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 terms 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 terms 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
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 level. 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 \( \alpha \) parameter accounts for the correlation between network usage characteristics and user locations. \( \alpha \) 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: \( T = \{1, 2, 3\} \) 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 users \((1 - \alpha)\) 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 \( \Omega = \{p_j, f_j, (x_{pj}, y_{pj}, z_{pj})\} \) 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 \( (x_{pj}, y_{pj}, z_{pj}) \) denotes the coordinate \((x_{pj}, y_{pj})\) on floor \( z_{pj} \) 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 \( g_i \) refers to a coordinate in three-dimensional space \((x_{gi}, y_{gi}, z_{gi})\), where \( z_{gi} \) is the floor where \( g_i \) 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. \( U_{i \in \mathcal{U}} \) is a set of demand nodes in sub-area type \( t \). The position of demand node \( i \) within the service area is denoted by \((x_{gi}, y_{gi}, z_{gi})\),
where \((x_i, y_j)\) is the coordinates on floor \(z_i\) where the demand node \(i\) is located. The user activity level \((\alpha_i)\) and the average data rate requirement \((R_i)\) 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 \((\alpha_i\) and \(R_i)\) are given as input to the design process. Other decision variables include \(u_{ij}^t\) and \(g_{ih}\). \(u_{ij}^t\) is a user association binary variable that equals 1 if demand node \(i \in U\) associates to \(ap_j \in A; 0\) otherwise. \(g_{ih}\) 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 \((P_{\text{threshold}})\) and the SIR level \((\text{SIR}_{\text{threshold}})\), user profiles (e.g., the user activity level \((\alpha_i)\) and the average user data rate requirement \((R_i)\), 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 \((P_{\text{h}})\), interference level \((\text{Intf}_j)\), and average obtainable data rate \((R'_i)\). The mathematical model of MOP for the WLAN design is written as follows:

**Objectives:**

1) Maximize signal coverage area

\[
\text{Maximize } f_1 = \sum_{\forall h \in G} \sum_{\forall j \in A} g_{ij} \]

(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

\[
\text{Maximize } f_2 = \sum_{\forall t \in T} \left( \sum_{\forall j \in A} \sum_{\forall i \in U} \beta_i \times u_{ij}^t \right) \]

\[
/ \sum_{\forall i \in T} (\beta_i \times |U_i|) \]

(2)

\(f_2\) measures the user satisfaction level. It is the normalized number of users that can obtain the required data rate. \(\beta_i\) 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, \(\beta_i = R_i \div C\).

**Constraints:**

\[
\sum_{\forall j \in A} u_{ij} \leq 1, \forall i \in U \]

(3)

\[
u_{ij} \left( P_{R_{ij}} - P_{\text{threshold}} \right) \geq 0, \forall i \in U, \forall j \in A \]

(4)

\[
u_{ij} \left( P_{R_{ij}} - \text{Intf}_{ij} - \text{SIR}_{\text{threshold}} \right) \geq 0, \forall i \in U, \forall j \in A \]

(5)

\[
u_{ij} \left( P_{R_{ij}} - R_i \right) \geq 0, \forall i \in U, \forall j \in A \]

(6)

\[
g_{ih} \left( P_{R_{ij}} - P_{\text{threshold}} \right) \geq 0, \forall h \in G, \forall j \in A \]

(7)

\[
g_{ih} \left( P_{R_{ij}} - \text{Intf}_{ij} - \text{SIR}_{\text{threshold}} \right) \geq 0, \forall h \in G, \forall j \in A \]

(8)

\[
u_{ij} \in \{0, 1\}, \forall i \in U, \forall j \in A \]

(9)

\[
g_{ih} \in \{0, 1\}, \forall h \in G, \forall j \in A \]

(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 \(ap_j \) \(P_{\text{h}}\) in dBm) and the SIR level with respect to the \(ap_j\) (the received signal strength \((P_{\text{h}})\) in dBm) less the interference level \((\text{Intf}_j)\) dBm)) meet the receiver sensitivity threshold \((P_{\text{threshold}})\) and the SIR threshold \((\text{SIR}_{\text{threshold}})\) 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 \((r'_i)\) is greater than the specified user data rate \((R_i)\). 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.
strength and the SIR level. The decision variable \( g_{ij} \) can be equal to one if the received signal strength at the STP \( h \) transmitted from the \( a_{pj} \) (\( P_{R_{ij}} \)) and the SIR level with respect to the \( a_{pj} \) (i.e., \( P_{R_{ij}} - \text{Int}_{f_{ij}} \)) meet the received sensitivity threshold (\( P_{R_{\text{threshold}}} \)) and the SIR threshold (\( \text{SIR}_{\text{threshold}} \)). Otherwise, \( g_{ij} \) is equal to zero. Constraints (9) and (10) specify that variable \( u_{ij}^t \) and \( g_{ij} \) 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 \( 33m \times 21m \). The service area is divided into grids of size \( 1m \times 1m \). The grid points specify the STPs. In fig.5-8, the symbol \( \bullet \) represents the demand nodes located in public areas for scheduled activities, the symbol \( \mathbf{\bullet} \) represents the demand nodes located in public areas for unscheduled activities, and the symbol \( \star \) 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.

Max \( F = w_{1}f_{1} + w_{2}f_{2} \) \hspace{1cm} (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 \( \{w_{1j}, w_{2j}\} \). \( F_{i}^{*} \) 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 \((f_{1}=75.4\%, f_{2}=58\%)\).

\[ w_{1q} = (q-1)/(Q-1), \quad w_{2q} = 1- w_{1q} \] \hspace{1cm} (12)

where \( q = 1, 2, ..., Q \), \( Q \) is 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
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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References:
Table 1 Network usage characteristics

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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidate set for Variables:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Set of candidate power levels for variable $p_j$</td>
<td>{0, 7, 13, 15, 17, 20, 24} in dBm</td>
</tr>
<tr>
<td>F</td>
<td>Set of candidate frequency channels for variable $f_j$</td>
<td>{2.412, 2.437, 2.462} in GHz</td>
</tr>
<tr>
<td>Static Parameters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>User active level</td>
<td></td>
</tr>
<tr>
<td>$R_t$</td>
<td>Average user data rate requirement in sub-area type $t$</td>
<td>See Table 1</td>
</tr>
<tr>
<td>$P_{\text{threshold}}$</td>
<td>Received sensitivity threshold</td>
<td>-80 dBm</td>
</tr>
<tr>
<td>$SIR_{\text{threshold}}$</td>
<td>Signal to interference ratio threshold</td>
<td>10 dB</td>
</tr>
<tr>
<td>C</td>
<td>Data rate capacity of the $ap_j$ for $\forall j \in A$</td>
<td>11 Kbps</td>
</tr>
<tr>
<td>Path loss Parameters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_0$</td>
<td>Reference distance $d_0$</td>
<td>1 meter</td>
</tr>
<tr>
<td>$n$</td>
<td>Path loss exponent</td>
<td>3.3</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Standard deviation representing shadow fading</td>
<td>3.5 dB</td>
</tr>
<tr>
<td>Antenna Parameters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_{AZ}$</td>
<td>Antenna gain (peak directivity)</td>
<td>2.5 dB</td>
</tr>
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</table>