^2 (see Equations 7 and 8). Hence the payoff of each BS operating independently is equal to (½) - c. Hence for the coalition to be individually rational, the following condition must be satisfied when selecting the coalition parameters *a* and c.

$$y_i \ge \frac{1}{2} - c, for\ i = 0, \dots, N-1 \qquad (41)$$

This requirement yields the inequality equation (for $i = 0, \dots, N-1$)

$$c \le \frac{d_i^2}{2}\frac{\tanh\left[\frac{a}{2d_i^2}(A_i - d_i^2)\right]}{(A_i - d_i^2)} \qquad (42)$$

And from the optimum value of z, we have the equality constraint given by

$$c = \frac{a}{4}\left[1 - tanh^2\left(\frac{az_{opt}}{2}\right)\right] \qquad (43)$$

Considering the equality in (42), for small values of L_i (small tilt angle from the nearest coordinate axis), the value of c calculated for BS b_0 is the minimum. Hence the values of *a* and c that satisfy (43) and (42) will make the coalition formed stable by assigning payoffs that satisfy (41).

A closed form solution is difficult to arrive at since there are different values of distances and angles and also the equation involves a combination of linear and hyperbolic functions with inequality relationships. As a demonstration let us take the case where N = 5, $d_i = d_1$, $M_i = 1$ and $L_i = 0$ for all i. In this case $z_{opt} = 9/25$ and the coalition parameters $a = 0.5$ and c = 0.121 will result in a fair and stable coalition by assigning a payoff of 0.38 for each BS.

IV. Simulation Result

We used NS2 to simulate our work. In the simulation we used a wireless LAN consisting of 5 BS-s and 20 mobile nodes deployed randomly in the service area. The distances and angles are given as follows:

- d_1 = 70 m
- d_2 = 90 m and $\beta_2 = 95^0$
- d_3 = 100 m and $\beta_3 = 172^0$
- d_4 = 87 m and $\beta_4 = 80^0$ (Clock wise)

The mobile nodes transmit FTP traffic constantly to an FTP server through the base stations they are attached to. Each base station is supplied with an initial energy of 1 Joule.

The simulation runs for an hour and the total energy consumed by the base stations are recorded and used to compare three radio range assignment scenarios. The three scenarios are:

- Each base station using a radio range of $r_i = R_{max}$ for all i. R_{max} is the maximum radio range associated with the maximum transmit power as specified in the IEEE 802.11 g standard. R_{max} = 200 meters.
  - Each base station using a radio range of $r_i = \max(d_i)$ = 100 m.
  - Base stations using our proposed radio range assignment.

The simulation results for the three scenarios are shown in Figure 6. The simulation results show that our proposed scheme for radio range assignment results in a significant saving in total transmit power compared to the two power assignment strategies. Particularly the power savings obtained are very high when compared to the default power assignment as is the case for many randomly deployed wireless LANs.

V. Conclusion

In this paper we studied the power control problem in general topology wireless networks using computational geometry and coalition formation game theory. Our results show that by assigning different radio ranges for BS-s rather than equal radio ranges, we can save a substantial amount of transmit power. Our mathematical result shows that we can save a substantial amount of total transmit power by using our strategy rather that the default-transmit power assignment strategy. The paper also illustrates the analytical results using simulation work done using NS2.

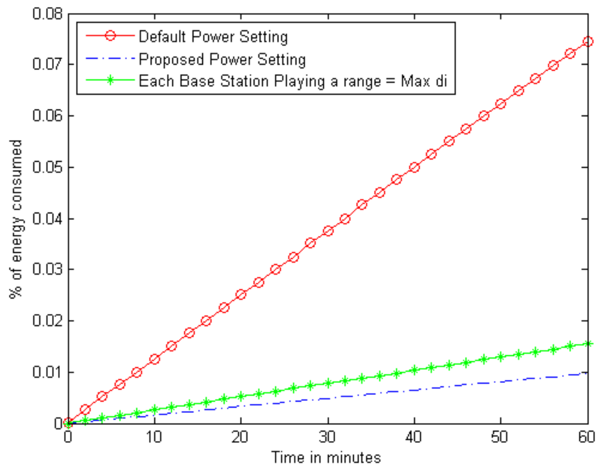

Fig. 6 – Simulation results for the three scenarios.

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