NEXT GENERATION WIRELESS LAN SYSTEM DESIGN [1]

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ABSTRACT

An important issue in the widespread deployment of infrastructure based wireless local area networks (WLANs) is the network design. In this paper, we propose a new WLAN design approach that focuses on assuring sufficient data rate capacity to meet expected user demand in the coverage area, while still satisfying signal coverage and interference level requirements. Noting the low cost of WLAN access points, we formulate a novel mathematical network design model within the framework of constraint satisfaction problems. Our model is termed the ***capacity based WLAN constraint satisfaction problem (Cap-WLAN CSP)****. The solution of the Cap-WLAN CSP model yields a network design based on data rate demand by providing the access point locations, the frequency channel allocation, and power levels required for the WLAN to meet expected user demands. Our numerical results illustrate that the capacity based approach is more appropriate for the design of WLAN systems than those of traditional coverage based designs.*

I. INTRODUCTION

Wireless local area networks (WLANs), such as those built on the IEEE 802.11b standard, are experiencing tremendous growth, providing consumers and businesses mobile data networking capabilities that complement the mobile voice capabilities of cellular phones. The deployment of WLANs and the growth in the number of subscribers has been phenomenal and is expected to continue or increase at its fast pace [1-3, 13]. The fact that laptop computers and other mobile devices (e.g., PDAs) are becoming cheaper, smaller and more powerful has driven the demand for WLAN services. An important issue in such wide spread deployment of WLANs is the network design.

The network design determines the number, location and configuration (e.g., frequency, power level, etc.) of WLAN access points (APs) and the network capacity (aggregate bit rate) provided to a specific geographic area. In current practice, WLANs are largely designed in the basis of a trial and error, measurement based approach. Specifically, one places APs in buildings at opportunistic locations, measures the received signal strength in the desired coverage areas of the building and adjusts the AP locations, power levels, frequency channel etc., based on the observed coverage [15]. All of this is done manually, and is labor intensive. Such an approach is expensive and time consuming when deploying large numbers of WLAN APs.

In the research literature, work has appeared on developing algorithms for the design of WLANs in an indoor environment [4-6]. This work seeks to create a coverage based WLAN design; that is ensuring that an adequate received signal strength and signal-to-interference ratio (SIR) are maintained in the intended service area. These papers are similar in that they formulate optimal access point/ base station placement problems with very similar objective functions and vary only slightly in the assumptions and the approaches to solve the optimization problem. The current coverage based WLAN design approach is sufficient for small networks of a few APs where user density is low and traffic load is light. However, as the number of WLAN users and applications increases, network capacity becomes an issue and a ***fundamentally different approach*** to network design is required. A network design solution must account for wireless user density, expected user subscriber profiles, traffic models for various applications, and support for QoS classes. Support for these requirements in turn requires designing the WLAN system based on a data rate density criterion because the first step towards providing any kind of QoS is to ensure availability of the necessary bandwidth (data rate). However, current work in WLAN design ignores this issue and concentrates on providing signal coverage and acceptable interference levels in cells. While these factors play a crucial role in the overall design, they are not sufficient for guaranteeing a particular aggregate data rate capacity in a specific geographic area. In the recent literature Kabara[7] and Hills [8] discuss the need for considering of capacity requirements in WLAN design and Tutschku [11, 14] presents similar arguments for the consideration of traffic load in the design of circuit switched cellular voice networks.

In this paper, we present a new design methodology for infrastructure based WLANs capable of supporting a data rate demand ***(data rate density)*** in a given area. The design methodology will determine the number of access points (APs), frequency channels, power level and the placement of the APs, that will satisfy a set of constraints that include the data rate density requirement, radio propagation conditions and physical limitations like receiver sensitivity. Unlike current optimization approaches we formulate the design problem as a constraint satisfaction problem (CSP) [12] that we will refer to as Capacity based WLAN constraint satisfaction problem (Cap-WLAN CSP).

The remainder of the paper is organized as follows. Section II presents the formulation of the Cap-WLAN CSP and discusses a solution technique. Section III illustrates network

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design results and discusses computational complexity. Finally, section IV concludes the paper.

II. CONSTRAINT SATISFACTION PROBLEM FORMULATION

The optimization based WLAN design approaches [4-6] aim to minimize the number of and optimize the location of the access points. This objective results in a very large and complex solution space and such design formulations are NP hard, thus heuristic sub-optimal solution techniques to the optimization models have been proposed. However, it is unnecessary in the design of WLAN systems to minimize the number of the APs due to the low cost of the AP compared to the wireless devices with which they are communicating. However, over-provisioning the service areas leads to serious system performance degradation due to co-channel interference. Thus, we propose that it is more appropriate and effective to formulate the design problem as a constraint satisfaction problem rather than an optimization problem. Our algorithm represents a service region as discrete space of grid size 1m × 1m. The grid points represent candidate locations to install APs and specify the locations that require radio signal coverage. In our design experiments we consider two cases, the first allows APs to be located at any grid intersection. The second restricts AP locations to a more narrowly defined feasible space (e.g., located only in hallways).

The general Cap-WLAN CSP design approach is shown in figure 1. The network design algorithm is structured into two main parts. The first part involves determining the minimum number of APs necessary for a given service requirement and initializing APs' configuration. The second stage implements a solution algorithm for the CSP and determines the AP parameters, including locations, power levels, and frequency channel, such that the designed WLAN system satisfies the service requirements. Two sets of input components are provided to the Cap-WLAN CSP algorithm. The first set of inputs defines the service environment including the spatial traffic demand distribution and the physical structure of the service area. The second set of inputs incorporates the path loss models that approximate radio propagation in the given physical service environment.

The Cap-WLAN CSP formulation is defined by the triple (**V, D, C**), where **V** = the set of variables, **D** = the set of finite domains associated with the variables, and **C** = the set of constraints. We represent any two-dimensional space with *(x, y)* coordinates. Let *A* denote the set of *N* access points $\{ap_1, ap_2, \ldots, ap_n\}$, *U* denote the set of wireless users or demand nodes in the service area $\{u_1, u_2, \ldots, u_m\}$, *GC* denote the set of grid points $\{g_1, g_2, \ldots, g_c\}$ representing the area that requires radio coverage.

We define a set of variables **V** = $\{p_j, f_j, u_{ij}, g_{hj}, (x_j, y_j)\}$ where p_j is the power level of access point *j*, *"jÎA*; f_j is the frequency channel of access point *j*, *"jÎA*; u_{ij} is a binary variable that indicates whether user *i* associates with access point *j* or not, *"iÎU, "jÎA*; g_{hj} is a binary variable that indicates whether grid point *h* can receive signal from access point *j* or not, *"hÎGC, "jÎA*; (x_j, y_j) indicates the location of access points, *"jÎA*.

We also define the domains of the variables, **D** be the set of domains of the form $\{\mathbf{D_p}, \mathbf{D_f}, \mathbf{D_{uij}}, \mathbf{D_{ghj}}, \mathbf{D_{(xj,yj)}}\}$ where: $\mathbf{D_p}$ = the domain of p_j variable for *"jÎA*, $\mathbf{D_f}$ = the domain of f_j variable for *"jÎA*, $\mathbf{D_{uij}}$ = the domain of u_{ij} variable = {0, 1} for *"iÎU, "jÎA*, $\mathbf{D_{ghj}}$ = the domain of g_{hj} variable = {0, 1} for *"hÎGC, "jÎA*, $\mathbf{D_{(xj,yj)}}$ = the domain of (x_j, y_j) variable = $\{x_{min} < x_j < x_{max}$ and $y_{min} < y_j < y_{max}\}$ for *"jÎA*.

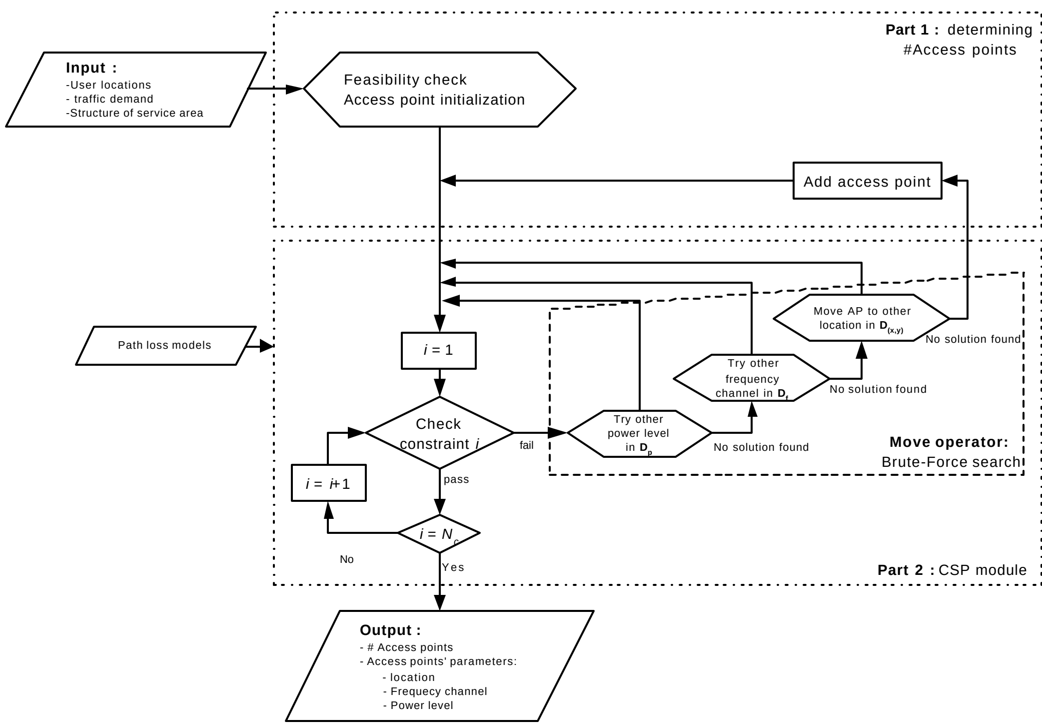

Figure 1 Cap-WLAN CSP Algorithm

We define a set of constraints **C** = {**C1**, **C2**, **C3**, **C4**, **C5, C6**}. Each constraint put restrictions and requirements to the WLAN design as follows: **C1** states that each wireless terminal is associated to one access point. **C2** states that the signal received at each wireless terminal must be greater than the receiver threshold sensitivity. **C3** assures that the traffic demand of wireless terminals assigned to a particular AP does not exceed the data rate capacity of the AP. Here, we incorporate the effective capacity coefficient (b) to capture the effects of capacity reduction due to the number of wireless terminals and wireless terminals' traffic characteristics associated to the AP. **C4** specifies the interference threshold of the wireless terminal. **C5** states that a portion of mean data rate from all wireless users in a service area is served by available APs. a specifies a portion of all traffic demand that we consider serving. **C6** states that the radio signal will be available across the specified coverage space. This condition allows the grid point to be able to receive radio signal from more than one access points, i.e. it allows over-lapping of the access points' coverage areas. $g_{hj} = 1$ if the received signal strength at the grid point h from the access point j is greater than P_R and the associated interference level is below P_I; $g_{hj} = 0$ otherwise. Note that constraint **C1**, **C2**, **C4** and **C6** include the path loss model, which may vary for different service area environments. To solve the Cap-WLAN CSP, we employ a brute force search technique, where variable values are tested in sequence. In the next section we demonstrate that a brute-force search is in some case efficient enough.

Figure 2 Constraint Satisfaction Problem Formulation: 2-D capacity-based WLAN design

Path loss model:

$$L\left(f_j,(x_i,y_i),(x_j,y_j)\right) = L(d_0)+10n_0\log\left(\frac{d_{ij}}{d_0}\right)+K_s$$

$$L(d_0) = 10\log\left(\left(\frac{4pd_0 f_j}{3\times 10^8}\right)^2\right)$$

Input parameters:

d_0	the reference distance
d_{ij}	the distance between user i and access point j
n_0	the path loss exponent
K_s	the shadow fading margin
P_R	the received signal strength threshold
P_I	the signal interference power threshold
C_{ap}	access point capacity
d_i	traffic demand from user I
β	access point effective capacity coefficient
α	portion of traffic demand guaranteed to be served

Constraints:

C1: $$\sum_{j=1}^{n} u_{ij} = 1 \quad ,\forall i\in U$$

C2: $$\sum_{j=1}^{n} u_{ij}\left(p_j - L\left(f_j,(x_i,y_i),(x_j,y_j)\right)\right) \geq P_R, \forall i\in U$$

C3: $$\sum_{i=1}^{m} d_i u_{ij} \leq bC_{ap} \quad ,\forall j\in A$$

C4: $$10\log\left(\sum_{\substack{k=1\\ f_k=f_j}}^{n}(1-u_{ik})\log^{-1}\left(p_k - L\left(f_k,(x_i,y_i),(x_k,y_k)\right)\right)\right) \leq P_I \quad ,\forall i\in U,\ u_{ij}=1$$

C5: $$\sum_{j=1}^{n}\sum_{i=1}^{m} d_i u_{ij} \geq a\sum_{i=1}^{m} d_i$$

C6: $$\sum_{j=1}^{n} g_{hj} \geq 1 \quad ,\forall h\in GC$$

III. NUMERICAL RESULTS

A. 802.11b design example

Numerical network design experiments were conducted for a small and large single-floor service area with low and high data rate requirement scenarios. The small service area is the fourth floor (21m × 35m) of the Information Science (IS) building at the University of Pittsburgh. The large service area is the first floor (60m × 65m) of the Hillman library at the University of Pittsburgh. We classify wireless users into three categories based on typical demands in this environment. Those with handheld computers (smaller devices with lower computational power, smaller memory like an HP Jornada) access the network at 50 Kbps. The second class of wireless devices need a medium data rate of 250 Kbps as they employ laptops to mostly read email and access some Internet sites with little multimedia content. The third category consists of high data rate wireless terminals who use their laptops at the fullest network speed possible (current measurements indicate that typical laptops transmit or receive data at about 2 Mbps). These wireless terminals utilize remote file systems and streaming audio/video.

The domains for the variables were tailored to current 802.11b practices; $\mathbf{D_p}$ = {15, 20, 24} in dBm, and $\mathbf{D_f}$ = {2.412, 2.437, 2.462} in GHz. These experiments employed the log distance path loss model [10] to estimate radio propagation characteristics. Input parameters were selected with respect to the service environment, the building structure and the 802.11b specification. Here, $n_0 = 3.02$ [10], $K_s = 10$ [10], $P_R = -80$ dBm, $P_I = -90$ dBm, and $C_{ap} = 11$ Mbps [9]. The design aims to serve all traffic demand, i.e., $a = 1$ on a 1m x 1m grid. Due to the contention based MAC protocol, it is assumed that the access points' throughput reduces to 90% of the access point full capacity, i.e. $b = 0.9$.

Figure 4 illustrates the case of the small service area with a coverage-based design. In this example the WLAN system utilizes two access points to cover the entire service areaat the specified signal strength threshold, given the propagation environment. However, this design does not provide adequate capacity to all wireless users. In this network there are a total of 33 users, 23 users require 250 Kbps each and 10 users require 2 Mbps each, this results in total traffic demand of 25.75 Mbps. Hence, the use of two access points can not support all traffic load. For this same service scenario, however, the Cap-WLAN CSP design approach estimates the number of APs from the aggregate traffic demand, which in this case requires a minimum of three APs. Then a brute-force search algorithm determines access points' parameters, including locations, power levels, and frequency channels as shown in figure 5.

Another example of the small service area illustrates the more complex case where we consider a higher user density and traffic demand as depicted in figure 6. 68 wireless users are classified as 16 of 50 Kbps wireless terminals, 38 of 250 Kbps wireless terminals, and 14 of 2 Mbps wireless terminals. In this case a minimum number of four APs are required. The solution for this case assigns different power levels to access points resulting in different coverage size as depicted in figure 6. The majority of low bit rate users are covered by access point AP1. In the left and top right corners of the service area, small groups of users demanding much higher data rate are served by smaller coverage of AP0, AP2, and AP3.

The effects of density and distribution of wireless users on the WLAN system infrastructure are more obvious in large service areas. Consider the design of the large service area with the light and heavy load scenarios. Figure 7 and 8 show different system configurations for both scenarios. Again for the light load scenario, the design is comparable to the coverage-based design where sufficient signal strength is provided across the service region. We can observe that the coverage-based design is not suitable for heavy load scenarios, whereas the capacity-based design approach taking into account user density and traffic load yields an effective system configuration for the high traffic load environment.

B. Computational Requirements

The brute-force search algorithm is simple to implement but in the worst case, the whole solution space must be searched exhaustively. Consider the complexity of the CSP module for the problem with n number of variables, e number of constraints, and each variable consists of a candidate values. There are altogether a^n possible combinations (candidate solutions) of n-tuples. Thus, the complexity of the exhaustive-search algorithm is $O(ea^n)$. We can see that the complexity of the CSP module increases exponentially with the number of variables n. Table 1 shows computational times running on a 350MHz Sun Ultrasparc II processor to solve the WLAN design for the small service area with various user density and traffic scenarios by the brute-force approach. Figure 3 depicts the rising of the computational time as the number of wireless users and the traffic load increase. We see that the computation time rises to more than 5000 seconds for even a moderate, 90, number of users. However, as discussed earlier, we also considered the case of a restricted set of locations for the AP. In this case we see that when we restrict AP locations to lay within the hallway area, which are often desirable locations because of proximity to power and wired network infrastructure. We see that by restricting the space even the brute force search time, while growing is only 1 second for a 90 user space.

Table 1 Computational time of brute-force search

# Demand nodes in service area	Aggregate traffic demand (Mbps)	# Access points required	CPU time (sec)	
			Search the entire area	Search along the wall
7	5.25	2	0.004	0.004
15	16.00	2	0.006	0.006
30	25.75	3	0.040	0.039
45	28.50	3	0.058	0.047
60	34.95	4	700	0.851
75	38.85	4	1904	0.911
90	39.60	4	5256	1.113

IV. CONCLUSIONS

In this paper we propose a new WLAN design strategy called ***capacity based WLAN design***. The problem is formulated as a constraint satisfaction problem, which can guarantee not only radio coverage to the target service area but also provide a specified data rate capacity to carry the traffic demand from each user in the service area. We conducted several design experiments, which illustrate the benefits of the capacity-based WLAN design approach over the traditional coverage-based design. Currently, by limiting the search space to the most desirable locations even a brute-force search technique succeeds in reasonable time.

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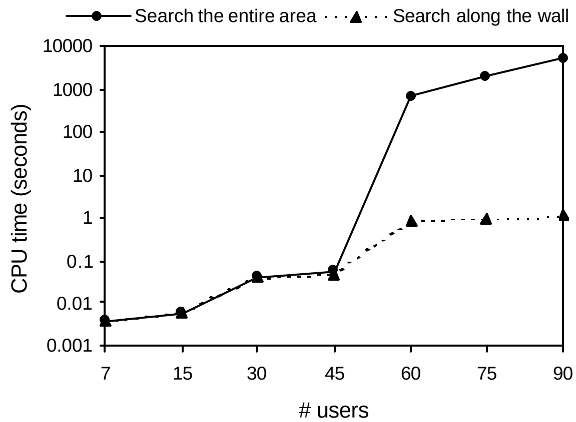

Figure 3 Exponentially computational time of bruce-force search approach

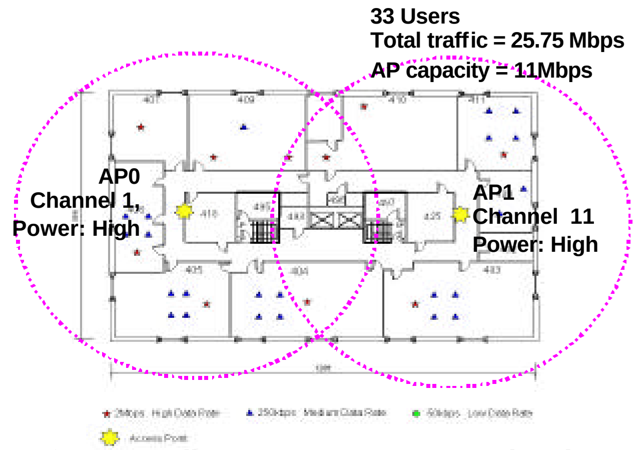

Figure 4 Small service area using coverage-based design

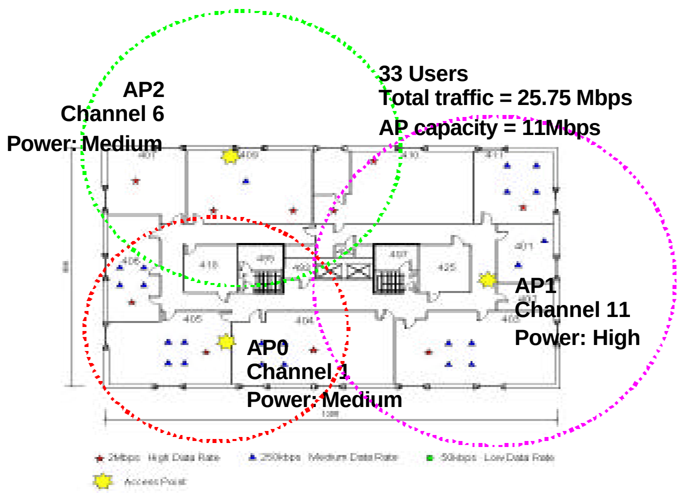

Figure 5 Small service area using capacity-based design

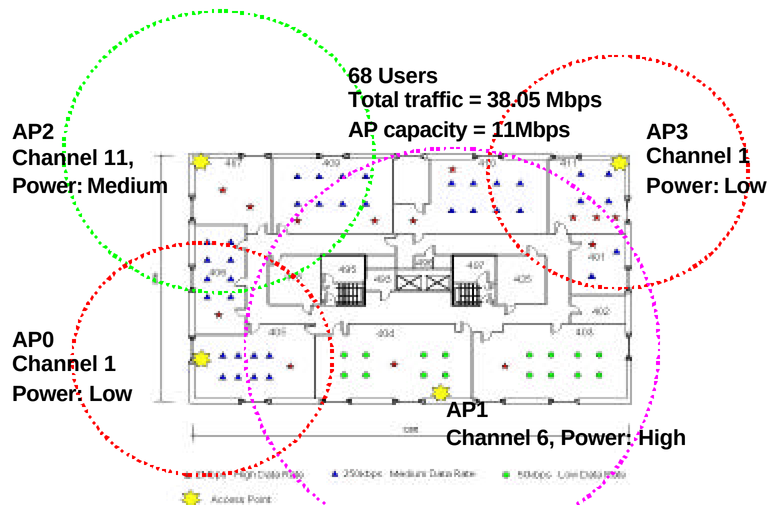

Figure 6 Small service area with heavy load using capacity-based design

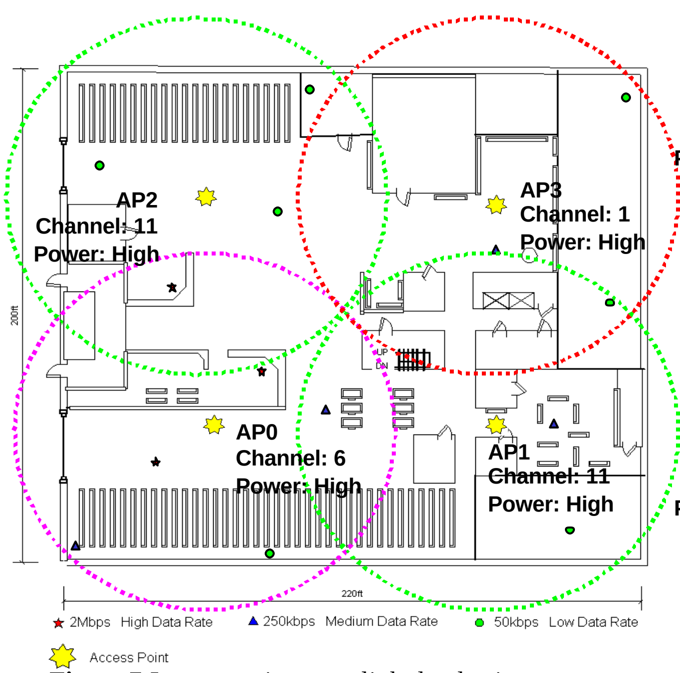

Figure 7 Large service area, light load using capacity-based design
(Comparable to coverage-based design)

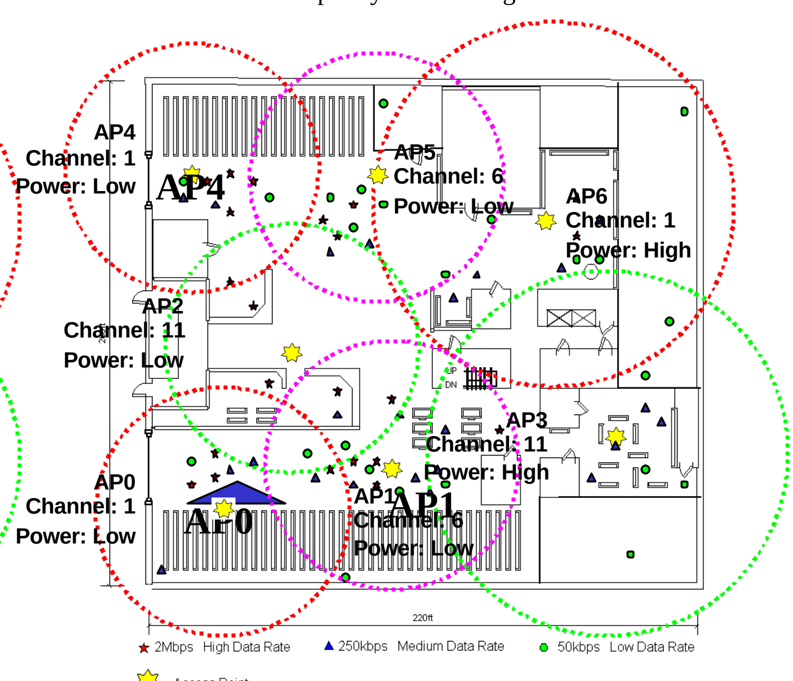

Figure 8 Large service area, heavy load using capacity-based design