Network Design and Optimization for Quality of Services in Wireless Local Area Networks using Multi-Objective Approach

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Abstract: - A multi-objective wireless local area network (WLAN) design models have been developed to optimize the network quality of services. The proposed model combines three problems together, including the optimal access point placement, the frequency channel assignment and the power level assignment. In addition, it accounts for user population density in the service area, traffic demand characteristics and the physical structure of the service area. The design model aims to determine a network configuration that optimizes the network quality of services in term of the radio signal coverage and the data rate capacity to serve expected user traffic demand in the service area. Numerical results and sensitivity analysis is performed to analyze the improvement of the network performance. We found that when we incorporate the issue of the user data rate capacity in the design model, we can greatly improve the quality of service in term of data rate requirement while slightly degrading the signal coverage availability. It is observed that as the weight factor of the user data rate capacity objective increases from 0 to 1, the user satisfaction level increases about 40% while the signal coverage availability decreases about 10%.

Key-Words: - Multi-objective, Optimization, Network design, Wireless Local Area Networks

1 Introduction

With the continued growth and the expansion of the infrastructure-based Wireless Local Area Network (WLAN) deployments, efficient network design methods are required so that the resulting WLANs can provide high Quality of Services (QoS). An infrastructure network employs an access point (AP) for central control of the communication between wireless users participating in a Basic Service Set (BSS). A coverage area within which wireless users are free to move around and yet still remain connected to the AP is called a Basic Service Area (BSA) which covers an area ranging from 20 to 300 meters in radius depending on the transmitting power level and the radio propagation environments [1]. For large service regions, a cellular architecture with multiple BSAs can be used in which the APs are interconnected via a wired distribution infrastructure to form a single system called an Extended Service Set (ESS). Fig.1 illustrates an ESS where three BSAs exist. Note that some of BSAs in the ESS can overlap. Recently research efforts using simulation tools [2] and analytical models [3-7] have been carried out to study performances and quality of services in WLANs. In this paper, we aim to solve the problem of laying out BSAs to cover a target region and achieve high quality of services. In particular, we aim to determine the optimal network

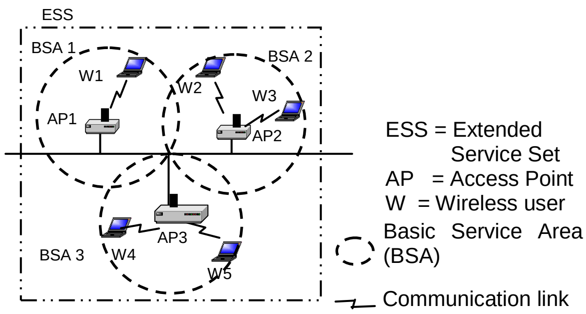

Fig.1 Infrastructure-based WLANs

configuration (i.e. the location, frequency channel and power level of each AP) in order to maximize the network quality of services in term of the radio signal coverage and the data rate capacity to serve expected user traffic demand in the service area.

The issue on the quality of signal in the target service areas and the concerns about the user data rate capacity are two important metrics to be accounted in determining the optimal network configuration. However, the majority of the published papers do not seek all three parameters of the network configuration and the attention is focused on either one of the design aspects. Traditional works focus on the AP placement problems. The design focus mainly on the signal quality aspect, aiming to maximize Signal to Noise Ratio (SNR) [8] or minimize path loss [9,10]. Other works [11,12] consider the frequency channel assignment problems for WLANs. Ref [11] aims at maximizing the total received signal strength whereas Ref. [12] aims at maximizing the coverage availability. Ref. [13] considers both the AP placement and the frequency assignment problems by maximizing data rate capacity of the network but not considering the signal coverage aspect.

In this paper we propose a multi-objective WLAN design approach, optimizing both the signal quality and the data rate capacity aspect to solve the AP placement, frequency channel and power level assignment problem. Moreover, the proposed model accounts for user population density in the service area, traffic demand characteristics and the physical structure of the service area.

The rest of the paper is organized as follows. The next section describes the problem definition of the WLAN design model and gives the mathematical formulation of the design model. Section 3 gives numerical results and discussion. Section 4 provides conclusions.

2 Problem Formulation

The task of WLAN design is to place a given number of access points (APs) in a service area that may be located on a single floor or range across multiple floors. The APs may be configured with different power levels and frequency channels. The power level and frequency channel of an AP, together with the environment specific path loss and an antenna radiation pattern, determines the region (called Basic Service Area (BSA)) in which the AP can support traffic demand to/from wireless users.

We propose a problem formulation for WLAN configuration design seeking the optimal location, frequency channel and power level of each AP in a service area, in order to optimize the network quality objectives described below.

2.1 Network Quality Objectives

2.1.1 Radio Signal Coverage Objective

We consider signal quality in the proposed network design model because the service availability of the network depends on availability of the radio signal and the level of interferences in the area. To achieve a particular data transmission rate, wireless users must be within a certain range of the received signal strength and the SIR threshold. Thus, an important design objective is to maximize the signal coverage availability. We evaluate the signal coverage availability by defining Signal-Test-Points (STP) where the received signal strength and the SIR are assessed. To maximize the signal coverage availability is to maximize the number of STPs of which the received signal strength and the SIR level are greater than the specified threshold.

2.1.2 Data Rate Capacity Objective

As the user population grows and multimedia applications requiring higher data rate spread, the obtainable user data rate (throughput of each wireless users) becomes an essential concern in designing WLANs [1]. According to capacity analysis of the CSMA/CA protocol used in WLANs, the average user obtainable data rate can vary depending on the number of active wireless users on the AP. As the number of wireless users with active data transfer connections to a particular AP increases, the effective AP capacity decreases. Thus, the location of APs should be a function of the density characteristics of the wireless users as well.

Network trace studies [14-18] report that average obtainable user data rates does not depend merely on the number of wireless users existing in the service area, but also on the activity of users. Additionally, traffic volume in the network correlates with user behavior [14]. User behavior in turn correlates to the types of locations where users are situated and the major activities users typically pursue in those locations [14-18]. The following sections discuss the incorporation of information about characteristics of WLAN usage and traffic patterns into the design model.

2.2 Demand Node Representation

The demand node concept used in facility location problems describes the geographic pattern of demand for retail goods and services [23]. The concept was extended to wide-area wireless network design to represent the distribution of expected network traffic in a service area [19,20]. In designing WLANs a demand node represents an individual prospective wireless user in a service area. The definition allows a designer to describe precisely the potential number of wireless users and their locations, in order to appropriately place APs to accommodate expected traffic demand. In WLANs, users communicate through APs using the CSMA/CA protocol in which users compete for channel access and share AP capacity. Therefore, information about the number of users is required to calculate an average user data rate whereas the information about user locations is needed to approximately assign users to an AP based on an acceptable radio signal level.

Network trace studies characterized the usage of WLANs in various environments such as on university campuses [15,17], in corporate office buildings [14], in academic building [18], and in a large auditorium [16]. Similarities exist in network usage characteristics among different network environments [14-18]. Traffic load at APs depends on users' level of data transfer activity in addition to the number of wireless users situated within the radio coverage area of APs. Network trace studies show a correlation between users' level of data transfer activity and locations where users are present [14-17].

In the proposed WLAN design model, a user activity level (α_t) accounts for the correlation between network usage characteristics and user locations. α_t is the percentage of wireless users in a sub-area of type t who are simultaneously active in data transfer through APs. Active users participate in medium contention to gain access to a communication channel and share AP capacity. We define three types of sub-areas: $t \in T = \{1, 2, 3\}$ where 1 denotes private sub-areas, such as offices, 2 denotes public sub-areas for unscheduled activities, such as student lounges, and 3 denotes public sub-areas for schedule-based activities, such as classrooms. The remaining user ($1 - \alpha_t$) are idle users who, although situated in a sub-area of type t, do not generate data transfer activity over the network at a particular time and therefore do not affect AP capacity [16]. An average user data rate requirement in sub-area of type t (R_t) imposes a desired link rate that should be available to active users in average.

2.3 Multi-Objective Problem Formulation

The WLAN configuration design problem is formulated as a Multi-Objective Problem (MOP), which combines two measures of network service qualities: radio signal coverage and data rate capacity. MOP seeks an optimal network configuration, i.e. the optimal location, frequency channel and power level of each AP in a service area.

Let A denotes a set of APs used in the service area, where n is the total number of APs required. Let $\Omega_j = \{p_j, f_j, (x_j, y_j, z_j)\}$ denote a set of decision variables which are parameters assigned to ap_j for $j = 1, 2, \ldots, n$. p_j denotes the power level assigned to ap_j. f_j denotes the frequency channel assigned to ap_j, and (x_j, y_j, z_j) denotes the coordinate (x_j, y_j) on floor z_j where ap_j is located.

Let G denotes a set of signal test points (STPs) representing locations for testing the received signal strength and the SIR level. Each STP g_h refers to a coordinate in three-dimensional space (x_h, y_h, z_h), where z_h is the floor where g_h is located.

Let U denotes a set of demand nodes where index t indicates the type of sub-area where demand node i is located. $U_t \subset U$ is a set of demand nodes in sub-area type t. The position of demand node i within the service area is denoted by (x_i, y_i, z_i), where (x_i, y_i) is the coordinates on floor z_i where the demand node i is located.

The user activity level (α_t) and the average data rate requirement (R_t) specify the network usage characteristics of the demand node. The set of demand nodes together with the sub-area classification and parameters specifying network usage characteristics (α_t and R_t) are given as input to the design process.

Other decision variables include u_{ij}^t and g_{hj}. u_{ij}^t is a user association binary variable that equals 1 if demand node $i \in U$ associates to $ap_j \in A$; 0 otherwise. g_{hj} is a signal availability binary variable that equals 1 if STP $h \in G$ can receive a signal from $ap_j \in A$; 0 otherwise.

Let P is the set of candidate power levels (discrete values) for variable p_j. F is the set of candidate frequency channels for variable f_j and O is the set of candidate locations for AP placement.

Parameters in the design process are classified into static and dynamic parameters. Static parameters do not change during the design process because they depend solely on standard requirements and the characteristics of user activity in service area. Static parameters specifying the physical signal requirements (e.g., the received signal strength ($P_{Rthreshold}$) and the SIR level ($SIR_{threshold}$)), user profiles (e.g., the user activity level (α_t) and the average user data rate requirement (R_t)), and the data rate capacity of AP (C).

Dynamic parameters are recomputed each time a variable changes value during the design process.

Dynamic variables include received signal strength ($P_{R_{ij}}$), interference level ($Intf_{ij}$), and average obtainable data rate (r_i^t). The mathematical model of MOP for the WLAN design is written as follows:

Objectives:

1) Maximize signal coverage area

$$Maximize \quad f_1 = \frac{\sum_{\forall h \in G} \sum_{\forall j \in A} g_{hj}}{|G|} \tag{1}$$

f_1 measures the signal coverage availability. It is the normalized number of STPs which the received signal strength and the SIR level are greater than the specified threshold.

2) Maximize user satisfaction

$$Maximize \quad f_2 = \frac{\sum_{\forall t \in T} \left(\beta_t \times \left(\sum_{\forall j \in A} \sum_{\forall i \in U_t} u_{ij}^t \right) \right)}{\sum_{\forall t \in T} \left(\beta_t \times |U_t| \right)} \tag{2}$$

f_2 measures the user satisfaction level. It is the normalized number of users that can obtain the required data rate. β_t is a relative important weight of user type t. It is defined as the ratio of the required data rate of user type t to the maximum bit rate capacity of the AP, $\beta_t = \frac{R_t}{C}$.

Constraints:

$$\sum_{\forall j \in A} u_{ij}^t \quad \le \quad 1, \forall i \in U \tag{3}$$

$$u_{ij}^t \left(P_{R_{ij}} - P_{Rthreshold} \right) \quad \ge \quad 0, \forall i \in U, \forall j \in A \tag{4}$$

$$u_{ij}^t \left(P_{R_{ij}} - Intf_{ij} - SIR_{threshold} \right) \quad \ge \quad 0, \quad \forall i \in U, \forall j \in A \tag{5}$$

$$u_{ij}^t \left(r_i^t - R_t \right) \quad \ge \quad 0, \forall i \in U, \ \forall j \in A \tag{6}$$

$$g_{hj} \left(P_{R_{hj}} - P_{Rthreshold} \right) \quad \ge \quad 0, \forall h \in G, \forall j \in A \tag{7}$$

$$g_{hj} \left(P_{R_{hj}} - Intf_{hj} - SIR_{threshold} \right) \quad \ge \quad 0, \quad \forall h \in G, \forall j \in A \tag{8}$$

$$u_{ij}^t \in \{0,1\}, \forall i \in U, \forall j \in A \tag{9}$$

$$g_{hj} \in \{0,1\}, \forall h \in G, \forall j \in A \tag{10}$$

Constraint (3) specifies that each user can associate to at most one AP. The decision variable u_{ij}^t can be equal to one if the received signal strength that user i received from the ap_j (P_{Rij} in dBm) and the SIR level with respect to the ap_j (the received signal strength ($P_{R_{ij}}$ in dBm) less the interference level ($Intf_{ij}$ in dBm)) meet the receiver sensitivity threshold ($P_{Rthreshold}$) and the SIR threshold ($SIR_{threshold}$) as specified by constraint (4) and (5), respectively. In addition, when u_{ij}^t is equal to one, constraint (6) must be satisfied. It ensures that the average data rate available to wireless user i which is a type t user (r_i^t) is greater than the specified user data rate (R_t). The 802.11 capacity model and the user activity pattern correlated with the type of sub-areas where users locate are incorporated in this constraint to estimate the average data rate that the active wireless user can obtain [21,22]. u_{ij}^t is equal to zero otherwise. Constraints (7) and (8) assess the radio signal quality at the STP h, testing the received signal strength and the SIR level. The decision variable g_{hj} can be equal to one if the received signal strength at the STP h transmitted from the ap_j ($P_{R_{hj}}$) and the SIR level with respect to the ap_j (i.e., $P_{R_{hj}} - Intf_{ij}$) meet the received sensitivity threshold ($P_{Rthreshold}$) and the SIR threshold ($SIR_{threshold}$). Otherwise, g_{hj} is equal to zero. Constraints (9) and (10) specify that variable u_{ij}^t and g_{hj} are binary {0, 1} variables, respectively.

3 Numerical Results

Numerical experiments were conducted on the service area in the building with four floors. The building comprised of classrooms, offices, laboratories, student lounges, and a library. The dimension of each floor is 33m × 21m. The service area is divided into grids of size 1m×1m as shown in fig.6. The grid points specify the STPs. In fig.7-10, the symbol ● represents the demand nodes located in public areas for scheduled activities, the symbol ▲ represents the demand nodes located in public areas for unscheduled activities, and the symbol ★ represents the demand nodes located in private areas. User activity levels corresponding to each sub-area type are based on studies showing that users in private sub-areas are the most active network users, followed by users in the public areas for unscheduled activities and then users of public areas for schedule-based activities [14-18]. Similarly, the average user data rates are taken from observed network usage characteristics [14-18]. Table 1 summarizes the network usage characteristics.

Table 2 summarizes the input parameters of the network design problem. The design aims for 95% coverage availability at the edge of AP coverage areas. In this case, a fading margin of 5.75 dB is applied in the signal coverage calculation.

We applied the proposed MOP to the WLAN configuration design for the four-story building. A scalarizing function (11) (a weighted sum of the objectives) is applied to convert a multi-objective problem to a single objective problem.

$$\text{Max } F = w_1 f_1 + w_2 f_2 \qquad (11)$$

The patching algorithm [13] is applied to solve the scalarizing function. The maximum point found is a particular point on the Pareto front. For example, in fig.2, F_i is a scalarizing function when using a weight set i (w_{1i}, w_{2i}). F_i^* is a single point on a feasible region boundary where the line defined by the weighted sum F_i is tangent. F_i^* is a particular point on the Pareto front that is the maximum of F_i.

3.1 Effects of weight factors

Sensitivity analysis is conducted to study effects of weight factors on the WLAN quality of service in term of the signal coverage availability and the user satisfaction level. In particular, we generate an approximated Pareto front by running the program many times using different weight sets. Each weight set converges to different maximum point on the Pareto front. The results plotted in fig. 3 demonstrate this behavior. The plotted is obtained by running the patching algorithm to solve the network design optimization five times, using five different weight sets (Q = 5) in which the weight values are spread equally as written in Eq. (12). We use seven APs in this experiment. The points in fig. 3 are the maximum points found with each set of weights. Two end of the front are at (f_1=67.6%, f_2=34%) and (f_1=58%, f_2=75.4%).

$$w_{1q} = (q-1)/(Q-1), \quad w_{2q} = 1 - w_{1q} \qquad (12)$$

where $q = 1, 2, \ldots, Q$,
Q = the number of different weight sets

In fig.3, We can observe that as the w_{2q} increases from 0 to 1, the user satisfaction level increases about 40% whereas the signal coverage availability decreases about 10%. We can see that when we incorporate the issue of the data rate capacity in the design model, we can greatly improve the quality of service in term of data rate requirement while slightly degrading the signal coverage availability.

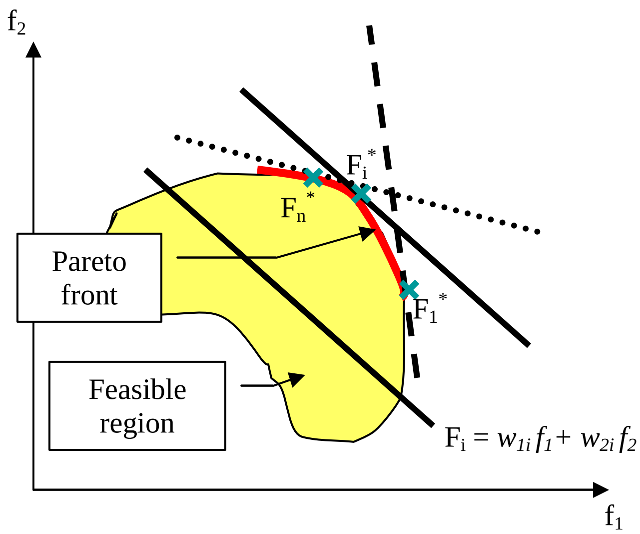

Fig.2 Weighted sum of the objectives and the Pareto front

3.2 Distribution of the Pareto front

We conduct another set of experiments using different values of Q to observe the distribution of the Pareto front. Fig. 4 presents the results obtained by using seven values of Q (Q = 4, 5, …, 10) to generate weight sets. The points found with a set of weights generated by each Q are depicted with a different shape. It can be observed that the points spread out more toward the middle and the lower right corner of the front. The upper left corner of the front is around (f_1=67.6%, f_2=34%) where the weight set is (w_{1q} =1, w_{2q} =0). We can draw a similar observation that slightly increasing value of w_{2q} can improve the user satisfaction level greatly while slightly degrading the signal coverage availability. For example, at the weight set of (w_{1q} =0.87, w_{2q} =0.13), the user satisfaction level increases 22% whereas the signal coverage availability reduces 3.6% (i.e., f_1=64%, f_2=56%).

3.3 Effects of the number of APs

The last set of experiments aims to study effects of the number of APs used in the network on the signal coverage availability and the user satisfaction level. The results of using different number of APs (4, 5, …, 10) are plotted in fig.5. In this set of experiments, Q is equal to 7. The results show that the user satisfaction level is proportional to the number of APs. The more APs used in the network, the higher level of user satisfaction. Increasing the number of APs used in the network improves the user satisfaction level more than improving the signal coverage availability. It can be observed that as the number of APs increases from 4 to 10, the user satisfaction level increases almost 20% whereas the signal coverage availability increases about 3%. The reason is that the more APs used, the more capacity the network has for accommodating user traffic demand. Since a limited number of channels exist in the available frequency spectrum for an 802.11 WLAN, a multi-cell network deployment (using high number of APs) requires that some channels are reused. Reuse of frequency channels in neighbouring cells can cause interferences which affect the signal coverage availability in the service area.

4 Conclusion

This paper presents a novel mathematical model for a WLAN configuration design which is formulated as a Multi-Objective Problem that combines two

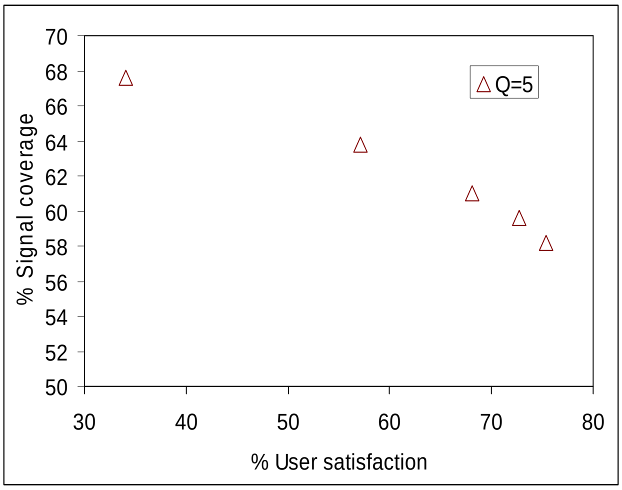

Fig.3 Results with different weight sets (Q=5)

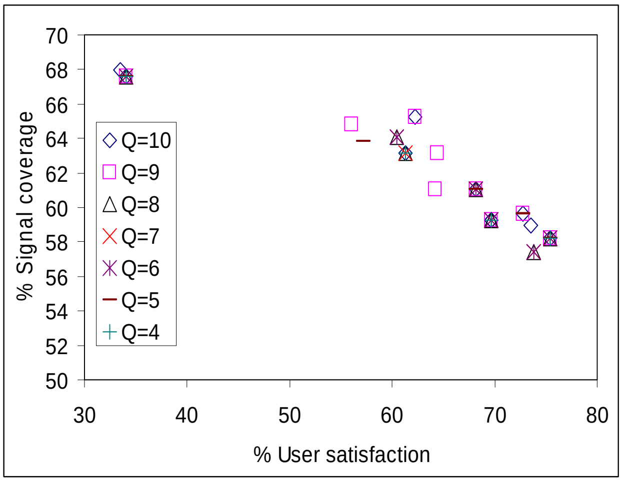

Fig.4 Results with different weight sets (Q=4,5,…,10)

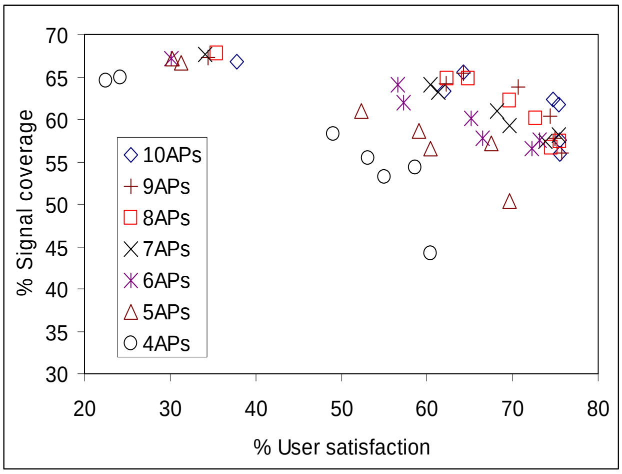

Fig.5 Results of using different number of APs

measures of network service qualities: radio signal coverage and data rate capacity. A scalarizing function is applied to convert a multi-objective problem to a single objective problem. Sensitivity analysis is conducted to study effects of weight factors on the WLAN quality of service in term of the signal coverage availability and the user satisfaction level. From numerical results we can conclude that incorporating the issue of the data rate capacity in the design model can greatly improve the quality of service in term of data rate requirement while slightly degrading the signal coverage availability.

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Table 1 Network usage characteristics

Sub-areas	User activity level	Average user data rate (Kbps)
Type 1: Private sub-areas (such as graduate student and library staff offices)	$\alpha_1 = 0.50$	$R_1 = 460$
Type 2: Public sub-areas for unscheduled activities (such as library study areas, student lounge)	$\alpha_2 = 0.40$	$R_2 = 260$
Type 3: Public sub-areas for schedule-based activities (such as classrooms, laboratories)	$\alpha_3 = 0.35$	$R_3 = 80$

Table 2 Network parameters used in the multi-objective optimization for WLAN design

Parameter	Definition	Value
Candidate set for Variables:		
P	Set of candidate power levels for variable p_j	{0, 7, 13, 15, 17, 20, 24} in dBm
F	Set of candidate frequency channels for variable f_j	{2.412, 2.437, 2.462} in GHz
Static Parameters:		
α_t	User active level defines percentage of wireless users in sub-area type *t* that are engaged in data transfer activities (i.e., participating in channel contention and sharing AP capacity)	See Table 1
R_t	Average user data rate requirement in sub-area type *t*	
$P_{Rthreshold}$	Received sensitivity threshold	-80 dBm
$SIR_{threshold}$	Signal to interference ratio threshold	10 dB
C	Data rate capacity of the ap_j for $\forall j \in A$	11 Kbps
Path loss Parameters:		
d_0	Reference distance d_0	1 meter
n	Path loss exponent	3.3
δ	Standard deviation representing shadow fading	3.5 dB
Antenna Parameters:		
G_{AZ}	Antenna gain (peak directivity)	2.5 dB

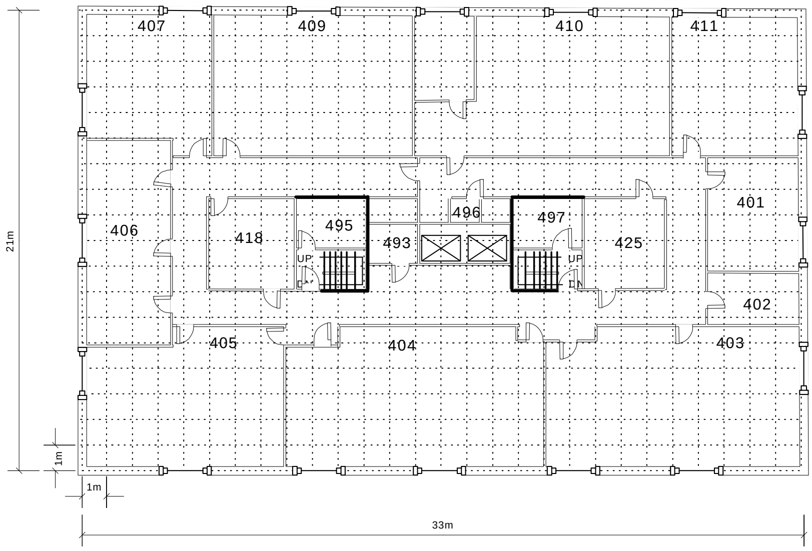

Fig.6 Grid point resolution of the ervice area

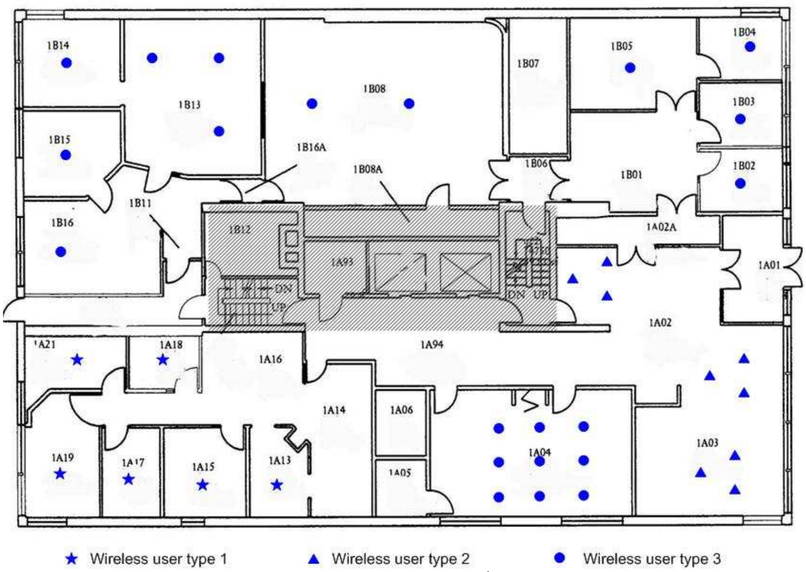

Fig.7 Service area (the 1st first floor)

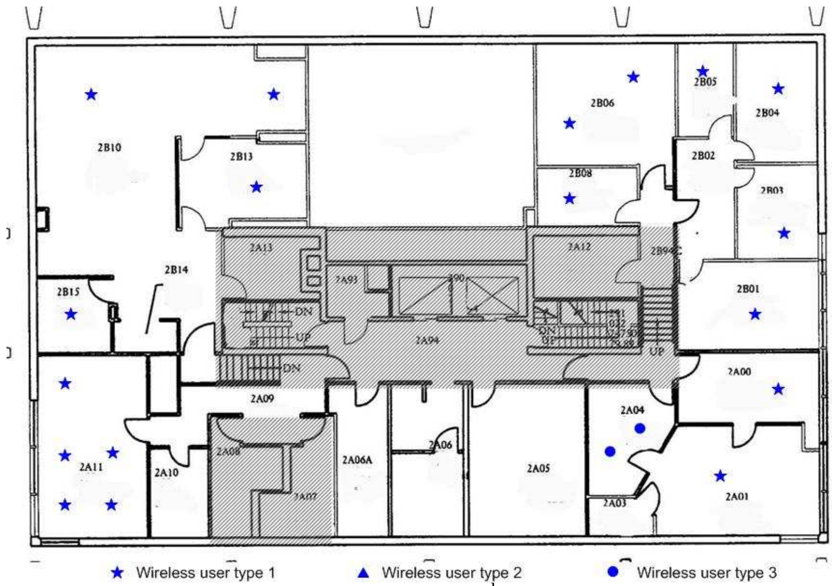

Fig.8 Service area (the 2nd second floor)

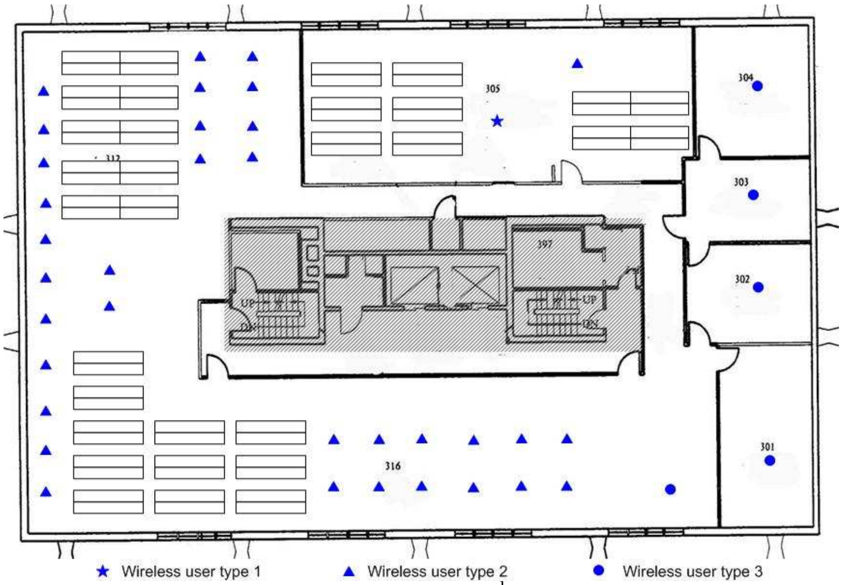

Fig.9 Service area (the 3rd third floor)

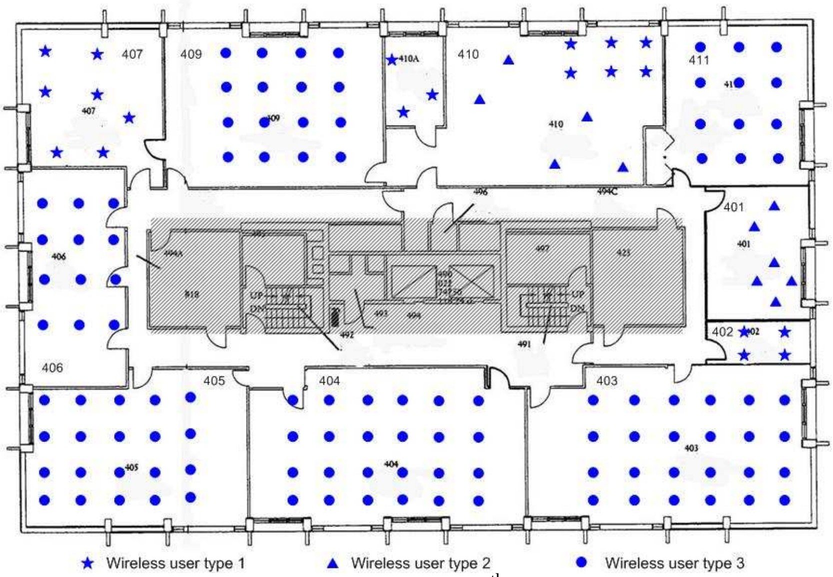

Fig.10 Service area (the 4th forth floor)