

# Coordinated Fair Resource Sharing in Dense Indoor Wireless Networks

Ying Wang<sup>1</sup>, Jun Zhang<sup>2</sup>, Jason Min Wang<sup>1</sup>, Brahim Bensaou<sup>1</sup>

<sup>1</sup>Department of Computer Science and Engineering, The Hong Kong University of Science and Technology

<sup>2</sup>Network and Computer Science Department, Telecom ParisTech

ywangbf@cse.ust.hk, jun.zhang@telecom-paristech.fr, jasonwangm@cse.ust.hk, brahim@cse.ust.hk

**Abstract**—In dense indoor multi-cell wireless networks, such as WLANs and OFDMA-based femtocell networks (e.g., LTE, WiMAX), the wireless bandwidth waste has become more dramatic due to the large interference and contention occasioned by uncoordinated channel access methods such as CSMA. Coordinating resource allocation in the network can be a good compromise solution to this problem. However, in general, resource allocation in wireless networks is a complex multi-dimensional problem that involves four tasks: client association to select a base station to associate with, antenna beam selection when directional antennas are used, link scheduling to ensure conflict freedom, and power adaptation to reduce mutual interference. In this paper we study the joint optimization of the above four components, and propose a unified conflict-free scheduling algorithm that solves the joint problem with two alternative objectives: (1) *power-utility-maximization* and (2) *fair-throughput-maximization*. Our scheduling algorithm can be directly implemented in OFDMA-based femtocell networks. In addition, to enable realistic deployment in WLANs, we design the so-called TD-CSMA, a coordinated access protocol that is compatible with the legacy IEEE 802.11 MAC protocol. With extensive simulations in ns-2 we notably show that our model outperforms some benchmark algorithms on a wide range of metrics.

## I. INTRODUCTION

Large interference and contention could lead to severe wireless resource waste in multi-cell wireless networks, such as wireless LANs (WLANs) and orthogonal frequency-division multiple access (OFDMA) based femtocell networks (e.g., LTE, WiMAX). Especially, in dense indoor environments (e.g., femtocell networks in an office building and WLANs in a university library), transmissions suffer from very high collision frequency due to the rich indoor signal propagation. In such environments, users often experience larger delays and lower throughput and can sometimes experience starvation [1]. Therefore, how to efficiently and fairly allocate the wireless resources becomes a critical issue in such networks.

In general, wireless resources in such networks are variable along four dimensions: *time*, *frequency*, *power*, and *space*. A large volume of work has already been devoted to the time and frequency dimensions, where link scheduling is invoked to resolve contention by scheduling link resources along the *time* and *frequency* domains. For example, in WLANs, time resources are assigned by scheduling link access time in a MAC protocol [2]; frequency resources are assigned via channel assignment [3]. In OFDMA-based femtocell networks, link

scheduling is often done in two-dimensional (time-frequency) blocks (the basic unit of resource allocation at the MAC)[4]. Furthermore, power adaptation is another common approach to reduce interference, thereby improve the link signal quality [5]. Directional antennas (antenna beam selection) have only been used in outdoor environments. Nevertheless, recent works in [6], [7] have shown that a great deal of *spatial* reuse can be achieved even indoors, provided the beams of the antennas are oriented intelligently to mitigate the interference. Finally, at a larger time scale, ditching the naive greedy association commonly used in such networks, intelligent association control can be invoked to balance the load on the base stations of the network (APs in WLANs or femtocell base stations) and to reduce the unfairness and starvation problems [8].

As discussed above, wireless resource allocation involves four components: client association, antenna beam selection, link scheduling, and power adaptation. Dealing with each component separately or simply combining them could lead to sub-optimal resource allocation. This is because these components are not completely independent of each other and one component is often coupled with another. Despite the large body of previous work on this issue (summarized in Section II), the relationship among the four components has not been fully explored. To the best of our knowledge, no previous work has considered the four components together. To efficiently and fairly utilize the multi-dimensional resources in multi-cell wireless networks, in this paper we study a general framework to jointly optimize client association, antenna beam selection, link scheduling, and power adaptation. In a dense indoor environment, the joint problem is even more challenging, since there exist rich reflections, scattering, and multipath fading effects.

Specifically, we consider a dense indoor multi-cell wireless network (e.g., WLAN or femtocell network) with each AP (or femtocell base station) being equipped with a multi-beam directional antenna. We focus on downlink traffic served by the base stations to the clients equipped with omni-directional antennas. The wireless network uses open-access, allowing each client (user) to associate with any base station that can serve it. We study the joint optimization of client association, antenna beam selection, link scheduling, and power adaptation. Two alternative objectives are explored: i) *power-utility-maximization*, aiming to maximize the utility of the throughput achieved per joule of power used; and ii) *fair-throughput-maximization*, seeking the balance between individual throughput and fairness regardless of the energy used. In recognizing the NP-hardness of the problem, we propose

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a unified conflict-free heuristic scheduling algorithm that can handle both objectives.

It should be pointed out that our proposed conflict-free scheduling algorithm can be easily adapted to OFDMA-based femtocell networks as well as WLANs. On one hand, it can be directly applied to OFDMA-based femtocell networks. On the other hand, for a realistic deployment in WLAN, we further design the TD-CSMA protocol that implements the unified conflict-free scheduling algorithm on top of legacy IEEE 802.11 MAC protocol.

In summary, our contributions are as follows:

- To the best of our knowledge, we are the first to study the joint problem of client association, antenna beam selection, link scheduling, and power adaptation in wireless networks.
- To solve the problem, we propose a unified conflict-free scheduling algorithm for the two objectives, i.e., power-utility-maximization and fair-throughput-maximization. Our algorithm is practical in the sense that it applies to both indoor dense WLANs and OFDMA-based femtocell networks.
- The protocol level ns-2 simulation results show that in indoor environments, our model notably outperforms the benchmark algorithms. Furthermore, turning on multiple beams turns out to achieve better performance than using single-beam antennas thanks to the enhanced spatial reuse.

The rest of the paper is organized as follows. Section II gives a overview of related work. In Section III, we present our system model and problem formulation. We elaborate on the proposed algorithm in Section IV and explain the details of the TD-CSMA protocol in Section V. Section VI provides some simulation results. Finally, we conclude our work in Section VII.

## II. RELATED WORK

Recent works have focused on jointly optimizing two or three of the four components to improve the system performance. We present some of the most prominent ones in the following:

- *Joint client association and antenna beam selection*: in [9] client scheduling is decoupled from the greedy algorithm of association and beam selection in OFDMA small-cell networks. The algorithm is re-executed in rounds to recalculate the schedules.
- *Joint link scheduling and antenna beam selection*: some works focused on modifying the MAC protocol in WLAN to enable interoperation with directional antennas, adopting either a TDMA-based access method in [10], [6], [7] or a CSMA-based approach in [11], [12], [13], [14]).
- *Joint client association and link scheduling*: a distributed Gibbs sampler based algorithm was proposed to optimize channel assignment and association in [15].
- *Joint antenna beam selection and power adaptation*: [16] proposed a cross-layer adaptive beam-forming for multicast communication in indoor WLANs. Compared to traditional single-beam systems, the work in [17], [18] found that the network throughput could be improved by turning on multiple beams simultaneously and adjusting their transmit power.
- *Joint client association, beam selection, and link scheduling*: in [11] the joint problem under the IEEE 802.11 MAC

protocol was solved via an optimization theoretic approach. In [6], [7]<sup>1</sup> the problem of indoor WLANs was addressed, without considering power adaptation.

- *Joint client association, link scheduling, and power adaptation*: In [4] the max-min fair resource allocation problem in a two-tier OFDMA-based femtocell network was studied using conflict graph model. In the conflict graph, only pairwise conflicts among links are considered, rather than signal to interference and noise ratio (SINR). The graph construction also requires a huge overhead.
- In [19], a unified framework was proposed to solve the joint channel access, client scheduling, channel selection, and association problem in self-organized wireless networks. The framework does not consider antenna beam selection nor power control. In addition, it adopts a random channel access model rather than a scheduled one and thus does not ensure conflict freedom.

## III. SYSTEM MODEL

### A. Model Description

Consider an indoor multi-cell wireless network with down-link traffic, with a large number of mutually interfering links<sup>2</sup>, and denote by  $A$  the set of base stations (APs or femtocell base stations, including the macrocell base station), each equipped with a multi-beam directional antenna. Denote by  $C$  the set of clients, each possessing an omni-directional antenna. To efficiently use the power resource, each base station can turn on at most  $K$  beams and apportion the power among them with a maximum total transmit power budget of  $P_{max}$  (can be different from one base station to the other). Any arbitrary combination of beams can be turned on simultaneously (e.g., via beam-forming).

All nodes in the network occupy the full bandwidth when transmitting. As in real production networks (e.g., office femtocell networks and enterprise WLANs), base stations are connected via a high speed wired network (back-haul network) and are monitored by a central node. For ease of exposition we will use the terms base station and AP interchangeably without further clarification.

Non-line-of-sight (NLOS) propagation is rich in reflections, scattering, and multipath fading effects. In such scenario, a client has more choices of links as it may receive sufficiently large signal power from several candidate beams possibly emanating from the same base station. However, after selecting the serving beam for a client, signals from the remaining candidate beams may become interference. To combat such interference, especially when the network density is large, we propose to schedule links within the network in a conflict-free manner. To achieve this:

- In WLANs, time is divided into coarse slots (in the ms order of magnitude). In each time slot  $t$ , a subset of clients is served simultaneously via a set of non-conflicting beams. Each beam can only serve one client, once, in a revolving dynamically scheduled TDMA frame. Although we assume

<sup>1</sup>We use the approach of [6] as our benchmark in our simulation.

<sup>2</sup>Such network may have a small number of APs and a moderate number of clients (or a large number of femtocell base stations and a relatively small number of users), yet reflections off walls and the confined area in which the network is operated make it dense in the sense that each transmission has a very high probability of colliding with another transmission.

that an active node occupies the full bandwidth, orthogonal channel assignment can be easily added into our framework by replacing the time (one dimension) slot with time-channel (two dimensions) unit. Nevertheless, because channel switching time causes high overhead, channel assignment should operate in a larger time-scale than time scheduling.

- In OFDMA-based femtocell networks, each OFDMA frame is a two-dimensional resource (slot-subchannel) and occupies the full bandwidth. A subset of non-conflicting links are served in one slot, which is the minimum time unit of resource allocation in one OFDMA frame. By allocating subchannels, each beam of a femtocell base station can serve multiple users in a slot. The scheduling policy repeats itself in the OFDMA frame time scale.

### B. Formulation

We formulate the joint problem as a unified multi-objective mixed-integer non-linear optimization problem and investigate two different goals: i) the *power-utility-maximization*, seeking to achieve high average link throughput per joule used in transmission while maintaining high throughput and fairness; ii) the *fair-throughput-maximization*, seeking to achieve a high throughput and fairness for each client by using an arbitrary amount of power within the limits of the power budget.

The power-utility-maximization problem contains three objectives:

- 1) The first objective is to maximize the total utility of the network capacity used by the clients; that is, if we denote the capacity for a client  $c$  in a slot  $t$  over the full bandwidth as  $\rho_{ct}$ , then the total utility of the network can be written as  $\sum_{c \in C} U\left(\sum_{t=1}^T \rho_{ct}/T\right)$ , where  $\sum_{t=1}^T \rho_{ct}/T$  denotes the capacity obtained by client  $c$  over a scheduling period of length  $T$  (serving all the clients once) and  $U(\cdot)$  is a concave utility function that embodies the diminishing return principle, to ensure fairness in capacity allocation to different clients.

- 2) The second objective is to maximize the average power utility, (a measure of efficiency of power utilization) defined as the transmitted data rate per joule consumed, that is:

$$\frac{1}{|C|} \sum_{c \in C} \left( \frac{\sum_{t=1}^T \rho_{ct}}{\sum_{t=1}^T \varepsilon_{ct}} \right),$$

where  $\varepsilon_{ct}$  is defined as the power apportioned by the base station to transmit to client  $c$  in a slot  $t$ .

- 3) Given such objectives, the third objective becomes obviously to minimize the scheduling period  $T$ .

Achieving the three objectives: i) leads to a good tradeoff between a high total network capacity and fairness; ii) a high average power utility; and iii) a high service frequency for each client.

The fair-throughput-maximization problem can be formulated in the same manner as above by relaxing the power-utility optimization objective in item 2) above. Since the two goals are similar, we can unify their objective functions by combining them via an auxiliary variable  $\zeta \in \{0, 1\}$ , where  $\zeta = 1$  for the power-utility-maximization, and  $\zeta = 0$  otherwise. The result is the following multi-objective optimization problem:

$$\max_{\substack{I_{akt}, N_{ac}, T, \\ P_{akt}, \rho_{ct}, \varepsilon_{ct}}} \left[ \sum_{c \in C} U\left(\frac{1}{T} \sum_{t=1}^T \rho_{ct}\right), \frac{\zeta}{|C|} \sum_{c \in C} \left(\frac{\sum_{t=1}^T \rho_{ct}}{\sum_{t=1}^T \varepsilon_{ct}}\right), 1/T \right] \quad (1)$$

$$\text{s.t.} \quad \sum_{k \in K_a, t \in [1, T]} I_{akt} \leq N_{ac}, \forall a \in A, \forall c \in C, \quad (2)$$

$$\sum_{a \in A} N_{ac} = 1, \forall c \in C, \quad (3)$$

$$\sum_{a \in A, k \in K_a} I_{akt} \leq 1, \forall c \in C, \forall t \in [1, T], \quad (4)$$

$$\sum_{c \in C} I_{akt} \leq \gamma_{max}, \forall a \in A, \forall k \in K_a, \forall t \in [1, T], \quad (5)$$

$$\sigma_{ct} \geq S_{min} \sum_{a \in A, k \in K_a} I_{akt}, \forall c \in C, \forall t \in [1, T], \quad (6)$$

$$P_{akt} I_{akt} S_{akc} \geq R_{min} I_{akt}, \quad (7)$$

$$\sum_{k \in K_a} P_{akt} \leq P_{max}, \forall a \in A, \forall t \in [1, T]. \quad (8)$$

$$\rho_{ct} = B\gamma_{ct} \log(1 + \sigma_{ct}), \forall c \in C, \forall t \in [1, T], \quad (9)$$

$$\sigma_{ct} = \sum_{a \in A, k \in K_a} \sigma_{akt}, \forall c \in C, \forall t \in [1, T], \quad (10)$$

$$\sigma_{akt} = \frac{I_{akt} S_{akc} P_{akt}}{NF + \sum_{(a', k', c') \in \mathcal{X} \setminus \{(a, k, c)\}} I_{a'k'c'} S_{a'k'c'} P_{a'k't}}, \quad (11)$$

$$\forall a \in A, \forall k \in K_a, \forall c \in C, \forall t \in [1, T], \quad (11)$$

$$\gamma_{ct} = \frac{\sum_{a \in A, k \in K_a} I_{akt}}{\sum_{a \in A, k \in K_a} I_{akt} (\sum_{c' \in C} I_{akt'c'})}, \forall c \in C, \forall t \in [1, T], \quad (12)$$

$$\varepsilon_{ct} = \sum_{a \in A, k \in K_a} I_{akt} P_{akt}, \forall c \in C, \forall t \in [1, T], \quad (13)$$

$$P_{akt} \geq 0, \forall a \in A, k \in K_a, \forall t \in [1, T], \quad (14)$$

$$I_{akt} \in \{0, 1\}, \forall a \in A, k \in K_a, \forall c \in C, \forall t \in [1, T], \quad (15)$$

$$N_{ac} \in \{0, 1\}, \forall a \in A, \forall c \in C. \quad (16)$$

Constraint (2) restricts the client service to one slot in one scheduling period if associated, (3) guarantees each client can associate with one and only one AP, and in (4) each client can only be served by one beam from any AP in any time slot. Constraint (5) restricts the maximum number of clients  $\gamma_{max}$  that can be served by the same beam in the same slot. For WLANs,  $\gamma_{max} = 1$  since each beam can serve at most one client once. For OFDMA-based femtocell networks,  $\gamma_{max}$  can be defined properly so as to ensure a minimum bandwidth share for each client. Constraint (6) sets the condition for a packet to be received successfully by a client  $c$  in time slot  $t$ , which occurs if its SINR value  $\sigma_{ct}$  is larger than the capture threshold  $S_{min}$ , and in (7), the strength of the received signal at each client  $c$  being served in slot  $t$  must be stronger than a receiving threshold  $R_{min}$  for the packet to be decoded. Note that the sum in the right hand side of (6) ensures that the constraint degenerates for clients not served in slot  $t$ , that is, if a client  $c$  is not served by any beam in slot  $t$ ,  $\sigma_{ct} = 0$ , multiplying  $S_{min}$  by  $\sum_{a \in A, k \in K_a} I_{akt}$  ensures that the right hand side is also 0 for such combination of  $c$  and  $t$ . In (7), the presence of  $I_{akt}$  in both sides is to ensure the constraint holds for all the quadruples  $(a, k, c, t)$  including those for which  $I_{akt} = 0$  regardless of the value. Constraint (8) restricts the total transmission power of all active beams of each AP by the power budget. The capacity of each client is calculated in the SINR model accounting for the cumulative interference under a fixed modulation scheme. In constraints (9)-(12), for a fixed modulation scheme, the capacity  $\rho_{ct}$  at the floor of client  $c$  in slot  $t$  can be expressed in terms of SINR at the floor of client  $c$  in time slot  $t$ ,  $\sigma_{ct}$  and the channel bandwidth  $B\gamma_{ct}$

obtained the client  $c$ .  $\gamma_{ct}$  is the fraction of bandwidth obtained by client  $c$  at slot  $t$  assuming equal bandwidth sharing among multiple users per beam (in (10), if both of the numerator and denominator are 0,  $\gamma_{ct}$  equals 1). The power cost of client  $c$  in a slot  $t$  is defined as  $\varepsilon_{ct}$  in constraint 13. Constraints 14-16 define variables  $P_{akt}$ ,  $I_{akct}$ , and  $N_{ac}$ :  $I_{akct}$  is a binary decision variable that indicates if client  $c$  is served from beam  $k$  of base station  $a$  in time slot  $t$ ,  $N_{ac}$  is the binary indicator of association between client  $c$  and base station  $a$ , and  $K_a$  is defined as the set of beams of base station  $a$ .  $P_{akt}$  is the transmission power assigned to beam  $k$  of base station  $a$  in time slot  $t$ ,  $S_{akc}$  is the path-loss factor from an AP  $a$  to client  $c$  via beam  $k$ .

Problem (1), is a discrete scheduling problem with mixed integer and non-integer variables and is subject to non-linear constraints with multiple objectives. It can easily be shown to be NP-hard as follows: setting the bandwidth  $B$  to 0, fixing the association variables  $N_{ac}$ , fixing the serving beams and beam powers, cause the first two objectives to vanish. Either one of the power-utility-maximization problem and the fair-throughput-maximization problem becomes a discrete-time conflict-free link scheduling problem. This simpler instance is equivalent to a graph colouring problem on the link conflict graph. Since graph colouring is well known to be NP-hard, then problem (1) is also NP-hard. To solve problem (1), we propose a unified heuristic algorithm to achieve either one of the two objectives in the next section.

#### IV. HEURISTIC ALGORITHM

##### A. Algorithm Description

The procedure of the unified algorithm is given in Algorithm 1 that takes as input, the measured path-loss information  $\{S_{akc} | \forall a \in A, \forall k \in K_a, \forall c \in C\}$  and the objective identification variable  $\zeta$ . When the objective is power-utility-maximization ( $\zeta = 1$ ), the algorithm aims at reducing transmit power while maintaining high throughput and fairness between clients when assigning links to time slots. When the objective is fair-throughput-maximization ( $\zeta = 0$ ), the algorithm focuses mainly on achieving high throughput with fairness in total oblivion to the power consumed.

Intuitively, our algorithm tries to get close to the optimal solution of the joint problem by intelligent decision making and constraint satisfaction in each step. The algorithm partitions the client set  $C$  into several groups; each group contains only clients whose transmissions are conflict-free, and each client is assigned to exactly one group and each group  $G_t$  is served in time slot  $t$ . We define  $G$  as the set of triples  $(a, k, c)$  that have not yet been assigned so far, and vector  $\vec{P} = (P_1, \dots, P_c, \dots, P_{|C|}), c \in C$  records the link power assigned to all clients. Initially,  $G = \chi$ , where set  $\chi = \{(a, k, c) | a \in A, k \in K_a, c \in C\}$  is the collection of all possible triples. Each client is assigned an initial link power of  $P_{max}/K$ , i.e., the total power budget of each AP is shared equally among its beams.

As long as  $G$  is not empty, in each round we try to add one triple from  $G$  into the current group  $G_t$ . For each round,  $(a_m, k_m, c_m)$  tracks the triple that leads to the maximum minimal SINR value for the current group. The goal of doing this is to try to add as many clients as possible in one slot to

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#### Algorithm 1 Unified Scheduling Algorithm

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**Require:** Path-loss  $\{S_{akc}\}$ , Objective  $\zeta \in \{0, 1\}$

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1:  $t \leftarrow 1, G \leftarrow \chi, G_1 \leftarrow \emptyset, \vec{P} \leftarrow \mathbf{1} \frac{P_{max}}{K}$ 
2: while  $G \neq \emptyset$  do
3:    $S_{maxmin} \leftarrow S_{min}$ 
4:    $(a_m, k_m, c_m) \leftarrow (-1, -1, -1)$ 
5:   for each  $(a, k, c) \in G$  do
6:     if  $S_{a,k,c} P_{max}/K \geq R_{min}$  then
7:       if  $(a, k) \neq (a', k'), \forall (a', k', c') \in G_t$  then
8:          $S_{cur} \leftarrow \min_{(\bar{a}, \bar{k}, \bar{c}) \in G_t \cup \{(a, k, c)\}}$ 
9:            $\sigma_{\bar{a}, \bar{k}, \bar{c}}$ 
10:        if  $S_{cur} \geq S_{maxmin}$  then
11:           $S_{maxmin} \leftarrow S_{cur}$ 
12:           $(a_m, k_m, c_m) \leftarrow (a, k, c)$ 
13:        if  $(a_m, k_m, c_m) == (-1, -1, -1)$  then
14:           $t \leftarrow t + 1$ 
15:           $G_t \leftarrow \emptyset$ 
16:        else
17:           $G_t \leftarrow \{(a_m, k_m, c_m)\} \cup G_t$ 
18:           $G \leftarrow G \setminus \{(a, k, c) | (a, k, c) \in G \text{ and } c == c_m\}$ 
19:        OPTIMIZE $(\vec{P}, \zeta)$ 
20: return  $\{G_i | i = 1, \dots, t\}, \vec{P}$ 

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**function**  $\text{ALLOCATE}(P_{c_m}, \zeta)$

$$P_{c_m} = \begin{cases} P_{max}/K, & \zeta = 0 \\ \max\{\frac{P_{c_m} S_{min}}{\sigma_{a_m, k_m, c_m}}, \frac{R_{min}}{S_{a_m, k_m, c_m}}\}, & \zeta = 1 \end{cases}$$

**function**  $\text{OPTIMIZE}(\zeta, \vec{P}, \{G_i | i = 1, \dots, t\})$

**if**  $\zeta == 0$  **then**  
**for each** slot  $i$  **do**  
 Solve (17) for  $G_i$

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reduce the scheduling period length while maintaining fairness among the group users with the initial beam power setting. The algorithm chooses from the remaining clients the eligible triple that satisfies both the  $S_{min}$  and  $R_{min}$  constraints in (6) and (7) if added into the current group  $G_t$ . In WLAN, step 7 satisfies constraint (5) when  $\gamma_{max}$  equals 1, otherwise this step can simply be replaced by checking if one beam serves less than  $\gamma_{max}$  users in femtocell network. For each remaining client,  $S_{cur}$  is the minimum SINR value assuming the client is added into the current group  $G_t$ . If no eligible triple is found, the algorithm goes to the next slot  $t+1$ . Otherwise, the algorithm selects the best triple  $(a_m, k_m, c_m)$  and adds it to the current group  $G_t$ , i.e., client  $c_m$  is fixed to be associated with AP  $a_m$  via active beam  $k_m$  and is scheduled in time slot  $t$ .

Function  $\text{ALLOCATE}$ , serves to distinguish between one of two optimization goals. If the goal is fair-throughput-maximization, the link power of the clients  $c_m$  is allocated equally among the existing beams, then in function  $\text{OPTIMIZE}$ , the power is readjusted by the optimal solution of problem (17). If the goal is power-utility-maximization, the link power  $P_{c_m}$  is reduced to a value that exactly satisfies constraints (6) and (7). Since each client is served exactly once in the period, one client can only be associated with one AP, and each client can only be served by one beam in one slot (constraints (2), (3), and (4) are all satisfied), after adding the triple  $(a_m, k_m, c_m)$ , all the triples that contain client  $c_m$  are

removed from set  $G$ . Serving each client exactly once in a period keeps client fairness in terms of service frequency. The algorithm continues until  $G$  is empty. At the end, the final value of  $t$  gives the schedule period  $T$ ;  $\bar{P}$  gives the power allocation scheme and for each  $t$ ; and  $G_t$  gives the identity of the base stations, the beams and the clients to receive data in slot  $t$ .

Function OPTIMIZE is only invoked for the fair-throughput-maximization, to improve the capacity of each client in each slot within the available power budget. In indoor environments with multi-path effect and varying channel, the higher the SINR value the more reliable the link is; therefore, based on the fixed scheduling scheme obtained previously, one could improve the link capacity fairly by increasing the SINR of all links subject to mutual interference constraints. This can be done by solving in each slot  $t$  problem (17),  $G_t$  being the fixed set of triples  $(a, k, c)$  in time slot  $t$  calculated previously.  $B_c$  is the bandwidth share of client  $c$ , and  $\sigma_c$  is the SINR value of client  $c$  in group  $G_t$  (subscript  $t$  is dropped in equation (17)).

$$\begin{aligned}
& \max_{P_{ak}, \rho_c} \sum_{(a,k,c) \in G_t} U(\rho_c) \\
& \text{s.t. } \rho_c \leq B_c \log(1 + \sigma_c), \quad \forall (a, k, c) \in G_t, \\
& \sigma_c = \frac{S_{akc} P_{ak}}{NF + \sum_{\substack{(a', k', c') \in \\ G_t - \{(a, k, c)\}}} (S_{a'k'c'} P_{a'k'})}, \quad \forall (a, k, c) \in G_t, \\
& \sigma_c \geq S_{min}, \quad \forall (a, k, c) \in G_t, \\
& P_{ak} S_{akc} \geq R_{min}, \quad \forall (a, k, c) \in G_t, \\
& \sum_{(a,k,c) \in G_t} P_{ak} \leq P_{max}, \quad \forall a \in A, \\
& P_{ak} \geq 0, \quad \forall a \in A, \forall k \in K_a.
\end{aligned} \tag{17}$$

Problem (17) is not convex, however, by choosing  $S_{min}$  sufficiently large, we can approximate  $\sigma_c + 1$  in the capacity constraint (9) by  $\sigma_c$  yielding a problem that can be transformed into a convex optimization problem using the so-called log transformation [20]. Once this done, classic convex optimization techniques can be invoked to solve the problem in polynomial time. This part is omitted from the paper.

### B. Discussion and Complexity

The complexity of the unified scheduling algorithm is polynomial. In each round inside the while loop, one client is selected from the remaining set  $G$ . Inside each round, there are at most  $|A|K|C|$  triples to choose from; and inside the innermost loop (step 8), the minimum SINR in the group requires  $O(|C|)$ . Therefore the complexity of the scheduling algorithm before OPTIMIZE is invoked is  $O(|A|K|C|^3)$ , in addition to the time for solving  $T$  convex optimization problems, which depends on the search method. All in all, the algorithm runs indeed in polynomial time.

Note that the association happens at a coarser granularity than the scheduling (antenna beam selection, link scheduling, and power adjustment). In our algorithm, scheduling scheme can change every scheduling period with the association scheme being fixed. Whereas the client association is only required to change when the performance degradation caused by channel or traffic dynamics cannot be handled by rescheduling.

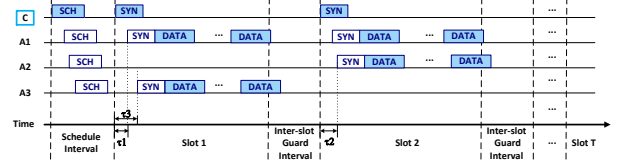


Fig. 1. Timeline showing the TD-CSMA protocol

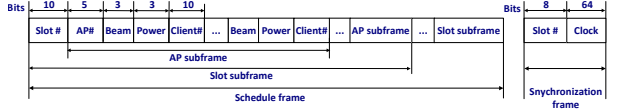


Fig. 2. Schedule frame and synchronization frame format

The algorithm relies on the measured path-loss  $\{S_{akc}\}$ . In real systems this can be obtained from periodic client feedback similar to [6]. Each AP takes turns to send packets via different beams. The clients listen and collect the corresponding RSSI values (e.g., the average RSSI value over an interval). Whenever channel variation results in severe throughput reduction, clients will record and update the path-loss information to the neighbouring APs, after which association or scheduling may be re-evaluated by the controller. Client measurement and reporting functions already exist and are part of standard WiMAX (or LTE) networks. For WLANs, such function can be easily included in the client via a user-space applet or included in the device driver. Such measurements can be completed in  $O(|A| \times K)$ .

## V. TD-CSMA PROTOCOL DESIGN

### A. TD-CSMA Protocol

Our general scheduling framework can be directly applied in OFDMA-based femtocell network. For example, in WiMAX, frame transmissions are synchronized across all the femtocell base stations by the macrocell base station. According to the policy provided by the central controller, each femtocell base station can reschedule the downlink transmission in each OFDMA frame and notify its users by broadcasting downlink map (WiMAX) before transmission.

Since CSMA-based WLANs lack the tight synchronization, implementing our model is not as straightforward as in a cellular network. To deploy conflict-free scheduling in WLAN without modifying the CSMA/CA MAC protocol, we design the so-called TD-CSMA, to run on top of CSMA/CA. Fig. 1 shows an example of the timeline of TD-CSMA. TD-CSMA works on the wired network, where the central controller runs our heuristic algorithm in rounds and informs the APs periodically of their slot, beam, target client, and beam power settings. At the beginning of each scheduling period, the controller broadcasts the schedule (SCH) frame to all APs. The frame detail is shown in Fig. 2. The SCH frame contains association, beam selection and power setting information, from which each AP knows its own transmission information in the ensuing scheduling period. Then at the beginning of each fixed duration time slot, the central controller broadcasts to all APs synchronization (SYN) frames to initiate the slot

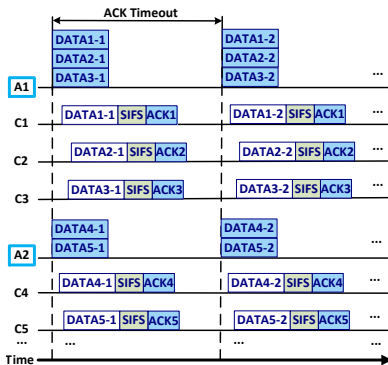


Fig. 3. Per-slot transmission

and allow the APs to synchronize their clocks on the controller. After receiving the SYN frame for a slot, all the APs scheduled in the current slot synchronize their timers, trigger the association with their clients (if not already done or keep the same association otherwise) and serve them according to the information in the SCH frame.

Assuming in the wired network, the propagation time on link  $i$  is  $\tau_i$ , then the schedule interval, is set to the length of the SCH frame plus  $(\max_i \tau_i)$ . Fig. 1 illustrates this by the different arrival times of the SCH frame from C to APs A1, A2 and A3. To avoid collisions between consecutive slots, the inter-slot guard interval is set to the transmission time of one data frame and one MAC ACK plus the maximum propagation time.

The SCH frame, shown in Fig. 2 is subdivided in several sections; one per slot. A slot subframe contains the slot Id and several AP subframes, one per AP. Each AP subframe includes the AP number and several triples showing the beam selection, power and the client Id. The continuous power value is quantized into 8 different levels represented by 3 bits in the power section. For example, assuming the number of clients is no more than 200, the schedule frame requires at most several hundred bytes, which is smaller than one IP packet. Each SYN frame shown in Fig 2 contains the slot number (8 bits) and the controller's current clock (64 bits) to enable synchronization.

The details of the transmission within one slot are shown in Fig. 3. The SYN frame indicating the start of a slot, each AP that is authorized according to the SCH frame in the current slot serves its clients via different beams in this slot on the wireless network using the CSMA-based IEEE 802.11 protocol. By virtue of our algorithm, the frames from different APs are conflict-free, however, the returning MAC ACK from the clients may collide in CSMA and trigger two undesirable side effects: i) a retransmission of the DATA frame (that is normally known to have been forcefully delivered conflict-free) and ii) the doubling of the contention window (which may create asynchrony between data frames in the same slot, triggering thus more collisions). To deal with these two problems, we set both minimum and maximum contention windows in all the APs to 1, disabling thus the backoff; we also set the retry limits of all APs to 1, allowing thus each frame to be transmitted only once (since the frame is known to

be scheduled conflict-free). Thus the MAC ACKs are ignored at the AP side, and when the ACK timeout expires, the AP sends the next packet (since the retry count is 1). Thanks to this, and the time synchronization at the beginning of the slot, i) DATA to DATA collision is not possible due to the conflict-free scheduling; ii) ACK to DATA collisions will not happen if the data frame length is fixed and clock drift between APs in a slot is less than the SIFS, and iii) the ACKs within a slot may still collide however they are ignored by the APs (i.e., the AP simply moves to the next packet).

To achieve a good synchronization across the network, each node maintains its timer. At the beginning of each slot, the timers of all APs will be synchronized with the controller based on the values coded in the SYN frame. Nevertheless, clock skew differs among different timers (nodes). The slot time length may be long enough to cause cumulative time offset which may be larger than SIFS. Thus DATA to ACK collisions may happen when data transmission overlaps with ACK transmission. According to the estimation in [21], the clock skew of an AP remains consistent over time and its absolute value ranges from 10 to 1000 ppm. For example, assuming the AP clock skew is 1000ppm and SIFS is  $10\mu s$ , the AP timer needs to be re-synchronized every 0.01s by the controller, to guarantee the cumulative time offset is smaller than the SIFS. In our protocol, the slot length is set to 0.01s and the inter-slot guard interval is set to  $250\mu s$  (based on a data frame of 1500 bytes, transmission rate of 54 Mbps, and propagation speed  $3 \times 10^8$  m/s). In addition, if for some reason, longer time slots are needed, the AP can insert its timestamps in periodic feedback frames to the controller and the controller decides when to send the re-synchronization frame according to the time offset.

## VI. PERFORMANCE EVALUATION

### A. Simulation Setup

We study the performance of our algorithms via ns-2 simulation in WLAN. We use ns-2 version 2.35. A patch for directional antenna, the "the enhanced network simulator (Tens)" [22], is applied to ns-2 source. In order to describe a close-to-real indoor environment in the physical layer of the simulation, we implemented an accurate indoor propagation model in ns-2 based on the Nakagami channel fading model, called here I-Nakagami.

The I-Nakagami model simulates reflection, multi-path fading and burst channel error effects indoors. In this model, walls are built to simulate reflection effects. It is assumed that when signal reaches the walls, it will be reflected back once and no penetration is considered. After the reflection, the signal strength drops to 80% of its original value to simulate absorption. In addition, the signal power strength follows the Nakagami distribution. The Nakagami model is well known to be a good approximation for multi-path fading with randomly distributed arriving signal amplitudes, phases and angles in fading channels with burst errors occurring due to obstacles and reflectors. The received power is an undulated value rather than a constant and it is possible that a packet in the same link goes above or below the physical carrier sensing threshold or capture threshold at different times. Therefore, packet errors happen with some probability when the received power is low.



In the simulation, we consider a large square enclosed environment with four vertical walls, typically a large hall. We study different hall sizes including  $20 \times 20m^2$ ,  $40 \times 40m^2$ , and  $60 \times 60m^2$ . The space is divided into a grid of  $20 \times 20m^2$  for each cell. Each AP is positioned in the center of a cell. Such scenario allows us to simulate symmetric and asymmetric topologies with base station numbers ranging from 1 to 9. For example in the  $40 \times 40m^2$  hall placing 3 base stations results in an asymmetrical topology. In all topologies, the clients are randomly distributed in each cell. In order to simulate a large interference in indoor dense multi-cell WLANs, APs are all hidden from each other and the number of clients is set to 20 times of the number of APs, yielding 20 to 180 clients, i.e., 20 to 180 links possibly all interfering with each other because of wall reflections. Each AP is equipped with a six-beam directional antenna and each client is equipped with an omni-directional antenna. For each group of AP topology, thirty different random client distributions are generated and simulated and their results are averaged.

There are mainly three steps in the simulation: measurement, algorithm execution and scenario simulation:

1) *The measurement step*: since real measurements are not available, for each client, the path-loss information is obtained from the proposed I-Nakagami model based on the node locations. The APs take turn to send out packets via different beams. All the clients listen to the channel and record the corresponding AP, beam and path-loss information. Similar to real experiments, the path-loss information obtained at the client also varies from time to time. In order to improve the accuracy, the expected received power is adopted. In real experiment, average value over an interval can be used.

2) *The algorithm execution step*: consists in running the appropriate algorithm to obtain the conflict-free schedule and other parameters. Our power-utility-maximization and fair-throughput-maximization algorithm as well as the benchmark algorithm are implemented in MATLAB. The channel bandwidth  $B$  is set to 20 MHz.

3) *The scenario simulation step*: according to the location information and the scheme obtained in the second step, the corresponding scenarios are created and simulated in ns-2. In the I-Nakagami model, the loss exponent is set to 2.75 and the shape factor is set to 1.5. The physical layer data rate is set to 54 Mbps. Saturated downlink UDP traffic at 30 Mbps is used for each AP-client pair. Each AP has a power budget of 0.005 Watt and each client has a fixed power of 0.0001 Watt. The MAC protocol is the proposed TD-CSMA protocol described above. As mentioned previously, the slot length is set to 0.01s and the inter-slot guard interval is set to 250  $\mu$ s. Furthermore, the noise floor  $NF$  is set to -104 dBm.

## B. Results Analysis

We start with the power-utility-maximization algorithm. Since in this algorithm, we try to reduce as much as possible the transmit power, it is worth investigating the effect of this on the packet error rates. Indeed, when the SINR is low the channel is highly variable and frame error rates can be very high. From the problem formulation and the algorithm, it is clear that the higher values of  $S_{min}$  and  $R_{min}$  are, the stricter the scheduling process is, the longer the scheduling period

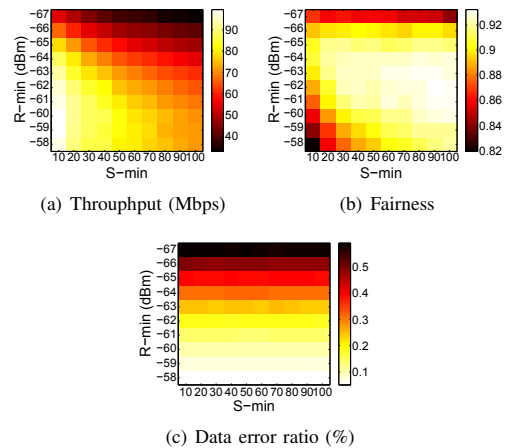


Fig. 4. Power-utility maximization performance as a function of  $S_{min}$  and  $R_{min}$

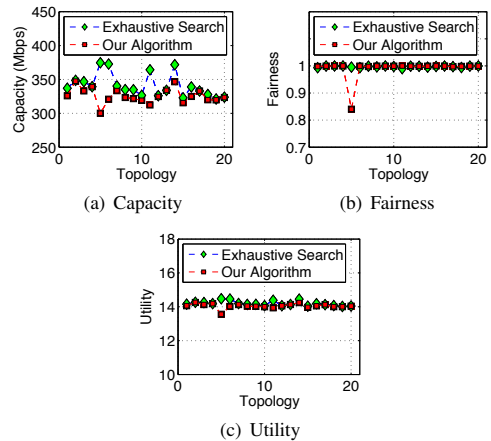


Fig. 5. Multi-beam heuristic vs. Optimal exhaustive search

is and the lower the frame error rates are. As such choosing the appropriate values of  $S_{min}$  and  $R_{min}$  is the key point of the scheduling process to balance the tradeoff between packet errors, scheduling period length, the achieved throughput and the transmit power. To investigate the influence of  $S_{min}$  and  $R_{min}$  on the performance, we conduct one hundred groups of simulation in the asymmetric AP topology (three APs), for all possible combinations of ten values of  $S_{min}$  (10 to 100) and ten values of  $R_{min}$  (-67 dBm to -58 dBm) for the multi-beam power-utility-maximization scheduling algorithm. The results are reported in Fig. 4 in the form of heat maps for the throughput, the fairness and the packet error ratio. Each grid represents thirty random client distributions averaged. As expected, when  $R_{min}$  increases from -67 dBm to -58 dBm while preserving  $S_{min}$  fixed, the average packet error ratio decreases from over 50% to around 5% only and thanks to the decreased packet error ratio the average total throughput increases. When fixing  $R_{min}$  and increasing  $S_{min}$  from 10 to 100, the packet error ratio remains in the same level while the throughput decreases due to the increased scheduling period length. High fairness is achieved for higher  $S_{min}$  and higher

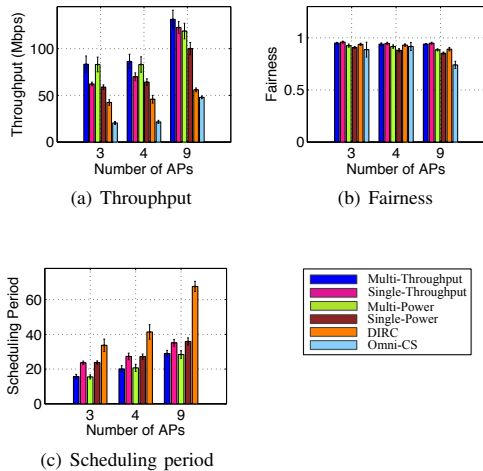


Fig. 6. Simulation results

$R_{min}$  since both low  $S_{min}$  and  $R_{min}$  may lead to unfair data drop within the clients. We choose  $S_{min} = 60$  and  $R_{min} = -58$  dBm in our scheduling algorithms since this combination can achieve fairly high throughput with lowest data error ratio.

To verify the quality of our heuristic scheduling algorithm we compare it to the optimal solution obtained by exhaustive search. Because of the complexity of the problem and its multi-dimensionality, we evaluate the first step of the fair-throughput-maximization algorithm where the beam power is fixed at  $P_{max}/K$  ( $S_{min} = 60$  and  $R_{min} = -58$  dBm) in a small network. In the setting, three clients are distributed randomly in a square between the two APs with three-beam antennas, yielding twenty possible different topologies. One exhaustive search in this scenario is in the complexity of  $\sum_{T=1}^{|C|} (K \times |A| + 1)^{|C| \times T}$  and for this simple example  $O(10^8)$  different scheduling combinations need to be scanned in the worst case to obtain the result. Fig. 5 compares the optimal total network capacity (obtained from the algorithm), fairness and utility for these twenty small topologies to our algorithm. As can be observed from the figure, our results are close to the optimum. In the worst case, our algorithm gets only 13.92% lesser in total capacity, 0.62 % drop in fairness, and 3.04 % decrease in the total utility.

We studied the performance of our algorithms for the two goals: power-utility-maximization algorithm (Power) and fair-throughput-maximization algorithm (Throughput). To investigate the benefit of scheduling multi-beam directional antennas versus single-beam antennas, we also studied the performance of our algorithms in two situations. In the first situation, each AP can turn on multiple beams in each slot (M-Power and M-Throughput), while in the second situation only a single beam is allowed per AP per slot (S-Power and S-Throughput). For comparison purpose, we also study the performance of legacy IEEE 802.11 with omni-directional antennas (Omni-CS) and one benchmark scheduling algorithm in [6], which is the closest to our work as far as we know. In Omni-CS, since APs are hidden, the RTS/CTS is turned on and other parameters are set as the standard IEEE 802.11g. In [6], a centralized algorithm (DIRC) is proposed to schedule links

for indoor WLAN with single-beam directional antenna APs and omni-directional clients. Since DIRC does not handle association, to avoid putting it at a disadvantage, we add our association scheme to it for fair comparison. In DIRC, each active AP has fixed power of  $P_{max}$ .

To make sure all comparisons are fair, we conduct our experiments under the same values of  $S_{min} = 60$ ,  $R_{min} = -58$  dBm for all the scheduling algorithms, namely M-Throughput, S-Throughput, M-Power, S-Power, and DIRC<sup>3</sup>. We examine several performance metrics, including: throughput, fairness, scheduling period length, power utility, and total transmit power. Throughput refers to the total aggregate received data per unit time of all clients. Based on the throughput of each client, fairness is calculated using Jain's fairness index. Scheduling period length is the number of time slots for serving every client once. Average power utility is the amount of data transmitted per unit energy used averaged over the clients, and finally, total transmit power refers to the total amount of power cost in the network (joule per second). The results are summarized in Fig. 6 and Table I, reflecting average results of thirty simulation runs, each corresponding to a different random client distribution.

We can typically see from the figures that in terms of throughput and fairness, our power-utility-maximization and fair-throughput-maximization algorithm show similarly good performance since both are close to achieving perfect conflict-freedom. In addition, our fair-throughput-maximization algorithm achieves a little higher throughput than power-utility-maximization thanks to the reduced packet error ratio from over 5% in the latter to less than 0.5%, as shown in Table I. Invoking either one of our scheduling algorithms with multi-beam directional antennas improves the throughput considerably compared to single-beam DIRC and Omni-CS. Although turning on the RTS/CTS alleviates the hidden terminal problem and starvation, Omni-CS obtains quite a low throughput due to the long back-off and large overhead brought about by carrier sensing. In addition, both our schedulers (Power and Throughput), even with single beam, achieve a much better throughput than the benchmark scheduler DIRC with single-beam. Our improvements are mainly because the intelligent combination of association, beam selection, link adaptation, and power adaptation, and cumulative interference based SINR model instead of the inaccurate SINR estimation via maximum interference in DIRC. In addition, our schedulers (Power and Throughput) prove to be better with multi-beam than with single-beam thanks to the increased spatial reuse.

As shown in Table I, our power-utility-maximization scheduling algorithm has the highest average power utility (1064 times that of the DIRC algorithm and 279 times that of the fair-throughput-maximization algorithm) and reduces significantly the transmit power (1/10 of that used by the DIRC algorithm and 1/10 of that used by the fair-throughput-maximization algorithm). The fair-throughput-maximization algorithm pays a higher cost in power to achieve higher SINR values within the available power budget.

<sup>3</sup>In DIRC, we set  $th_1$  equal to  $S_{min}$ .



TABLE I. POWER UTILITY, TX POWER AND DATA ERROR

	M-Pow	S-Pow	M-Th	S-Th	DIRC	Omni-CS
#APs	<b>Average Power Utility (Mb/<math>\mu</math>J)</b>					
3	<b>5.59</b>	5.16	0.01	0.01	5e-03	2e-06
4	<b>1.72</b>	1.67	0.02	0.01	5e-03	9e-07
9	<b>1.93</b>	2.25	0.01	0.01	4e-03	4e-07
	<b>Total Transmit Power (mW(mJ/s))</b>					
3	<b>0.91</b>	0.60	6.89	6.60	8.77	15.00
4	<b>0.99</b>	0.74	7.15	7.73	9.51	20.00
9	<b>1.57</b>	1.31	11.57	12.39	13.01	45.00
	<b>Data Error Ratio (%)</b>					
3	5.18	5.26	<b>0.48</b>	0.33	0.10	0.03
4	5.34	5.36	<b>0.62</b>	0.32	0.10	0.01
9	5.34	5.32	<b>0.65</b>	0.37	0.07	0.02

<sup>1</sup> The table entries are accurate to two decimal places.

## VII. CONCLUSION

In this paper we studied the joint problem of client association, antenna beam selection, link scheduling, and power adaptation in indoor dense multi-cell wireless networks. To settle the problem, we developed a general framework that applies to both WLAN and OFDMA-based femtocell network. We proposed a unified conflict-free scheduling algorithm with two distinct objectives: power-utility-maximization and fair-throughput-maximization. Our framework can be directly implemented in OFDMA-based femtocell network, and we further designed a new MAC protocol called TD-CSMA, compatible with legacy IEEE 802.11 MAC, for practical deployment in WLAN.

Extensive simulation results obtained from ns-2 highlight the considerable improvements achieved by our algorithms compared to the benchmarks, the feasibility of our TD-CSMA protocol, and the increased spatial reuse achieved by multi-beam scheduling over single-beam. Our next focus is to complete the implementation of TD-CSMA in OpenWrt for real deployment and testing.

## REFERENCES

- [1] K.-L. Hung and B. Bensaou, "Distributed rate control and contention resolution in multi-cell IEEE 802.11 WLANs with hidden terminals," in *Proceedings of the Eleventh ACM International Symposium on Mobile Ad Hoc Networking and Computing*, ser. MobiHoc '10. New York, NY, USA: ACM, 2010, pp. 51–60. [Online]. Available: <http://doi.acm.org/10.1145/1860093.1860101>
- [2] P. Liu, Z. Tao, and S. Panwar, "A cooperative mac protocol for wireless local area networks," in *Communications, 2005. ICC 2005. 2005 IEEE International Conference on*, vol. 5. IEEE, 2005, pp. 2962–2968.
- [3] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted coloring based channel assignment for WLANs," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 9, no. 3, pp. 19–31, 2005.
- [4] Z. Lu, T. Bansal, and P. Sinha, "Achieving user-level fairness in open-access femtocell based architecture," *IEEE Transactions on Mobile Computing*, pp. 1943–1954, 2012.
- [5] V. P. Mhatre, K. Papagiannaki, and F. Baccelli, "Interference mitigation through power control in high density 802.11 WLANs," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE. IEEE*, 2007, pp. 535–543.
- [6] X. Liu, A. Sheth, M. Kaminsky, K. Papagiannaki, S. Seshan, and P. Steenkiste, "DIRC: increasing indoor wireless capacity using directional antennas," in *ACM SIGCOMM Computer Communication Review*, vol. 39, no. 4. ACM, 2009, pp. 171–182.
- [7] —, "Pushing the envelope of indoor wireless spatial reuse using directional access points and clients," in *Proc. ACM Int. Conf. Mobile Computing and Networking*, 2010.
- [8] Y. Bejerano, S.-J. Han, and L. E. Li, "Fairness and load balancing in wireless LANs using association control," in *Proceedings of the 10th annual international conference on Mobile computing and networking*. ACM, 2004, pp. 315–329.
- [9] J. Yoon, K. Sundaresan, M. A. Khojastepour, S. Rangarajan, and S. Banerjee, "Probeam: a practical multicell beamforming system for OFDMA small-cell networks," in *Proceedings of the fourteenth ACM international symposium on Mobile ad hoc networking and computing*. ACM, 2013, pp. 147–156.
- [10] K. Sundaresan and R. Sivakumar, "A unified MAC layer framework for ad-hoc networks with smart antennas," *Networking, IEEE/ACM Transactions on*, vol. 15, no. 3, pp. 546–559, 2007.
- [11] J. Zhang, J. M. Wang, and B. Bensaou, "Joint association control, airtime sharing and contention resolution in multi-cell WLANs with directional antennas," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2013 9th International*. IEEE, 2013, pp. 837–842.
- [12] Y.-B. Ko, V. Shankarkumar, and N. H. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks," in *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 1. IEEE, 2000, pp. 13–21.
- [13] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, "Using directional antennas for medium access control in ad hoc networks," in *Proceedings of the 8th annual international conference on Mobile computing and networking*. ACM, 2002, pp. 59–70.
- [14] R. R. Choudhury and N. H. Vaidya, "Deafness: A mac problem in ad hoc networks when using directional antennas," in *Network Protocols, 2004. ICNP 2004. Proceedings of the 12th IEEE International Conference on*. IEEE, 2004, pp. 283–292.
- [15] B. Kauffmann, F. Baccelli, A. Chaintreau, V. Mhatre, K. Papagiannaki, and C. Diot, "Measurement-based self organization of interfering 802.11 wireless access networks," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE. IEEE*, 2007, pp. 1451–1459.
- [16] E. Aryafar, M. Khojastepour, K. Sundaresan, S. Rangarajan, and E. W. Knightly, "Adam: An adaptive beamforming system for multicasting in wireless LANs," in *INFOCOM, 2012 Proceedings IEEE. IEEE*, 2012, pp. 1467–1475.
- [17] S. Lakshmanan, K. Sundaresan, S. Rangarajan, and R. Sivakumar, "The myth of spatial reuse with directional antennas in indoor wireless networks," in *Passive and Active Measurement*. Springer, 2010, pp. 51–60.
- [18] H. Zhang, Y. Jiang, K. Sundaresan, S. Rangarajan, and B. Zhao, "Wireless data multicasting with switched beamforming antennas," in *INFOCOM, 2011 Proceedings IEEE. IEEE*, 2011, pp. 526–530.
- [19] I.-H. Hou and P. Gupta, "Proportionally fair distributed resource allocation in multiband wireless systems," *IEEE/ACM Transactions on Networking*, 2013.
- [20] M. Chiang, "Balancing transport and physical layers in wireless multi-hop networks: Jointly optimal congestion control and power control," *Selected Areas in Communications, IEEE Journal on*, vol. 23, no. 1, pp. 104–116, 2005.
- [21] S. Jana and S. K. Kasera, "On fast and accurate detection of unauthorized wireless access points using clock skews," *Mobile Computing, IEEE Transactions on*, vol. 9, no. 3, pp. 449–462, 2010.
- [22] S. Saha. (2009, Jun.) The Enhanced Network Simulator (access on Dec, 2012). [Online]. Available: <http://www.cse.iitk.ac.in/users/braman/tens/>