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Joint Access Point Placement and Channel Assignment for 802.11 Wireless LANs

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***Abstract*— To deploy a multi-cell 802.11 wireless local area network (WLAN), access point (AP) placement and channel assignment are two primary design issues. For a given pattern of traffic demands, we aim at maximizing not only the overall system throughput, but also the fairness in resource sharing among mobile terminals. A novel method for estimating the system throughput of multi-cell WLAN is proposed. An important feature of this method is that co-channel overlapping is allowed. Unlike conventional approaches that decouple AP placement and channel assignment into two phases, we propose to jointly solve the two problems for better performance. The optimal solution can be found using exhaustive searching. Due to the high computational complexity involved in exhaustive searching, an efficient local searching algorithm, called patching algorithm, is designed. Numerical results show that for a typical indoor environment, patching algorithm can provide a close-to-optimal performance with much lower time complexity than exhaustive searching.**

***Index Terms*— wireless local area networks, 802.11, access point placement, channel assignment.**

I. INTRODUCTION

THE wireless local area network (WLAN) has been an astounding success since IEEE 802.11 standards have been published to rule the development of WLAN. As more and more multi-cell 802.11 WLANs are being deployed to provide seamless coverage, a systematic approach for determining where an access point (AP) should be placed, and which channel an AP should be assigned become increasingly important.

Efforts dedicated to WLANs design have produced some useful results. Rodrigues [1] reported a real experience of AP placement in an indoor environment which aims at maximizing the total receiving signal strength. Lee [2] considered load balancing among multiple APs by minimizing the load carried by the heaviest-loaded AP. However, these two approaches can give no solution when co-channel interference between cells exists. Kamenetsky [3] combined pruning and other refining algorithms to solve AP placement in an 802.11-based ad-hoc network. Leung [4] discussed the frequency assignment for multi-cell WLAN while assuming an ideal hexagonal coverage for each AP. Park [5] introduced the throughput measurements in an office and a conference room. Hills [6] described the general procedure in a large-scale WLAN design, in which AP placement and channel assignment are carried out in two separated phases.

In this paper, we want to jointly solve the two problems, AP placement and channel assignment, by a single algorithm, with a new objective of simultaneously maximizing the system throughput and maintaining fair resource sharing among mobile terminals. To evaluate and compare different design solutions, an original method for throughput estimation is first proposed. Unlike existing approaches, our estimation method allows co-channel overlapping between cells. In order not to rely on the brutal force for finding the global optimal solution, a heuristic called patching algorithm is also proposed.

The rest of this paper is organized as follows. Section II gives a brief summary on IEEE 802.11 standards and describes a generic design process for deploying a multi-cell WLAN system. In Section III, a novel system throughput estimation method is derived, which takes co-channel overlapping into consideration. Then in Section IV, a new objective function for jointly solving AP placement and channel assignment is proposed. In Section V, the patching algorithm for local searching is designed. The performance of algorithm are evaluated and analyzed in Section VI. Finally, conclusion is given in Section VII.

II. 802.11 SPECIFICATION AND DESIGN PROCESS

Among the IEEE 802.11 standard series, 802.11b is the most-widely deployed version. It uses direct sequence spread spectrum (DSSS) as physical layer and adopts carrier sense multiple access with collision avoidance (CSMA/CA) in MAC layer. The data rates supported are 1, 2, 5.5 and 11Mbps depending on the received signal sensitivity thresholds (RXThresh). If the received signal strength is below RXThresh but above carrier sense threshold (CSThresh), carrier busy can be detected. In an 802.11b network, there are 13 channels regulated by ETSI or 11 channels regulated by FCC. Adjacent channels have spectrum overlapping; so generally only 3 fully isolated frequency bands can be assigned for eliminating adjacent channel spectral interference. To avoid collision caused by hidden terminals, Request-to-Send (RTS) / Clear-to-Send (CTS) mechanism is usually adopted.

The target of WLAN design is to satisfy the traffic demands from the mobile terminals while keeping the deployment cost low. A generic design process for deploying a multi-cell WLAN system consists of four phases [1,2]:

1) Partitioning the service area into grids: Each grid is the basic spot for terminal counting and signal strength measuring.

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(a) Channel idle (c) Channel collision

(b) Channel held by a successful transmission

Figure 1: Three scenarios of channel conditions

2) Choosing candidate locations for APs: Generally these candidate locations should be convenient for AP installing.

3) Signal strength measurement: The measurement should be taken at every covered grid for every AP candidate. The signal strength could also be predicted by analysis [7].

4) Deciding AP placement and channel assignment: Our research in this paper focuses on this phase.

III. THROUGHPUT ESTIMATION

To jointly carry out AP placement and channel assignment, we must have a simple and efficient way to evaluate and compare different solutions. In this section we propose an efficient method for throughput estimation of a multi-cell WLAN system.

Reference [8] analyzed the system performance of one AP's service region (i.e. a single cell), from which the probability (P_{tr}) that at least one mobile terminal (MT) transmits the packet in the considered slot time, and the probability (P_s) that a transmission seizes the channel successfully are derived as follows:

$$P_{tr} = 1 - (1-\tau)^n \tag{1}$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} \tag{2}$$

where n is the total number of mobile terminals in a cell; τ is the probability that a mobile terminal's backoff timer decreases to zero (and a packet will be sent). Please refer to [8] for more details.

Fig. 1 shows the three possible channel conditions: (a) channel idle; (b) channel held by a successful transmission; and (c) channel collision, i.e. more than one MT transmit at the same time. The corresponding channel idle probability P_{idle}, the successful transmission probability P_{succ}, and the channel collision probability P_{coll} can be obtained as follows.

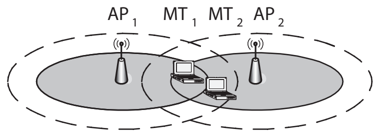
$$P_{idle} = 1 - P_{tr} \tag{3}$$

$$P_{succ} = P_{tr}P_s \tag{4}$$

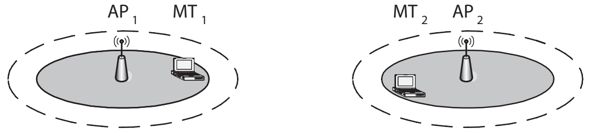
$$P_{coll} = P_{tr}(1 - P_s) \tag{5}$$

Based on 802.11b specification, let the channel idle duration time T_{idle} in Fig. 1a be 20 μs. In Fig. 1b, if RTS/CTS mechanism is adopted, the total channel holding time for MT$_i$'s packet transmission, T_i, is given by:

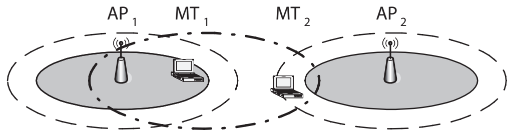
$$T_i = T_{RTS} + T_{CTS} + T_{preamble} + T_{MPDU-i} + T_{ACK} + T_{DIFS} + 3T_{SIFS} \tag{6}$$



(a) Overlapped cells



(b) Fully-separated cells



(c) Incompletely-separated cells

Figure 2: Relationship of AP cells. (The regular shaped cell is for illustration purpose only.)

$$T_{MPDU-i} = \frac{L_{PLCPheader}}{1Mbps} + \frac{L_{MACheader} + L_{data-i} + L_{FCS}}{DR_i} \tag{7}$$

where T_{DIFS}, T_{SIFS} are the corresponding interframe spaces; T_{RTS}, T_{CTS}, T_{ACK} are time for each handshaking message; $T_{preamble}$ is the time consumed by preamble; T_{MPDU-i} is the total transmission time for MT$_i$'s data packet; $L_{PLCPheader}$, $L_{MACheader}$, L_{FCS} are the sizes of the corresponding packet header and trailer fields; L_{data-i} is the size of the payload; the data rate *DR*$_i$ is 11, 5.5, 2 or 1Mbps depending on MT$_i$'s received signal strength.

When channel collision occurs, the sender can not receive CTS frame and the collision can be quickly detected; see Fig.1c. So the collision time T_{coll} is:

$$T_{coll} = T_{RTS} + T_{DIFS} \tag{8}$$

If constant MAC packet size is assumed, low data rate terminals will hold the channel longer than high data rate terminals [9]. For example, if CBR service is carried by 1500-byte UDP packet, the channel holding time for sending a UDP packet using 1/2/5.5Mbps data rate are 5.80/3.16/1.48 times of that using 11Mbps.

To cover the whole building or campus by multi-cell WLAN, some cells maybe be assigned to use the same channel. The relationship between such co-channel cells falls into three types:

1) Overlapped cells: In Fig. 2a, two overlapped cells AP$_1$ and AP$_2$ are illustrated. The shaded areas denote the receiving range (where signal strength $>$ RXThresh), and the dashed circles denote the interference range (where signal strength $>$ CSThresh). MT$_1$ can sense the carrier from both AP$_1$ and AP$_2$.

2) Fully-separated cells: In Fig. 2b, the received signal strength from AP$_1$ to MT$_2$ fades below the sensitivity threshold and it cannot provide adequate quality for demodulation. Likewise MT$_1$ cannot detect AP$_2$. And the distance between two cells is far enough, such that the associated MTs in one cell cannot interfere the data transmission in the adjacent cell.

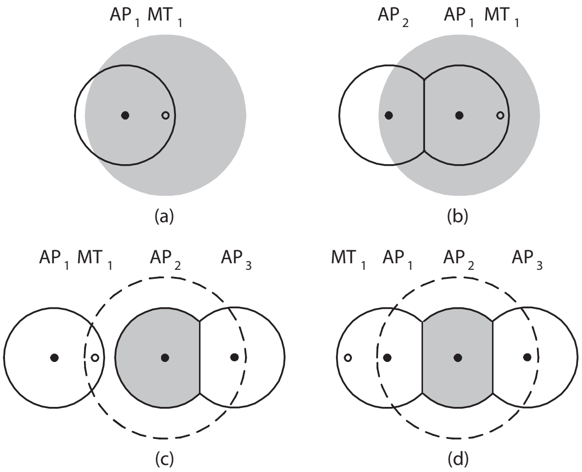


Figure 3: Restrain criteria

3) Incompletely-separated cells: In Fig. 2c, two cells are separated but the distance between them is not far enough; MT_1 located at the boundary of cell1 can receive the co-channel signals from its neighbor MT_2 who is associated with AP_2. (The dashed-and-dotted line shows the coverage of MT_1.) In this case, MT_1 cannot send packet to AP_1 simultaneously as MT_2 send to AP_2. They have mutual interference.

Both contention within a cell and the co-channel interference from adjacent cells can restrain a MT from data transmission. Assume MT_1 is associated to AP_1, the four possible coverage scenarios are shown in Fig. 3. For each scenario, the area that a potential restrainer of MT_1 may reside is shaded. (The solid and dashed circles delineate the boundaries of AP's receiving ranges and interference ranges respectively.)

From Fig. 3, the potential restrainers of MT_1 can be found:

1) Mobile terminals in MT_1's radiating range. The shaded area in Fig. 3a illustrates where the mobile terminals can be heard by MT_1 directly.

2) Mobile terminals located in AP_1's interference range will restrain MT_1, including those not associated to AP_1. Refer to Fig. 3b.

3) If MT_1 is in AP_2's interference range, mobile terminals associated to AP_2 will restrain MT_1. In Fig. 3c, when AP_2 communicates with its subscribers that are located in the shaded area, MT_1 detects the carrier busy. MT_1 will keep silence until transmission in AP_2's service area ends.

4) If AP_1 and AP_2 are so close that they can interfere with each other directly, mobile terminals associated to AP_2 are MT_1's restrainers. This is shown in Fig. 3d, where AP_1 detects transmission in AP_2's service area and then keeps silence. When MT_1 requests transmission to AP_1, AP_1 will not respond.

For a mobile terminal MT_i, its restraining range consists of the spots where its restrainers locate. Under the saturated traffic assumption, MT_i and its restrainers make the same amount of effort in requesting for the channel. The probability that MT_i successfully holds the channel for a packet transmission, Pr_i, is given by the following equation.

$$Pr_i = \frac{\frac{P_{succ}}{1+\sum\limits_j rsn_{ij}} T_i}{\frac{P_{succ}}{1+\sum\limits_j rsn_{ij}} [T_i + \sum\limits_j (rsn_{ij} \times T_j)] + P_{idle} \times T_{slot} + P_{coll} \times T_{coll}} \tag{9}$$

where rsn_{ij}=1 if MT_j is a restrainer of MT_i; otherwise rsn_{ij}=0. From (4), P_{succ} is the probability of a successful transmission. $\frac{P_{succ}}{1+\sum\limits_j rsn_{ij}}$ is the probability that the successful transmission is achieved by MT_i. The denominator in (9) is the expected interval between any two consecutive successful packet transmissions by MT_i. It consists of three components, the total channel holding time by successful transmissions from MT_i and all its restrainers, the channel idle time due to backoff, and the channel collision time. The numerator in (9) can be regarded as the amount of time that MT_i holds the channel for a successful transmission. From (9), we can see that more restrainers make it harder for MT_i to seize the channel.

Let THR_i be the throughput of MT_i. We have:

$$THR_i = DR_i \times \; Pr_i \times E_i \tag{10}$$

DR_i is the data rate of MT_i. The efficiency E_i represents the percentage of transmitting time that is used by MT_i to carry the payload of a MAC frame (i.e. excluding overheads such as inter-frame gap, preamble, and frame headers, adversely affect the throughput efficiency.) We have

$$E_i = \frac{L_{data-i}/DR_i}{T_i} \tag{11}$$

The total system throughput THR_{total} can then be estimated by adding the respective throughput of individual MTs.

$$THR_{total} = \sum_i THR_i \tag{12}$$

IV. New Objective Function

Several objective functions (OF) were proposed in the literatures respectively for AP placement or channel assignment.

In this section, we design a new objective function for joint optimization of AP placement and channel assignment. This function, shown in (13), aims at optimizing both the system throughput and the fairness among MTs. It is a product between THR_{total} from (12) and the fairness index β from (14). (Note that AP placement and channel assignment are carried out in the system design phase; a detailed throughput analysis based on the actual traffic generation is not needed. And the sustained traffic demand represents the worst situation that system will encounter.) In (14), β is defined as a measure of the fluctuations of the throughputs acquired by individual MTs.

$$OF = THR_{total} \times \beta \tag{13}$$

$$\beta = \frac{(\sum\limits_{i=1}^{N} THR_i)^2}{N \times \sum\limits_{i=1}^{N} THR_i^2} \tag{14}$$

N is the total number of MTs in the multi-cell system. The fairness index β approaches 1 when all MTs have exactly the

Table I: Patching Algorithm Psedo-Code

```
$k$=1; //Now we try to place the $k$-th AP
while ($k \leq$the number of APs planned to place) {
  $i$=the first AP candidate in the candidate set;
  while ($i \leq$the last AP candidate in the candidate set) {
    place AP$_i$ temporarily;
    $j$=1; //If $J$ channels available, $j$=1$\sim J$
    while ($j \leq$J) {
      assign channel $j$ to AP$_i$ temporarily;
      calculate the OF for the current $k$ placed APs, record it as OF$_{ij}$;
      $j$++; //try to assign another channel instead of previous channel
    }
    $i$=next; //try to place another candidate instead of previous AP
  }
  pick up the largest OF$_{ij}$;
  AP$_i$ is placed and channel $j$ is assigned to it permanently;
  update candidate set;
  $k$++; //ready to place the next AP
}
converge on the local optimum.
```

same throughput. When the throughputs are heavily unbalanced, β converges to $1/N$.

V. PATCHING ALGORITHM

Based on the objective function defined in (13), an optimal solution for joint AP placement and channel assignment can be found by exhaustive searching. If the number of AP candidates is large, the exhaustive search becomes extremely complex. Assume M APs should be chosen from L candidates and three isolated channels are available for channel assignment. The number of possible solutions is on the order of $C_L^M(3^{M-1}+1)/2$. Brutal force searching is thus not feasible. In this section, we propose a time-efficient local searching heuristic, called patching algorithm.

Patching algorithm places APs one by one to cover the traffic demands until a pre-defined number of APs are placed. At each step, patching algorithm attempts to select one AP from the remaining candidate pool, which can provide the largest OF value together with those already placed APs. The pseudo-code for patching algorithm is outlined in Table I.

The patching algorithm starts with an initial candidate set that contains all candidate APs, i.e. $\{\text{AP}_1,\text{AP}_2,\ldots\text{AP}_L\}$. Then the candidate that gives the largest OF value is selected for first AP placement. The AP candidate set is updated by deleting the placed AP. To select and place the second AP, we consider the remaining L-1 candidate APs together with three possible channel assignments each. Then we evaluate every possible combination of candidate placement and channel assignment. The candidate AP with a suitable channel that gives the largest OF value among all possible combinations is then selected for the second AP placement and channel assignment. The candidate set is then updated. This process is repeated until a pre-determined number of APs are placed. In each iteration, newly added AP may cause some MTs to re-associate with it, and the restrain range of some MTs will also be affected. If this happens, the throughput of those affected MTs should be re-estimated using (10). In each iteration of our search implementation above, only one solution can survive. For a more reliable convergence, we can allow more (e.g. 2) solutions to survive. Then the exploration will be repeated in these survivors' descendants. Here we use $P_{survive}$ to denote the number of survivors at each iteration.

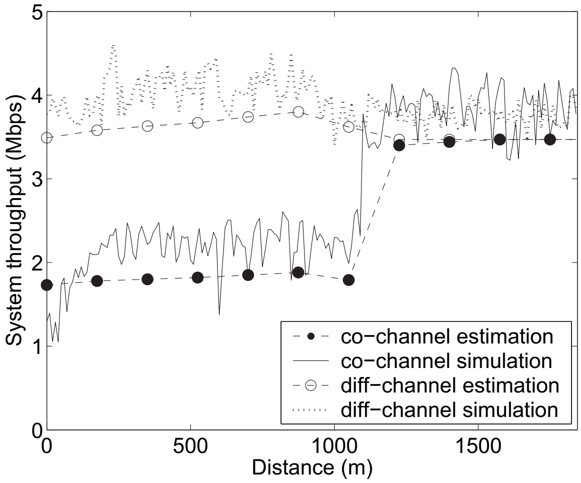


Figure 4: Total co-channel and diff-channel throughput according to the distance between two APs

VI. PERFORMANCE EVALUATIONS

A. Throughput Estimation Verification

First a simple scenario of two overlapped cells is simulated by NS-2 to verify the throughput estimation method we proposed in Section III. We consider two APs. MTs are uniformly distributed and communicate with the fixed network via these two APs. UDP connections carrying 1500-byte CBR packets are established from the MTs to the fixed network. Assuming the bandwidth of the wired links is large enough, so that the wireless interface is the only bottleneck in the transmission. The transmission power is set to 20dBm. The RXThreshs are -75/-79/-81/-84dBm respectively for different data rate receivers, and CSThresh is set to -94dBm.

If a same channel is assigned to these two APs, the estimated throughputs and those obtained by simulations are compared in Fig. 4. The x-axis is the distance between the two APs. When Distance=0m (i.e. these two APs are fully superposed) and assuming one user dwells in each grid, there are 13/8/4/12 mobile terminals working at 11/5.5/2/1Mbps data rates respectively. The channel holding time, T_i, obtained by (6)-(7) is 2368/3504/7480/13728μs respectively for different data rate MTs. From (9) and (11), we learn that the channel seizing probability Pr_i is 0.00908/0.0134/0.0287/0.0526 respectively and the efficiency E_i is 0.469/0.634/0.817/0.890 respectively. So the system throughput is given by

$$THR_{total} = 13 \times 11Mbps \times 0.00908 \times 0.469 + 8\times \\ 5.5Mbps \times 0.0134 \times 0.634 + 4 \times 2Mbps \times 0.0287 \\ \times 0.817 + 12 \times 1Mbps \times 0.0526 \times 0.890 = 1.73Mbps$$

It is evident from Fig. 4 that the system throughput is poor when the distance between APs is less than the interference radius R_{CS} ($\approx$1062m). In this case, the two co-channel APs cannot be fully utilized. This causes the system throughput

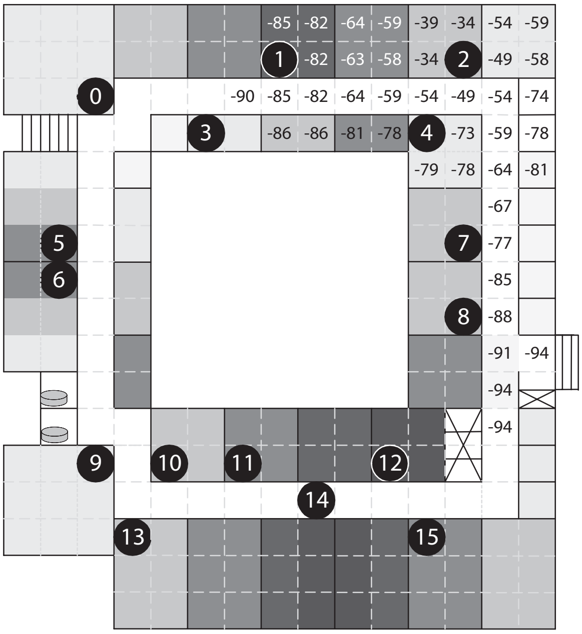
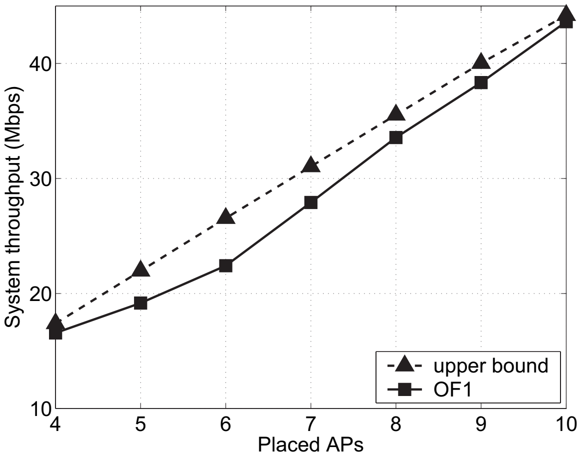
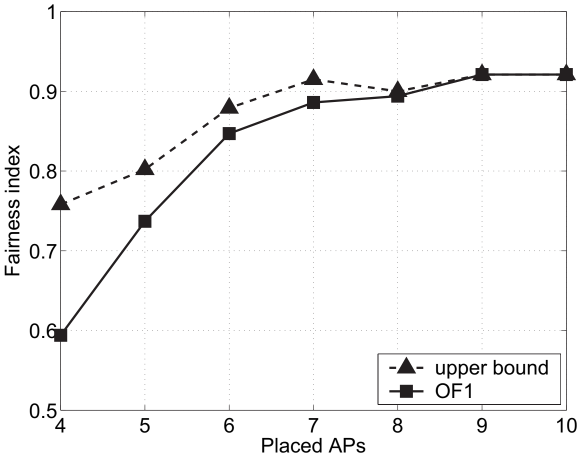


Figure 5: MT distribution and candidate AP locations in a building. (Remarks: The intensity of the grey level indicates the user density from 0 to 6 terminals per grid. If a grid can receive signal from AP_2 with a signal strength larger than or equal to CSThresh (-94 dBm), the grid is labelled by its received signal strength value. Otherwise, the grid is not labelled.)



(a) Throughput



(b) Fairness index

Figure 6: System throughput and fairness index of global optimums based on OF_1

of two fully superposed APs approximating to the throughput level of only one AP placed at that spot. If the distance is longer than R_{CS}, no interference exists between APs, both APs work with full utilization, so the system throughput is doubled to give 3.47 Mbps.

Fig. 4 also compares another scenario that different channels are assigned to the two APs, denoted by "diff-channel". We can see that the diff-channel overlapping between cells can slightly improve the system throughput. This is because mobile terminals residing at the boundary of AP_1 can only work at low data rate if they associate to AP_1; when overlap is provided by another AP_2 assigned with a different channel, some low data rate terminals can now re-associate to AP_2; then those terminals can get a higher data rate.

To conclude, the above study shows that our throughput estimation method can provide a satisfactory prediction with or without co-channel overlapping. The results in the subsequent subsections are thus based on this throughput estimation.

B. Environmental Assumption

Following the design process described in Section II, the service area partitioning for a typical building floor is shown in Fig. 5, with a gird granularity of 5m. A non-uniform distribution of 0 to 6 MTs per gird is illustrated by different grey levels. The 16 AP candidate locations are given and numbered from 0∼15.

The signal strength is predicted by Two-Ray-Ground model [12]. The received signal strength fades due to the path loss during propagation. Longer distance the signal traveled or more barriers it encountered causes heavier path loss. The typical pathloss values of signal traveling across concrete wall and turning right angle at the corner are 15dB and 10dB. The predicted receiving signal strengths in dBm for candidate AP_2 are shown in Fig. 5 as an example. Note that for those grids with signal strengths below CSTresh (-94 dBm) are not labeled.

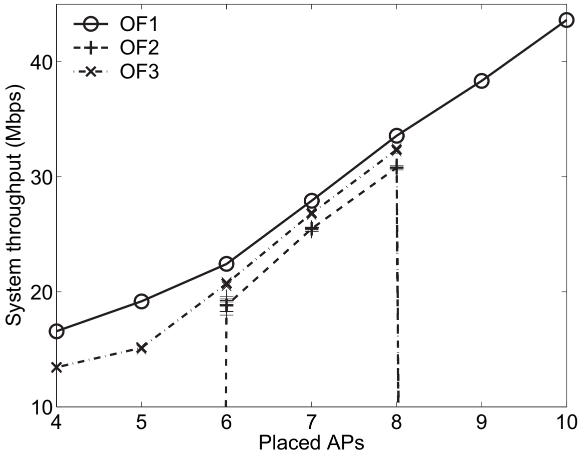
C. Objective Functions and Global Optimums

For convenience, let the objective function defined in (13) be OF_1, the objective function proposed in [2] be OF_2, and the objective function adopted in [1] be OF_3. OF_2 attempts to balance the loads among APs, whereas OF_3 tries to maximize the sum of received signal strengths.

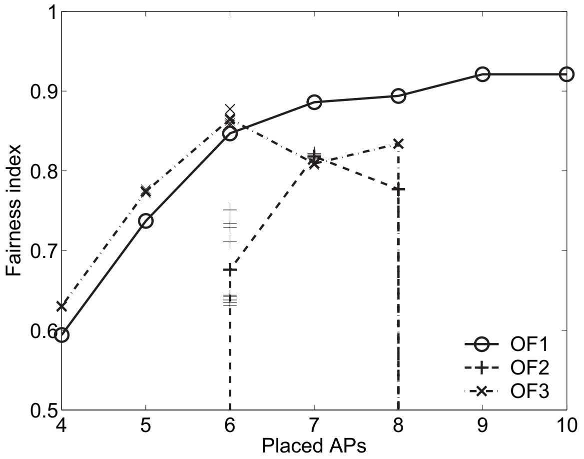
Based on the optimal values of OF_1 found, Fig. 6 separately plots its two components, system throughput THR_{total} and fairness index β, when 4 up to 10 APs are placed. In the same figure, the upper bounds on THR_{total} and β are also plotted. They are obtained by searching through all the possible solutions. For example, to choose 7 APs from 16 candidates with 3 available channels, there are 4,175,600 possible solutions. Among them, the highest throughput that can be achieved is 31.04Mbps. So 31.04Mbps is the upper bound on throughput

Table II: Computational Complexity

\ Visited solutions	**Exhaustive**	**Patching algorithm**	
**APs **	**searching**	$P_{survive} = 1$	$P_{survive} = 2$
4	25480	127	538
5	179088	163	1108
6	976976	193	2156
7	4175600	226	4057
8	14079780	253	7467
9	16777216	277	13481
10	16777216	298	23901



(a) Throughput



(b) Fairness index

Figure 7: System throughput and fairness index of optimums found by exhaustive search based on three objective functions

when placing 7 APs. From Fig. 6, we find that our joint AP placement and channel assignment based on (13) can achieve excellent system throughput, while maintaining a very high fairness index (usually > 0.8). The optimal solution for placing 7 APs is to assign channel_1 to AP_1, AP_6 and AP_{14}, assign channel_2 to AP_4 and AP_{15}, and assign channel_3 to AP_8 and AP_{13}. We can see that some APs are placed around the hotspot to ease its traffic demands.

Fig. 7 compares the optimal solutions obtained by exhaustive searching based on OF_1, OF_2 and OF_3. We can see that our joint AP placement and channel assignment based on OF_1 provides the highest system throughput and close-to-best fairness performance. Note that more than one optimal solution can be found based on OF_2 and OF_3. Their distributions are illustrated and their average values are connected by dashed lines. From Fig. 7, we can see that there is no solution for OF_2 when less than 6 APs are placed. This is because optimization method in [2] has a constraint that every MT must be served. If less than 6 APs are placed, no solution can be found to cover all terminals. Besides, when more than 8 APs are placed, there is no solution for both OF_2 and OF_3. This is because those placement algorithms do not allow co-channel overlapping. If more than 8 APs are placed, co-channel interference between APs cannot be avoided.

D. Patching Algorithm and Local Optimums

The patching algorithm described in Section V can significantly reduce the computational complexity. For solving the same problem as that in the previous subsection, Table II summarizes the number of solutions that are visited by the exhaustive searching and the patching algorithm respectively. It proves that patching algorithm can save convergence time.

The OF values found by the exhaustive searching and the patching algorithm are compared in Fig. 8. The patching1 line illustrates the performance of patching algorithm with one solution surviving at each iteration. The situation of two survivors at each iteration is shown by patching2 line. We can see that the performance of patching algorithm is very close to the optimal.

The patching algorithm considers AP placement and channel assignment jointly. We compare it with another method, Prun+RCC, in Fig. 9. Prun+RCC spits AP placement and channel assignment into two separated phases. The pruning algorithm (Prun) is adopted in AP placement phase for minimizing pathloss [3], and a random channel convergence (RCC) algorithm is used in the channel assignment phase [4]. RCC adjusts the channel assignment of the bottleneck AP's neighbors to minimize bottleneck AP's traffic load.

In Fig. 9, we can see that more than one optimal solutions (> 20) can be found by Prun+RCC algorithm. This is because the RCC algorithm only adjusts the channel assignment in bottleneck AP's neighbors. For a heavily unbalanced mobile terminal distribution, the bottleneck AP usually locates at the hotspot area. Adjusting the channels in its neighboring APs cannot reduce the load of the bottleneck AP effectively. If the bottleneck cannot be removed from the hotspot to other "cooler" spots, this algorithm cannot optimize the channel assignment in light traffic demand areas. As such, channels can be assigned to the APs in light traffic demand areas freely; this generates many local optimal solutions. In short, Fig. 9 shows that splitting AP placement and channel assignment into two isolated phases leads to poor performance than patching algorithm.

VII. CONCLUSIONS

In this paper, we first proposed an original method to estimate the throughput of a multi-cell 802.11b WLAN system. The co-channel overlapping between cells is allowed. Then an optimization method for joint AP placement and channel

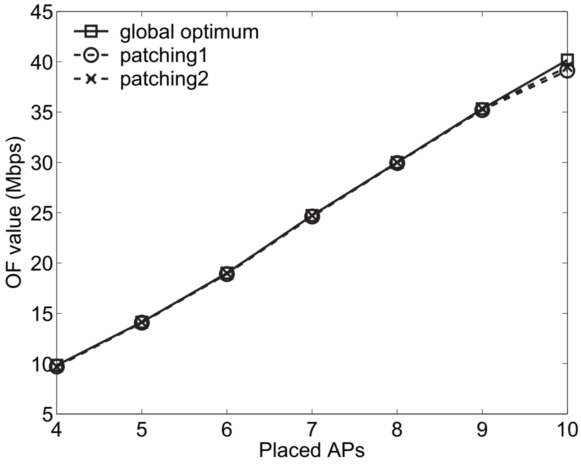


Figure 8: OF values got by patching algorithm and exhaustive searching

assignment was proposed, which aims at maximizing both the system throughput and the fairness index. Its optimal solutions can be found by exhaustive searching. To reduce the computational complexity, a simple local searching heuristic, called patching algorithm, was designed and analyzed. We showed that in a typical indoor environment, patching algorithm provides close-to-optimal system throughput and fairness index.

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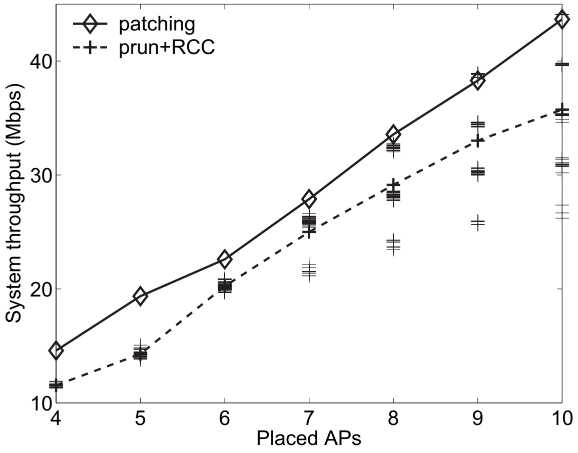
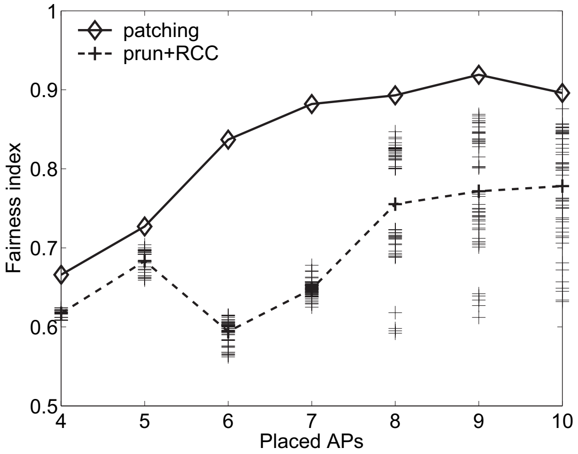
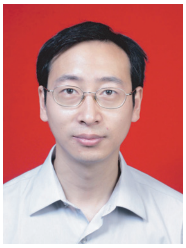


(a) Throughput



(b) Fairness index

Figure 9: System throughput and fairness index of local optimums



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