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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

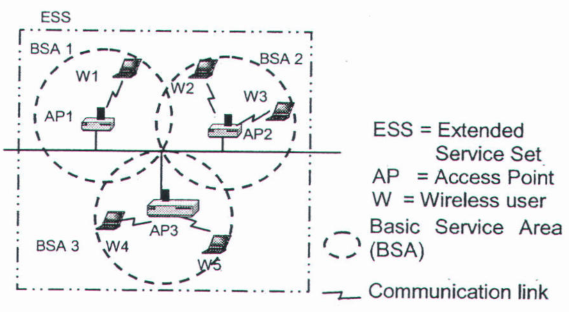

Fig.1 Infrastructure-based WLANs

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_j}), 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

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

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:

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

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

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

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

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

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

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

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

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_j} 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.

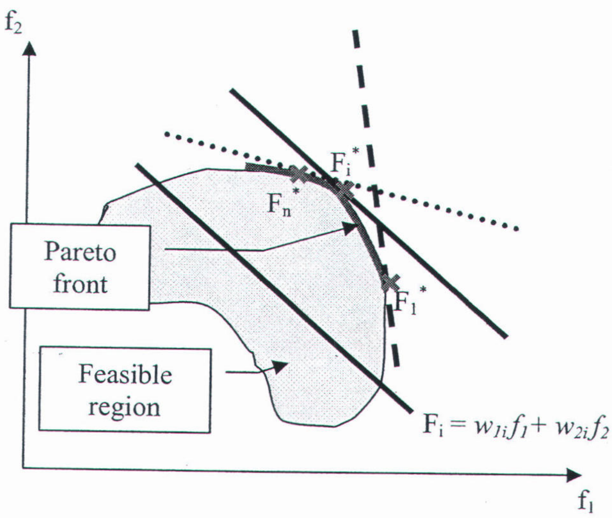

Fig.2 Weighted sum of the objectives and the Pareto front

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

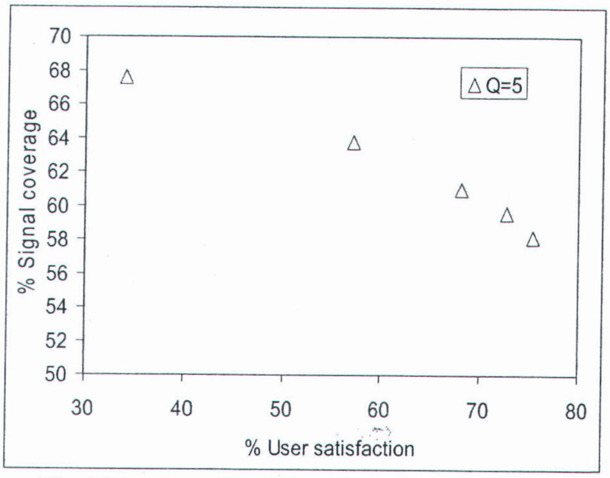

Fig.3 Results with different weight sets (Q=5)

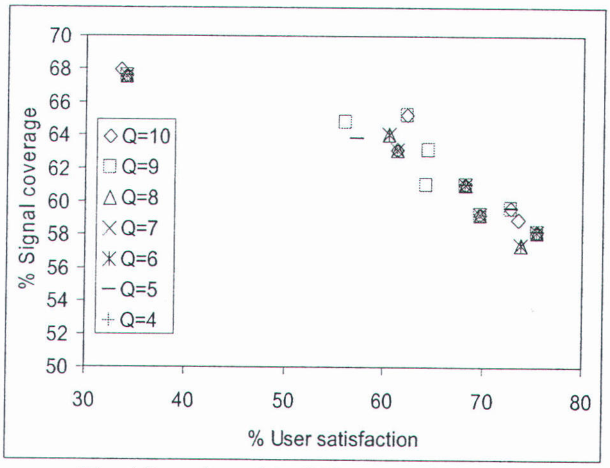

Fig.4 Results with different weight sets (Q=4,5,...,10)

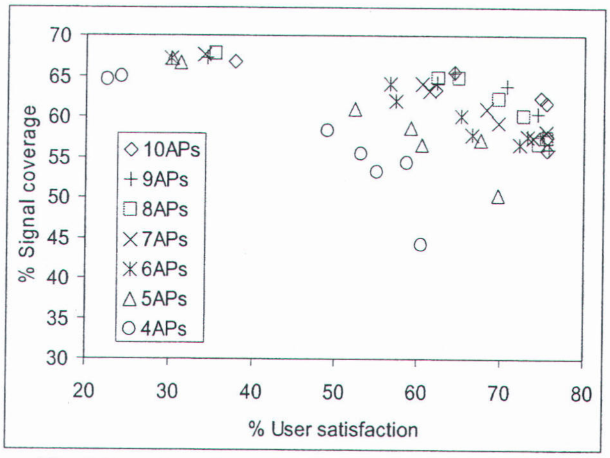

Fig.5 Results of using different number of APs

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

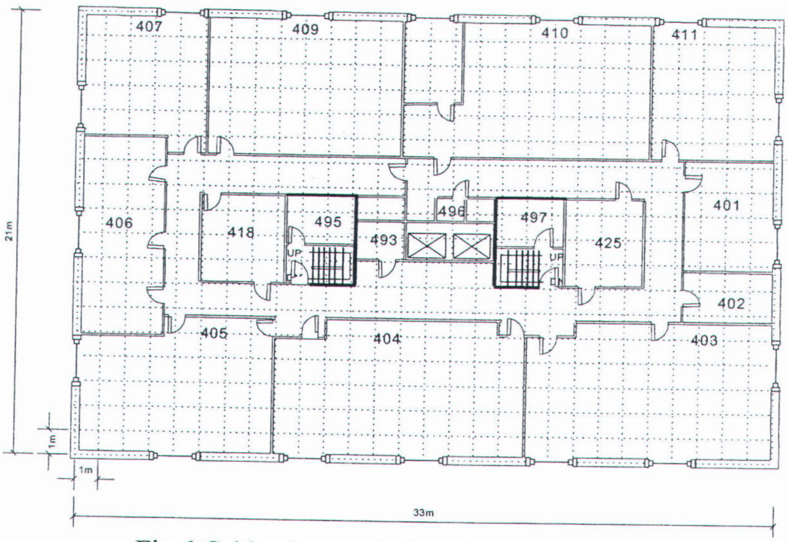

Fig.6 Grid point resolution of the ervice area

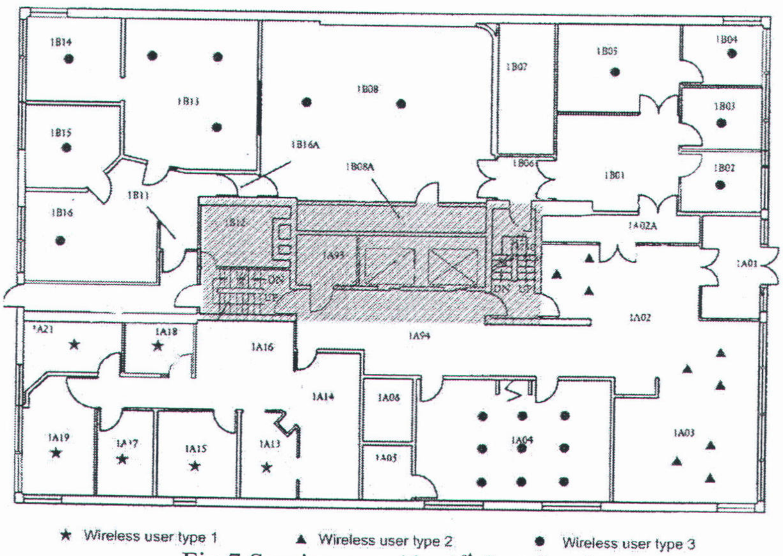

Fig.7 Service area (the 1st first floor)

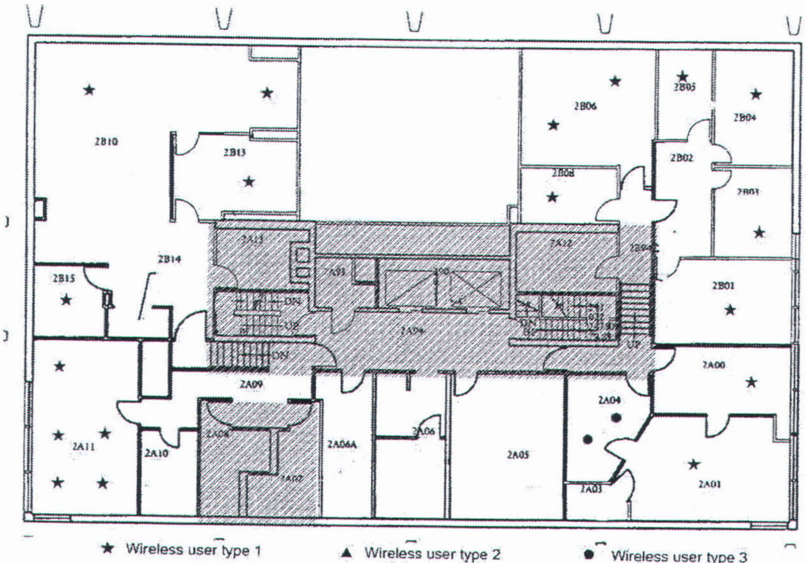

Fig.8 Service area (the 2nd second floor)

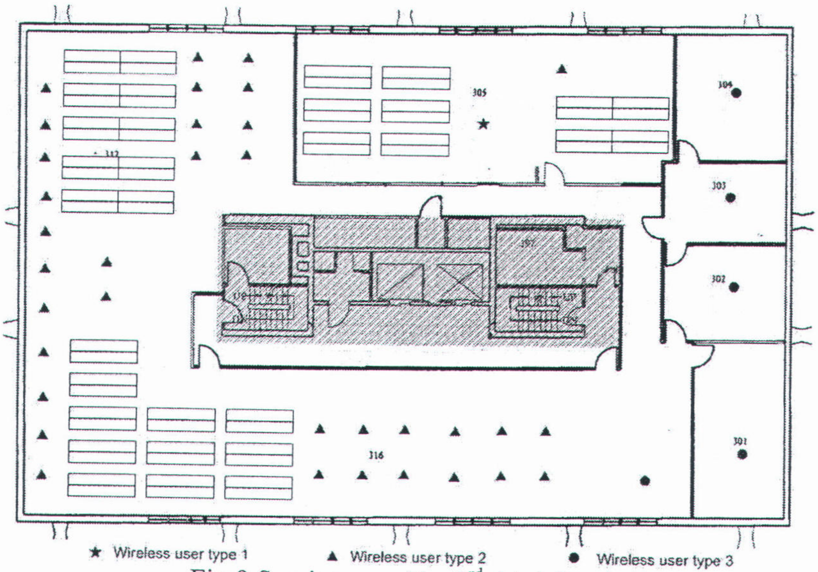

Fig.9 Service area (the 3rd third floor)

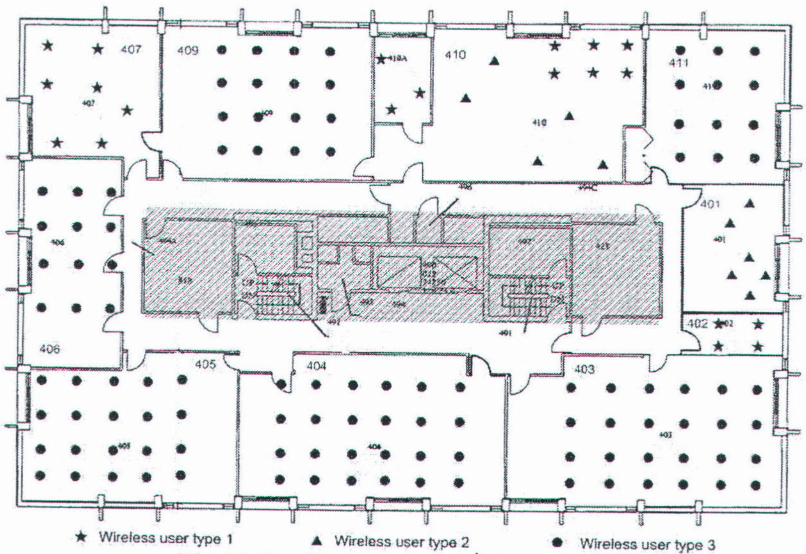

Fig.10 Service area (the 4th forth floor)

Heuristic Approaches to the Multi-objective Network Design and Optimization for Wireless Data Networks

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Abstract. In this paper, we present a multi-objective model for the wireless data network (WDN) design problem. The proposed model aims to determine the network configurations that optimize the network quality of services in term of the radio signal coverage and the network throughput availability to serve expected user traffic demand in the service area. The problem consists of the base station placement, the frequency channel assignment and the power level assignment. Since this problem is NP-hard, we develop a heuristic optimization techniques based on Tabu search algorithm to solve the problem. Numerical experiments were conducted to demonstrate the capability of the proposed multi-objective model and the heuristic algorithm.

Keywords: Multi-objective optimization, Heuristic techniques, Network design, Wireless data networks.

1 Introduction

Wireless data networks (WDN) have become potential solutions to bring broadband data access to users in area lacking of wired network infrastructure. Nowadays several wireless network technologies are available such as wireless local area networks (WLANs), UMTS networks and WiMAX networks. Efficient network design methods are required so that the resulting WDNs can provide high Quality of Services (QoS).

Several works in literature have devoted to the study of wireless network design problems. Some existing works consider the radio network design for the UMTS networks considering the base station placement problems by using a single objective function [1-6]. Several works consider the WLAN network design problems [7-12] and some works devote to the WiMAX network design problems [13-15]. Most works focus on the placement problems of the wireless base stations [7-8],[13-15]. The design mainly considers the signal quality aspect, aiming to maximize coverage area [7] or minimize path loss over the service area by using the convex combination of the

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average path loss and the maximum path loss [8]. Some works focus on minimizing the network cost by minimizing the number of installed base stations [13-15]. Other works consider the frequency channel assignment problems for WLANs [9-10]. [9] aims at maximizing the total received signal strength whereas [10] aims at maximizing the coverage availability. In [11-12], the authors consider both the base station placement and the frequency assignment problems by maximizing throughput capacity of the network but not considering the signal quality aspect.

The majority of the published works in literatures have paid attention on either the base station placement problems or the frequency channel assignment problems with the objective to minimize the network cost or maximize signal coverage quality. While their contribution is significant, the existing network design methods do not simultaneously consider two important metrics, the signal coverage quality and the user data rate capacity, in the network design methods. For this reason, more efficient WDN design techniques are needed.

In this paper we propose the multi-objective design approach to the WDN design problem. We aim to optimize not only the signal coverage availability but also the user satisfaction level on the available network throughput. The proposed network design model considers three important problems including the wireless base station placement problem, the frequency channel and the power level assignment problem. Additionally, the proposed method accounts for user distribution characteristics and is general that it can be applied to different wireless network technologies.

The rest of the paper is organized as follows. The next section describes the problem definition of the WDN design model and gives the mathematical formulation of the design model. Section 3 describes the proposed heuristic solution techniques to solve the WDN design problems. Section 4 presents the numerical results and discussions. Finally, section 5 provides conclusions.

2 Problem Definition and Formulations

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

Table 1 defines notations used in the model. The notations consist of sets, decision variables, and parameters. Parameters in the design process are classified into static and dynamic parameters. Static parameters do not change during the design process because they depend on standard requirements and the user traffic profiles. Static parameters specify the physical signal requirements, the Signal to Interference Ratio (SIR) level, the user traffic profiles and the base station capacity. Dynamic parameters are recomputed each time a variable changes value during the design process. Dynamic variables include the received signal strength, the interference level, and the average obtainable data rate. The mathematical formulation of MOP for the WDN design is written as follows:

Table 1. Notations used in the mathematical formulations

	Parameters	Definition
Sets:	U	Set of demand nodes (DNs)
	G	Set of signal test points (STPs)
	B	Set of candidate locations to install wireless base stations (BSs)
	P	Set of available power levels
	C	Set of available frequency channels
	T	Set of types of service levels
	U_t	A set of DNs with the service level type t $\bigcup_{\forall t \in T} U_t = U$
Decision variables:	p_j	Power level assigned to BS j
	c_j	Frequency channel assigned to BS j
	b_j	A site selection binary variable that equals 1 if site j is selected to install the wireless base station; 0 otherwise
	u_{ij}^t	A user association binary variable that equals 1 if DN $i \in U$ associates to BS j; 0 otherwise
	g_{hj}	A signal availability binary variable that equals 1 if STP $h \in G$ can receive a signal from BS j; 0 otherwise
Static parameters:	N	The number of wireless base stations to be installed in the service area
	R_t	The required network throughput for the service level type t
	$P_{Rthreshold}$	Received sensitivity threshold (dBm)
	$SIR_{threshold}$	Signal to interference ratio threshold (dB)
	W	Base station capacity (bps)
Dynamic parameters:	$P_{R_{ij}}(p_j, c_j, b_j)$	Received signal strength (in dBm) that DN i receives from BS at site j which uses power level p_j and frequency channel c_j
	$Intf_{ij}(p_j, c_j, b_j)$	Interference level (in dB) at DN i, when associating to BS at site j which uses power level p_j and frequency channel c_j
	r_i^t	Average network throughput available to DN i with the service level type t (in bps)

2.1 Objective Functions

The proposed WDN design aims to devise an optimal network configuration that maximizes the signal coverage availability and the user satisfaction level. These objectives are mathematically written as follows:

1) Maximize signal coverage availability

The first objective function (f_1) measures the signal coverage availability. It is the normalized number of signal test points (STPs) of which the received signal strength and the Signal to Interference Ratio (SIR) are greater than the specified threshold.

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

2) Maximize user satisfaction

The second objective function (f_2) measures the user satisfaction level. It is a normalized number of users that can obtain the required throughput. β_t is a relative important weight of the service level type t. It is defined as the ratio of the required throughput of the service level type t to the maximum capacity of the base station (BS), $\beta_t = R_t / W$.

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

2.2 Constraints

The network requirements, such as signal quality requirements and the base station capacity limitation, are incorporated into the mathematical model through the following constraints.

$$\sum_{\forall j \in B} u_{ij}^t \leq 1, \forall i \in U \tag{3}$$

$$u_{ij}^t \left(P_{R_{ij}} \left(p_j, c_j, b_j \right) - P_{Rthreshold} \right) \geq 0, \forall i \in U, \forall j \in B \tag{4}$$

$$u_{ij}^t \left(P_{R_{ij}} \left(p_j, c_j, b_j \right) - Intf_{ij} \left(p_j, c_j, b_j \right) - SIR_{threshold} \right) \geq 0 \ , \forall i \in U, \forall j \in B \tag{5}$$

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

$$g_{hj} \left(P_{R_{hj}} \left(p_j, c_j, b_j \right) - P_{Rthreshold} \right) \ \geq \ 0, \forall h \in G, \forall j \in B \tag{7}$$

$$g_{hj} \left(P_{R_{hj}} \left(p_j, c_j, b_j \right) - Intf_{hj} \left(p_j, c_j, b_j \right) - SIR_{threshold} \right) \geq 0, \forall h \in G, \forall j \in B \tag{8}$$

$$u_{ij}^t \geq b_j, \forall i \in U, \forall j \in B \tag{9}$$

$$g_{hj} \geq b_j, \forall h \in G, \forall j \in B \tag{10}$$

$$\sum_{\forall j \in B} b_j \leq N \tag{11}$$

$$u_{ij}^t \in \{0,1\}, \forall i \in U, \forall j \in B \tag{12}$$

$$g_{hj} \in \{0,1\}, \forall h \in G, \forall j \in B \tag{13}$$

$$b_j \in \{0,1\}, \forall j \in B \tag{14}$$

Constraint (3) specifies that each demand node (DN) can associate to at most one BS. The decision variable u_{ij}^t can be equal to one if the received signal strength that DN i received from BS at site j ($P_{R_{ij}}$ in dBm) and the SIR level with respect to BS at site 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 throughput available to DN i with the service level type t (r_i^t) is greater than the average network throughput requirement, R_t. The throughput analytical model is applied here to estimate an available network throughput, r_i^t. u_{ij}^t is equal to zero otherwise. Constraints (7) and (8) assess the radio signal quality at 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 STP h transmitted from BS j ($P_{R_{ij}}$) and the SIR level with respect to BS at site j (i.e., $P_{R_{ij}} - Intf_{ij}$) 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 if DN i and STP h associate to BS at site j, BS must be installed at site j, i.e. b_j is equal to one. Constraint (11) specifies the maximum number of BS to be installed in the service area. Constraints (12), (13) and (14) specify that variable u_{ij}^t, g_{hj} and b_j are binary {0, 1} variables.

2.3 Scalarizing Function

We convert the above multi-objective optimization problem into a scalar optimization problem using a scalarizing function written in Eq. (15).

$$Maximize\ F = w_1 f_1 + w_2 f_2 \tag{15}$$

where w_1 and w_2 are the weight coefficients associated with the normalized objectives (1) and (2), respectively. The relationship between the weight coefficients is that, given w_1, $w_2 = 1 - w_1$. Solving the scalar optimization problem, the maximum point found is a particular point on the Pareto front corresponding to the weight coefficients used. For example, in fig.1, F_q is a scalarizing function when using a weight set q (w_{1q}, w_{2q}). F_q^* is a single point on a feasible region boundary where the line defined by the weighted sum F_q is tangent. F_q^* is a particular point on the Pareto front that is the maximum of F_q.

An approximated Pareto front can be generated by solving the MOP model many times using different weight sets. Each weight set converges to different maximum point on the Pareto front. Let Q be the total number of weight sets and q be the index number of the weight set. The weight values are spread equally. The values of the q^{th} weight set (w_{1q}, w_{2q}) are written in Eq. (16).

$$w_{1q} = (q-1)/(Q-1), \quad w_{2q} = 1 - w_{1q} \tag{16}$$

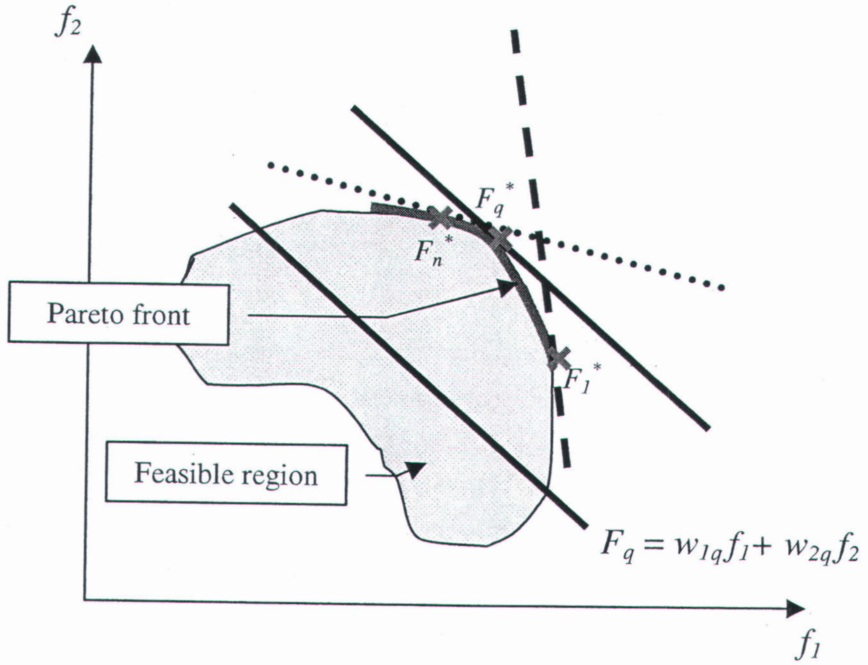

Fig. 1. Weighted sum of the objectives and the Pareto front

3 Heuristic Solution Techniques

This section presents a heuristic solution technique developed to solve the WDN design problem. The heuristic solution technique will determine the optimal network configuration specifying locations, power levels and frequency channels of the wireless base stations.

The overall framework of the heuristic solution technique consists of two phases, including the initialization and the optimization phase. The following sections describe the detailed implementation of each phase.

3.1 Initialization Phase

The initialization phase devises a good starting solution which provides initial values for wireless base stations' parameters. This phase uses a greedy based search technique to find the best solution that maximizes the scalarizing function in Eq. (15). The main idea is to place one wireless base station as a time and the process repeats until a pre-defined number of base stations are placed. In each iteration, the algorithm aims at deriving optimal parameters (site, power level, and frequency channel) for each base station. The algorithm works cumulatively in the way that the parameters of the new base stations are derived so that they, together with those already assigned base stations, can provide highest value of the scalarizing function, Eq. (15). The following shows the pseudo code of the initialization algorithm.

Algorithm 1. Initialization algorithm

Input: Objective functions (*f1*, *f2*), weight coefficients w_1 and w_2
Number of base stations
Service area characteristics (# floors, size, wall materials)
Wireless user characteristics (user density, distribution, traffic profile)

Output: Initial network configuration specifying values of power level and frequency channel assigned to each base station

Step 1: Initialize parameters
$k = 1$ // place the first wireless base station (BS)
Step 2: while ($k \le N$) do // Find parameters location, power level and frequency channel for b_k
For all $j \in B$ do
Place BS k at location j temporarily
For all $p \in P$ do
Assign power level p to BS k
For all $c \in H$ do
Assign frequency channel h to BS k
Compute the scalarizing function with BS k installed at j using p and c
Record the obtained value as $F_k(j,p,c)$
Select the maximum $F_k(j,p,c)$
Assign the optimal parameters (j,p,c) to BS k permanently
k++// place the next BS
Step 3: Return the best solution found and stop

3.2 Optimization Phase

The optimization phase to solve the multi-objective WDN design problem is developed based on the Tabu Search (TS) heuristic. TS was first suggested by Glover [16]. The basic idea of TS is to use memory strategies to guide the search process so that the solution space can be explored efficiently. TS process finds the best solution in the neighborhood of the current solution. The search avoids trapping in the local optima by allowing moves resulting in a degradation of the value of the objective function. Additionally, TS imposes restrictions on the choices of neighbor solutions in order to prevent cycling of solutions during particular iterations. Restrictions are imposed by making reference to memory structures.

In this paper, we develop knowledge-based move operators providing the neighborhood information that helps facilitate the search process. The basic idea is to use information about the network quality of service to navigate the search space and to change the values of potential variables that can contribute to optimize the objective functions.

The optimization phase begins by evaluating the initial network configuration (initial solution) generated by the initialization phase. The TS evaluates the neighbor solutions of the initial solution and moves to the best unrestricted solution (the solution with the highest degree of the quality of service improvement) in the neighborhood. Then, the best unrestricted solution is regarded as the current solution during the following iteration and is evaluated. The process of neighborhood evaluation is repeated until the termination rule is reached. The following shows the pseudo code of the TS optimization algorithm.

Algorithm 2. TS optimization algorithm

Input: Objective functions (*f1*, *f2*), weight coefficients w_1 and w_2
Number of base stations
Service area characteristics (# floors, size, wall materials)
Wireless user characteristics (user density, distribution, traffic profiles)
Initial network configuration

Output: Optimal network configuration (specifying base station parameters: locations, power levels, frequency channels)

Step 1: Set the current solution (s) = the initial network configuration
$i = 1$ // initialize the iteration number

Step 2: while ($i \leq Max\_iter$) do // Exploring the neighborhood
2.1: Generate neighborhood of s denoted as $N(s)$ according to the specified neighborhood structure and the knowledge-based move operators.
2.2: Determine the best solution in $N(s)$ while taking into account the tabu status and the aspiration criteria. The evaluation function is given by the scalarizing function in Eq. (15).
2.3: Determine the tabu tenure which is randomly generated from the interval $[t_{min}, t_{max}]$ with uniform distribution. Update tabu status.
2.4: Update s = the best solution in $N(s)$ and update the best-so far solution.
i++// do the next iteration

Step 3: Return the best solution found and stop

3.3 Neighborhood Structure and Knowledge-Based Move Operators

This section describes the neighborhood structure and the move operators developed in this paper to efficiently solve the multi-objective WDN design problem. Evaluating all solutions in the neighborhood can take a lot of computational time because each evaluation requires the computation of the received signal strength and the SIR levels at all signal test points (STPs). The number of STPs depends on the size of the service area and the grid spacing used. Moreover, the size of the neighborhood can be large, depending on the size of the candidate set of each variable.

To restrict the number of neighbor solutions examined in each iteration, we utilize the information about the quality of service status of the network to derive a set of potential neighbor solutions that are likely to lead the search to a better solution. The reason is that the current solution might violate some constraints or yield poor quality of services. In other words, signal strength and/or SIR level in some areas might be below the threshold and/or some wireless base stations might experience a traffic overload. The idea is to keep track of those location(s) where network performance is poor or does not meet the design requirements. This information is used to identify variables that should be adjusted to improve network performance based on the specified design criteria.

To manage the information about network quality of services, we divide the service area into a unit area (UA) where the performance information described below is evaluated and recorded. The reason that the performance information is managed per UA is to provide a good indicator about the locations of problems, in case those locations are spread across the service region. An example described later in this section will illustrate this scenario.

Table 2. Notations used in the neighborhood structure

Parameters	Definition
n_{UA}	Total number of UAs managed in the service area
G_i^{pr}	Set of STPs in UA_i where the received signal strength is below the threshold, for $i = 1,\ldots, n_{UA}$
G_i^{SIR}	Set of STPs in UA_i where the SIR level is below the threshold, for $i = 1,\ldots, n_{UA}$
B_i^{ov}	Set of base stations in UA_i that cannot provide the required average throughput to associated wireless users for $i = 1,\ldots, n_{UA}$

For each UA_i, the following information is observed and recorded.

1. Information related to low signal strength grids
   - Center of gravity of STPs in G_i^{pr} (denoted by CoG_i^{pr})
   - The lowest received signal strength among STPs in G_i^{pr} (denoted by l_i^{pr})
   - Location of the STP with the lowest signal strength (denoted by Loc_i^{pr})
2. Information related to low SIR grids
   - $|G_i^{SIR}|$, Number of STPs in G_i^{SIR}
   - Average SIR level of all STPs in G_i^{SIR} (denoted by avg_i^{SIR})
   - Center of gravity of STPs in G_i^{SIR} (denoted by CoG_i^{SIR})
3. Information related to overload wireless base stations
   - B_i^{ov}
   - Center of gravity of the locations of wireless users assigned to $b^{ov} \in B_i^{ov}$ (denoted by $CoG_i^{b^{ov}}$) where b^{ov} denotes an overload wireless base station

Fig. 2 illustrates the performance information observed within the example service area. The red grids represent the STPs where signal strength is below the received sensitivity threshold. The red cross-circle represents the centers of gravity for those grids with low signal strength. The blue grids represent the STPs where SIR is below the acceptable threshold. The blue cross-circle represents the center of gravity for those grids with low SIR level. The small green circles represent those wireless users whose average data rate is below the required rate. The green cross-circle represents the center of gravity for those wireless users.

The neighbors of the current solution are obtained by adjusting parameters of BSs which are likely to result in the improvement of the network quality of services. The information about the network quality of services described previously is used to identify a set of potential BSs whose variables should be adjusted. Then derive a set of neighbor solutions.

To generate neighbors of the current solution, two types of move operators are developed. They include greedy moves and conservative moves. Each type deals with changing the power level, the frequency channel and the location of the potential BSs.

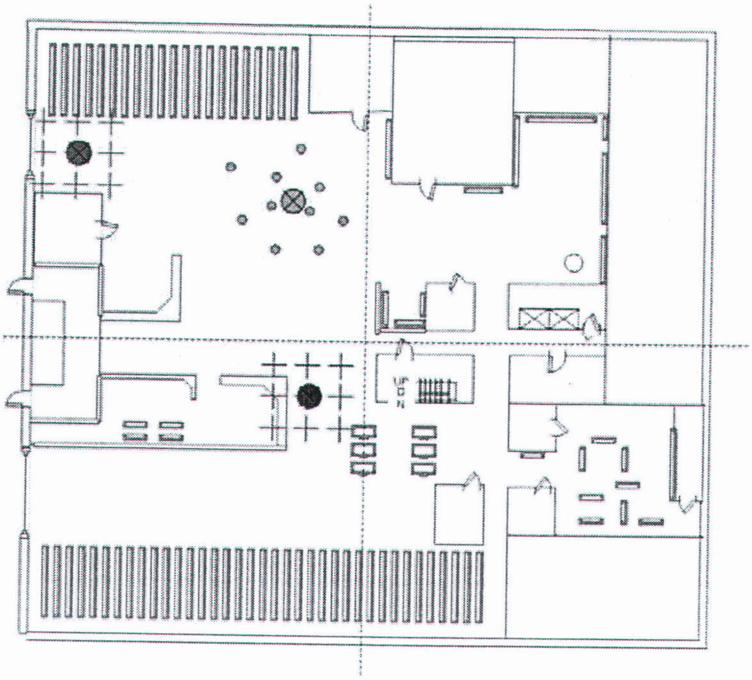

Fig. 2. Examples of performance information management

In greedy moves, parameters of all potential BSs are changed simultaneously. The advantage of this strategy is that the network performance in multiple areas can be improved in one iteration. This allows a fast convergence of the search. However, greedy moves can be too aggressive and cause unintended degradation of the network performance in some cases, especially when the search is approaching an optimal solution. Conservative moves overcome this problem by changing only one parameter of BS at a time. Another advantage of the conservative move strategy is that it allows the search to escape from those solutions in which the greedy moves could not derive any better solution.

4 Numerical Results and Discussions

This section demonstrates the numerical experiments of the wireless data network design. Here we consider a wireless local area network (WLAN) as an example of wireless data networks.

The numerical experiments were conducted on the service area of the building with four floors. The dimension of each floor is 33m × 21m. The service area is divided into grids of size 1m×1m where the grid points specify a set of STPs, G. We consider 50 candidate sites to install the wireless base stations (i.e., $|B| = 50$). These candidate sites were uniformly located in the building. We consider 300 DNs (i.e., $|U| = 300$) of which the locations were uniformly distributed in the service area. We consider three types of service levels (i.e., $|T| = 3$). Each service level requires different amount of bandwidths, including 460 kbps, 260 kbps and 80 kbps.

Table 3. Input parameters

Parameter	Value
P	{0, 7, 13, 15, 17, 20, 24} in dBm
C	{2.412, 2.437, 2.462} in GHz
$P_{Rthreshold}$	-80 dBm
$SIR_{threshold}$	10 dB
R	54 kbps

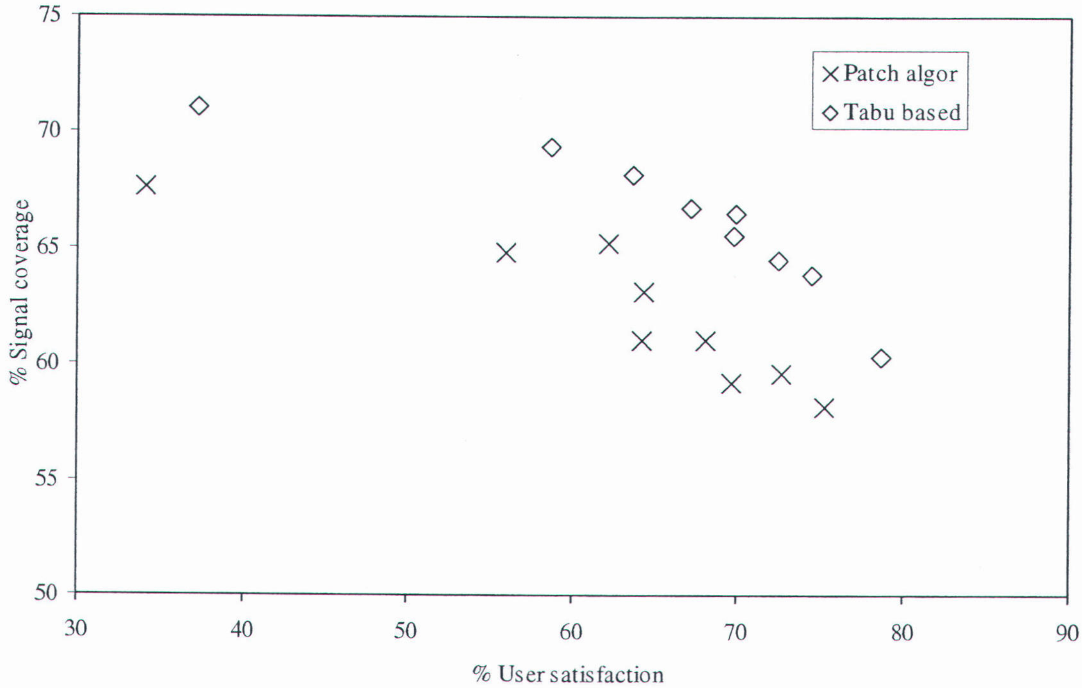

Fig. 3. Network quality comparison

Table 3 summarizes the input parameters of the network design problem. The design aims for 95% coverage availability at the edge of the signal coverage areas. In this case, a fading margin of 5.75 dB is applied in the signal coverage calculation which uses the partition-dependent path loss model with the path loss exponent of 3.3 and the reference distance of 1 m [17]. We consider the base stations using the antenna with gain 2.5 dB.

Parameters used in the TS optimization phase were selected from pilot studies that performed the best search. The *Max_iter* is set to 150. The tabu tenure [t_{min}, t_{max}] is set to [4, 8] and the number of unit areas, n_{UA}, is set to 8, i.e. 2s on each floor.

Fig. 3 plots the results obtained by using the patch algorithm [11] to solve the WDN design problem, compared with those using the proposed TS heuristic. The graph compares the network quality of services in term of the signal coverage availability and the user satisfaction level obtained by solving the problem nine times, using nine different weight sets (Q = 9). The points in fig. 3 are the maximum points found with different weight sets. The graph shows that the results obtained by the patch algorithm [11] are dominated by those obtained by the proposed TS heuristics. In other words, the propose TS heuristics can derive better network configurations resulting in higher network quality of services in term of the user satisfaction level and the signal coverage availability.

Furthermore, it can be observed from fig. 3 that as the w_{2q} increases from 0 to 1 (from left to right), the user satisfaction level increases about 40% whereas the signal coverage availability decreases about 10%. Thus, incorporating the issues of the radio signal quality and the user satisfaction level into the design model can significantly improve the network quality of services in term of the user satisfaction level while slightly degrading the signal coverage availability. These prove an efficiency of the proposed MOP model for the WDN design.

5 Conclusions

In this paper, we have studied the wireless data network design problem and developed a multi-objective mathematical model to determine three important parameters of the network configuration, including the number of base stations, their locations, frequency channels and power levels. In addition, we proposed a heuristic solution techniques based on Tabu search algorithm to solve the problem.

Numerical results have shown that the proposed multi-objective network design model that incorporates the issues of the radio signal quality and the user satisfaction level into the design model can significantly improve the network quality of services in term of the user satisfaction level while slightly degrading the signal coverage availability. Furthermore, the results have shown that the proposed heuristic techniques could yield network configurations of which the network performances outperform that of the network configurations obtained by other techniques. The proposed multi-objective model and heuristic algorithms can be applied to solve the network design problems of different types of the wireless data networks. We currently investigate this direction.

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Multi-Objective Network Design and Optimization for Wireless Local Area Networks

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Abstract: - This paper presents a multi-objective wireless local area networks design and optimization. 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 network quality of service.

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. 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 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) [2] or minimize path loss [3,4]. Other works [5,6] consider the frequency channel assignment problems for WLANs. Ref [5] aims at maximizing the total received signal strength whereas Ref. [6] aims at maximizing the coverage availability. Ref. [7] 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

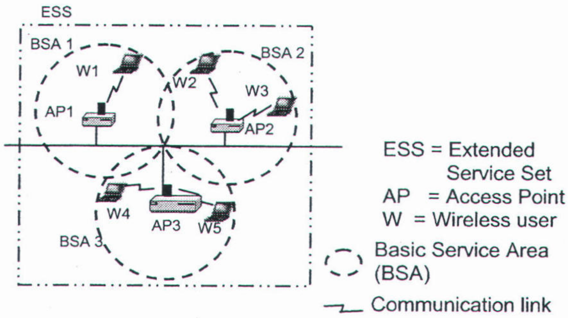

Fig.1 Infrastructure-based WLANs

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 Definition and Formulation

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 [8-10] 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 [8]. User behavior in turn correlates to the types of locations where users are situated and the major activities users typically pursue in those locations [8-10].

We incorporate information about characteristics of WLAN usage and traffic patterns into the design model by using the demand node concept [11]. A user activity level α_t parameter 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 [10]. 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.

2.2 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),

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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_j}), 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

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

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, $\beta_t = R_t / C$.

Constraints:

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

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

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

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

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

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

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

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

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_j} 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 [12]. 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

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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 ($P_{R_{1j}}$) and the SIR level with respect to the ap_j (i.e., $P_{R_{1j}} - Intf_{ij}$) 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. The grid points specify the STPs. In fig.5-8, 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 [8-10]. Similarly, the average user data rates are taken from observed network usage characteristics [8-10]. 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 [7] 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.

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=34%, f_2=67.6%) and (f_1=75.4%, f_2=58%).

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

where q = 1, 2, ..., 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% while 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.

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

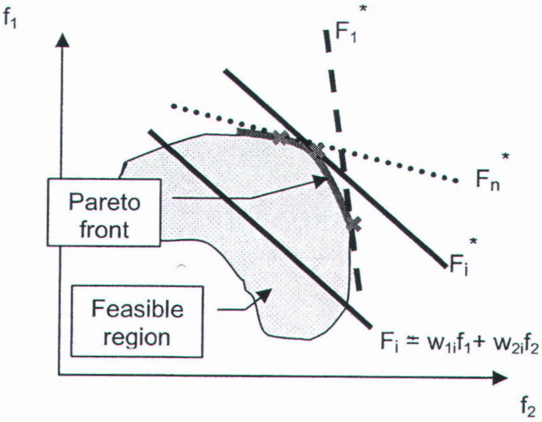

Fig.2 Weighted sum of the objectives and the pareto front

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%).

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 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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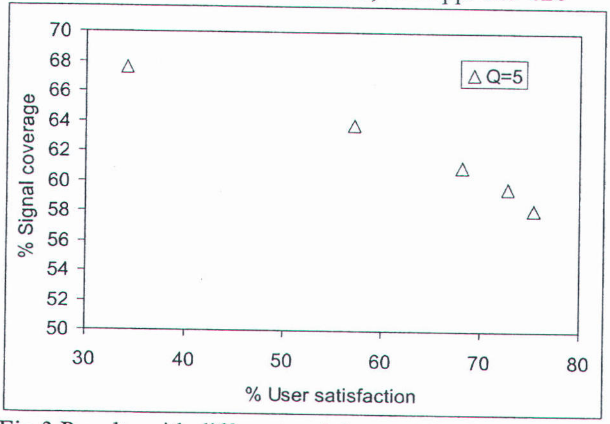

Fig.3 Results with different weight sets (Q=5)

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

Table 1 Network usage characteristics

Sub-areas	User activity level	Average user data rate (Kbps)
Type 1: Private sub-areas	$\alpha_1 = 0.50$	$R_1 = 460$
Type 2: Public sub-areas for unscheduled activities	$\alpha_2 = 0.40$	$R_2 = 260$
Type 3: Public sub-areas for schedule-based activities	$\alpha_3 = 0.35$	$R_3 = 80$

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	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

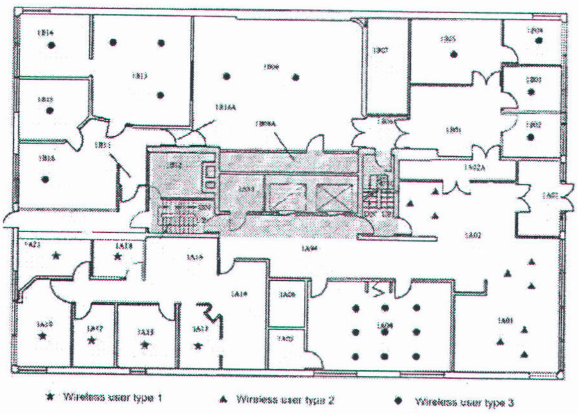

Fig.5 Service area (the 1st first floor)

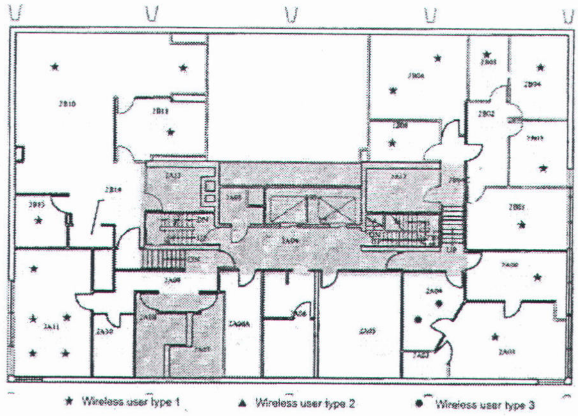

Fig.6 Service area (the 2nd second floor)

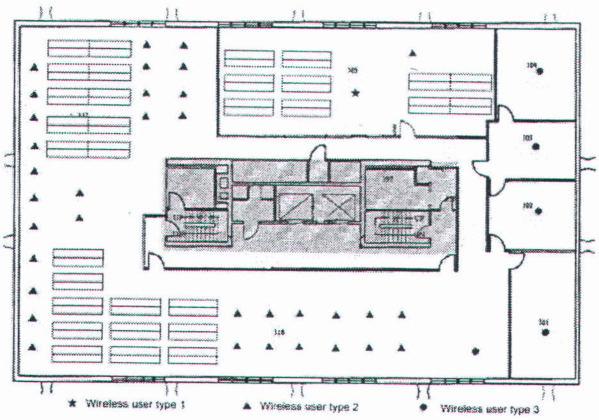

Fig.7 Service area (the 3rd third floor)

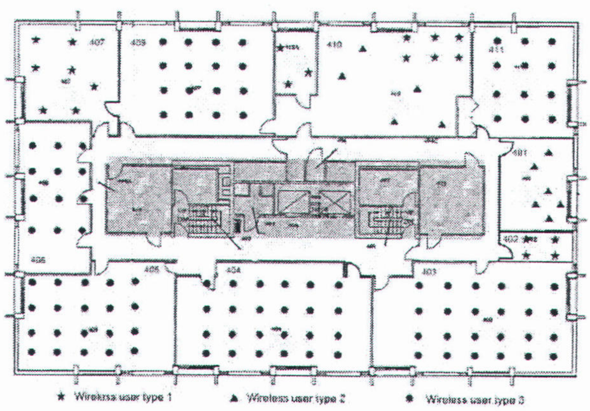

Fig.8 Service area (the 4th forth floor)