Cross-layer Network Design for Quality of Services in Wireless Local Area Networks: Optimal Access Point Placement and Frequency Channel Assignment

Chutima Prommak and Boriboon Deeka

Abstract—**This paper presents a novel network design algorithm for Wireless Local Area Networks (WLANs) considering optimal access point placement and frequency channel assignment problems. The proposed algorithm is a cross-layer approach, accounting the physical layer and the data link layer functionalities of the WLANs in the network design process. Specifically, a multi-objective optimization problem is defined. The proposed objective function separates the physical layer considerations and the data link layer contributions in order to differently change the weights of the two characteristics of WLANs. Numerical results are presented and the jointed impact of the physical and the data link layer functionalities on the WLAN quality of services are evaluated.**

Index Terms— **Network design, Wireless local area network, Quality of service, Network optimization.**

I. 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 terminals (WTs) participating in a Basic Service Set (BSS), a group of WTs within a contiguous radio coverage area of the AP. WTs cannot communicate directly with other terminals in the BSS. All data packets must be relayed through an AP. A coverage area within which WTs are free to move around and yet still remain connected to the AP is called a Basic Service Area (BSA)[1]. Each AP can cover a service 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). Figure 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 APs' locations and frequency channels in order to maximize the signal coverage and the system throughput.

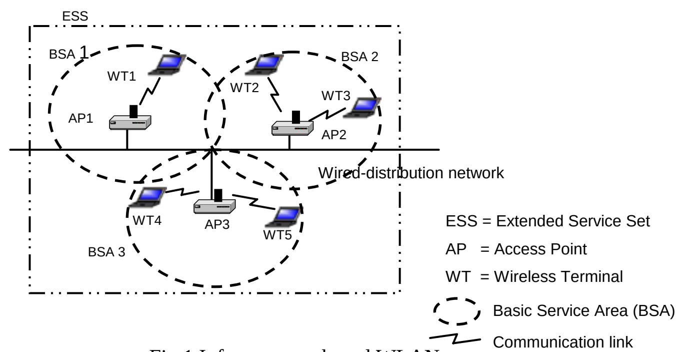

Fig.1 Infrastructure-based WLANs

AP placement and frequency channel assignment are difficult tasks in the network design for WLANs. The reasons are that both tasks are NP-hard problems [2]. The frequency spectrum for WLAN operation is limited and the unique Medium Access Control (MAC) functionalities specified by the Institute for Electrical and Electronic Engineers (IEEE) 802.11 working group [1] further complicates the assignment tasks.

The IEEE 802.11b and 802.11g operate at the 2.4 GHz band whereas the IEEE 802.11a operates at the 5 GHz band. In North America, 83.5 MHz bandwidth is available in the 2.4 – 2.4835 GHz band whereas 300 MHz bandwidth is allocated in the 5.15 – 5.35 MHz (lower-band) and 5.725 – 5.825 MHz (upper-band). The 802.11 standard divides the 2.4 GHz band into eleven channels with center frequencies located 5 MHz apart as shown in Figure 2. Each channel has a frequency bandwidth of 22 MHz. Among these eleven channels are three channels whose bandwidths do not overlap each other. Those channels are 1, 6 and 11, as there is a frequency space of 3 MHz between channels 1 and 6 as well as between channels 6 and 11. These three channels are called the non-overlapping channels, and they can be assigned to adjacent APs without interfering

Manuscript received March 10, 2007. This work was supported in part by the Suranaree University of Technology under Grant "Quality-of-Service Network Planning for Large Scale Wireless LANs".

Chutima Prommak and Boriboon Deeka are with the School of Telecommunication Engineering, Suranaree University of Technology, Nakorn Ratchasima 30000 Thailand, (phone: 66-44-224-392-3; fax: 66-44-224-603; e-mail: cprommak@sut.ac.th).

(Advance online publication: 19 February 2008)

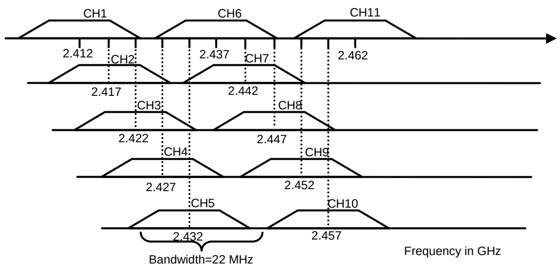

Fig.2 Frequency spectrum allocation for IEEE 802.11b and 802.11g

with each other. The remaining channels overlap with one of the three non-overlapping channels and are called the overlapping channels. Since a limited number of channels exist in the available frequency spectrum for an 802.11 WLAN, a multi-cell network deployment requires that some channels are reused. Reuse of frequency channels in neighboring cells can cause interferences which affect the quality of the signal in the service area. The signal quality in turn affects the transmission data rate of the WTs and the system throughput.

In the context of WLANs, the system throughput is the total amount of traffic that APs in the ESS can accommodate. The throughput level of each AP can vary depending on the number of WTs in the BSA of the AP [3]. The reason is that WTs in the same BSA rely on a common (broadcast) transmission medium. Only one WT can occupy the medium at a time. If multiple WTs simultaneously transmit, a collision may occur and the signal could be corrupted. The IEEE 802.11 standard specifies a MAC protocol, called Carrier Send Multiple Access/ Collision Avoidance (CSMA/CA), to coordinate transmission of the WTs. This coordination is achieved by means of control information. This information is carried explicitly by control messages traveling in the medium (i.e. ACK messages) and can be provided implicitly by the medium itself through the use of a carrier-sensing mechanism before each transmission to check if the channel is either active or idle. Control messages and message retransmission due to collisions consumes medium bandwidth. They are overhead required by a MAC protocol that coordinates transmissions of user terminals. According to the throughput analysis of the CSMA/CA protocol, the AP throughput varies depending on the number of users connecting with the AP [3]. As the number of WTs in the BSA increases, the AP throughput decreases.

According to the carrier-sensing mechanism, prior to the data transmission each WT will check if any terminal using the same frequency channel is transmitting. The transmission of the WTs in nearby BSSs that operate at the same frequency can restrain data transmission of other WTs. Inefficient reuse of frequency channels in multi-cell WLANs can reduce the system throughput. Thus, the network designers must be careful when assigning frequency channels to APs in multi-cell WLANs. An efficient frequency channel assignment technique accounting for the CSMA/CA protocol can help improve the AP throughput, resulting in higher user throughput and eventually the system throughput.

The issues on quality of signal in the target service areas and the concerns about system throughput are two important metrics to be accounted in the AP placement and frequency channel assignment process. However, in the majority of the published papers, the attention is focused on either one of the two aspects. Traditional works on the frequency channel assignment focus mainly on the signal quality aspects. For example, the frequency channel assignment used in the cellular network design is based on the use of channel-separation matrix [4], [5] and the graph coloring approaches [6]. Later works [7], [8], [9] considers the frequency channel assignment for WLANs. Reference [7] aims at maximizing the total received signal strength whereas reference [8] aims at maximizing the coverage availability which is defined as the area where the received signal strength and the signal to interference ratio (SIR) is greater than a specified threshold. Reference [9] provides a weighted graph coloring based formulation that takes into account the number of WTs within coverage of neighbor BSAs that can interfere each other in order to improve the signal quality in the WLANs.

Recent works [10] and [11] take into account the CSMA/CA functionalities. [10] focuses on interactions among APs by minimizing fraction of time at which the channel can be sensed busy by APs operating at the same frequency channel. This paper does not consider restraining by WTs and it does not concern about signal coverage quality. Reference [11] derives an equation to calculate an AP throughput by considering interaction among APs and WTs in the networks. Their problem formulation for the AP placement and the frequency channel assignment mainly focuses on maximizing system throughput but does not consider signal quality in the service area.

In this paper we propose a cross-layer approach, accounting the physical layer and the data link layer functionalities, to solve the AP placement and the frequency channel assignment problem (AP-FCAP) in the WLAN design. We present a multi-objective optimization formulation that allows optimizing both signal quality and system throughput criteria. The proposed model takes into account the interference level and the MAC protocol of the WLANs to reflect the target criteria.

The rest of the paper is organized as follows. The next section describes the problem definition of the AP-FCAP for WLANs and gives the mathematical formulation of the AP-FCAP model. Section III gives numerical results and discussion. Section IV provides conclusions.

II. Problem Definition and Formulation

In WLANs context, the frequency channel assignment problem involves assigning frequency channels from a set of available channels to the APs whereas the location assignment problem involves selecting locations to install APs from a set of candidate locations. In this paper we consider that all APs operate at the same transmitting power (which is a given value). The proposed cross-layer formulation for the AP-FCAP incorporates two important aspects of the WLAN operation, including the system throughput and the signal quality in the service area.

A. System Throughput Considerations

The system throughput is one of important measures indicating the quality of service level in WLANs [12]. According to the CSMA/CA functionalities, the AP throughput depends on the number of WTs connecting to the AP and the frequency channel at which the neighbor BSSs operate. The reason is that data transmission of WTs in near by BSSs can restrain data transmission of other WTs that operate at the same frequency channel [11]. Thus, a proper frequency channel assignment is crucial to achieve high system throughput and eventually the user quality of services.

Here we define the system throughput as a summation of throughput of all APs in ESS. We take into account the system throughput consideration in the AP-FCAP by incorporating the objective function that aims to maximize the system throughput. This objective can be written as follows:

$$f_1:\ max \sum_{\forall j \in A} t_j \tag{1}$$

We adopt a throughput estimation technique developed in [11] to compute AP throughput (t_j). Please refer to [11] for detail equation and parameters to compute t_j.

B. Signal Quality Considerations

In the proposed AP-FCAP model, we consider signal quality in the network 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, WT must be within a certain range of the received signal strength and the SIR threshold. Thus, another important objective function 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. This objective can be written as follows:

$$f_2:\ max \sum_{\forall g \in G} x_g \tag{2}$$

TABLE I
NOTATION USED

Notation	Definition
A	Set of access points (APs) in the network. $\|A\|$ is the total number of APs used in the network.
G	Set of Signal Test Points (STPs). It represents locations in the service area where the signal to interference ratio (SIR) level are assessed. $\|G\|$ is the total number of STPs in the service area.
s_g	SIR assessed at STP g, $g \in G$
s_t	SIR threshold
x_g	Binary variable equals 1 if $s_g > s_t$; 0 otherwise
t_j	Throughput of AP j, $j \in A$
f_j	Frequency channel of AP j, $j \in A$
w_1	Weight ascribed to the system throughput consideration
w_2	Weight ascribed to the signal quality consideration

C. A Cross-Layer Model

On the basis of the signal quality and the system throughput considerations, the problem of assigning the best locations and frequency channels to APs in WLANs, accounting the interference level and the CSMA/CA functionalities, can be mathematically formulated as the cross-layer model (f_3) written below.

$$f_3:\ max \quad w_1 \sum_{\forall j \in A} t_j + w_2 \sum_{\forall g \in G} x_g \tag{3}$$

The objective function f_3 is a popular approach used to deal with multi-objective optimization problems [13], transforming the problem f_1 and f_2 into a single objective function that maximizes a combination of the two problems by using factors w_1 and w_2 to weight the importance of each problem.

III. NUMERICAL RESULTS AND DISCUSSION

To evaluate the performance of the proposed cross-layer AP-FCAP model (f_3), we conducted numerical experiments using the same test scenario as that used in [11] where the building floor is divided into grid granularity of 5 m., a uniform distribution of 478 user terminals was considered and the 16 candidate locations to install APs were given. The Two-Ray-Ground model was used to predict the signal strength. We considered three non-overlapping frequency channels (1, 6, and 11) for the frequency assignment and used the SIR threshold of 10 dB. The signal strength thresholds of -75/-79/-81/-84 dBm are used for data rate of 11/5.5/2/1 Mbps, respectively [11].

The weight factor, w_1 and w_2, used in the f_3 model were decided by running pilot tests that vary w_1 and w_2 and selecting values that yield good network performances. Let $w_1 = 1 - w_2$. Figure 3 and 4 show results from the pilot tests that use different number of APs in the network (3 to 10 APs).

Figure 3 shows that the percentage of the coverage area is proportional to w_2; the lower value of w_2 used in the network design (the higher value of w_1), the lower percentage of the coverage area can be achieved. The highest percentage of coverage area can be achieved when setting $w_2 = 1$ (i.e., $w_1 = 0$) in all cases of the number of APs used. Figure 4 shows that when using a few APs (3 and 4 APs), the system throughput is proportional to the value of w_1. This relationship does not hold in the case of using more than 4 APs. In such case, the network design yields highest throughput when w_1 ranges from 0.3 to 0.5. The reason is that the more number of APs used in the network, the more chance of interference which results in poor signal quality and in return affects the obtainable user data rate and the system throughput. The network design must use appropriate value of the weight factor in order to achieve high system throughput without scarifying the signal coverage quality. From figure 3 and 4, we can see that when $w_1 = 0.4$ and $w_2 = 0.6$, the network design yields high system throughput and high percentage of the coverage area for all cases of the number of APs used. Therefore, we used $w_1 = 0.4$ and $w_2 = 0.6$ in the rest of our studies.

The first set of numerical experiments aims to compare the use of the three models, f_1 (the throughput based model), f_2 (the signal quality based model) and f_3 (the cross-layer model), in the network design for quality of services in WLANs. The solutions for the AP placement and frequency channel assignment were found by using the patching algorithm [11]. The resulting WLAN systems configuring with the AP locations and the frequency channels obtained by each model were compared in term of the coverage area, the user throughput and the system throughput.

Figure 5 and 6 compare the system throughput and the coverage area of the WLAN system using the AP locations and the frequency channels obtained by the model f_1, f_2 and f_3. The number of APs used in the network is varied from 1 to 10 APs. We can see that the cross-layer model, f_3, yields the WLAN system with high system throughput and good signal coverage. Figure 5 shows that f_1 results in the highest system throughput while f_2 results in the lowest system throughput. We can see that f_3 results in very high system throughput, much better than that of f_2 and only slightly less than that of f_1 for almost all the number of APs. Figure 6 shows that f_1 results in the lowest coverage area while f_2 and f_3 result in the highest coverage area.

Table II shows the number of WTs that in average can achieve particular throughput rates. We observe that in the WLAN system designed by the model f_1 50% of WTs cannot perform data transmission. The reason is that the model f_1 mainly focuses on maximizing system throughput. The resulting WLAN system contains coverage hole. This means the received signal strength and the SIR level of WTs in the hole area are lower than the threshold level. These WTs in average cannot perform data transmission whereas 9.43% of WTs in other areas can transmit data at high rate. On the other hands more than 99% of WTs in the WLAN system designed by the model f_2 can perform data transmission. The reason is that the model f_2 aims to maximize coverage area. So, most of WTs can receive good signal quality and can perform data

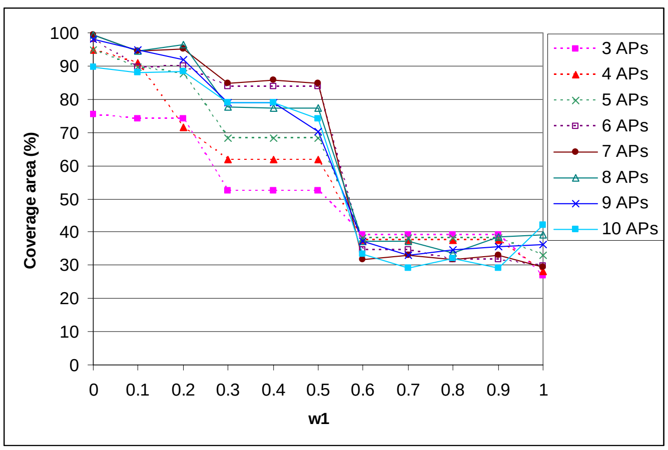

Fig.3 Coverage area of WLANs versus w_1

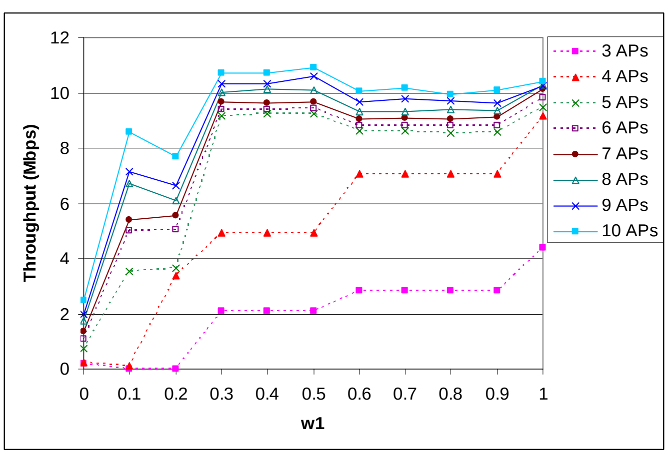

Fig.4 System throughput versus w_1

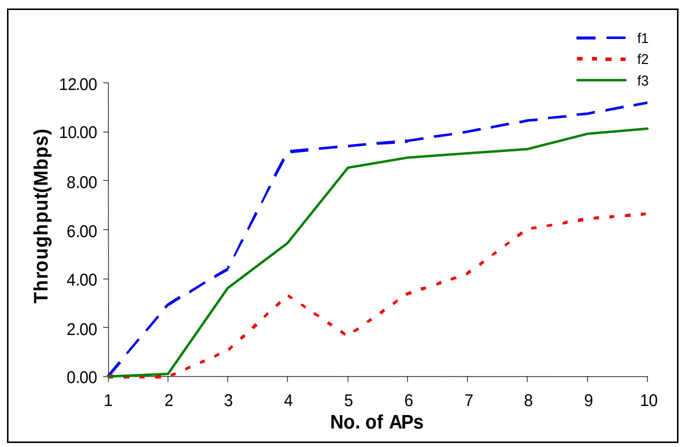

Fig.5 System throughput comparison as the number of APs increases

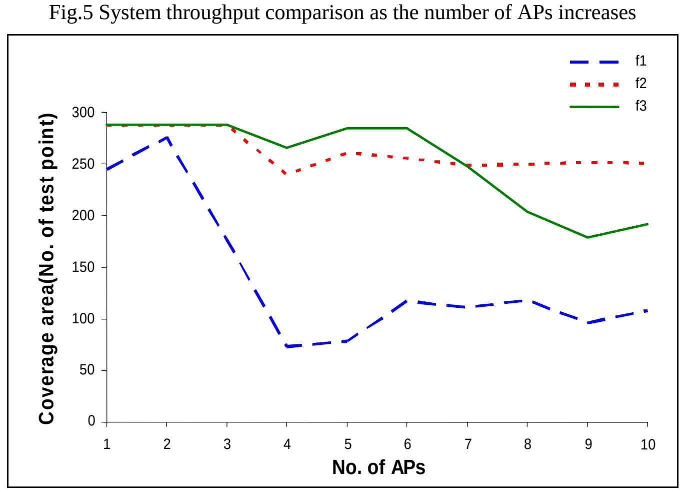

Fig.6 Coverage area comparison as the number of APs increases

transmission. However, the model f_2 does not consider the number of restrainers. As a result, more than 90% of WTs have throughput below 5 kbps. Consider the WLAN system designed by the model f_3. This system has good signal coverage across the service area. So, more than 90% of WTs can received good signal quality and be able to perform data transmission. With the consideration of CSMA/CA protocol and the effects of restrainers, 17.5% of WTs in this system can achieve throughput higher than 5 kbps.

We conducted another set of numerical experiments to study effects of number of users in the service area on the performance of the AP-FCAP model. We considered three scenarios of the user density; low, medium and high. We used a uniform distribution of 0 to 2 users per grid in the low user density scenario, 2 to 4 users per grid in the medium user density scenario, and 4-6 users per grid in the high user density scenario. From figure 7 and 8, we can observe that in all case of user density f_3 results in higher system throughput compared to that of f_2 and results in better signal coverage compared to that of f_1. Although f_1 yields WLAN system with higher system throughput but it results in much less signal coverage compared to that of f_3. For example, in case of high user density, coverage area of the WLAN system using f_1 is 50.8% less than that using f_3.

IV. Conclusion

A novel cross-layer model that accounts the system throughput and the signal quality in the service area has been formulated as a multi-objective optimization problem. The numerical results show that the proposed model can enhance the WLAN system performance in term of system throughput and coverage area whereas the signal quality based model results in low system throughput and the throughput based model results in poor signal coverage.

TABLE II
User Throughput in WLAN using 7 APs

Achievable Throughput (bps)	Percentage of users at a certain throughput		
	f_1 model	f_2 model	f_3 model
0	50.10	0.84	8.60
0-10	11.11	24.00	22.29
10-50	10.90	0.00	0.00
50-100	0.00	0.00	0.00
100-500	0.00	27.67	24.01
500-1000	0.00	26.12	18.66
1000-5000	10.27	10.37	8.97
5K-10K	8.18	9.53	8.05
10K-50K	0.00	1.47	0.00
50K-100K	9.43	0.00	9.43
100K-500K	0.00	0.00	0.00

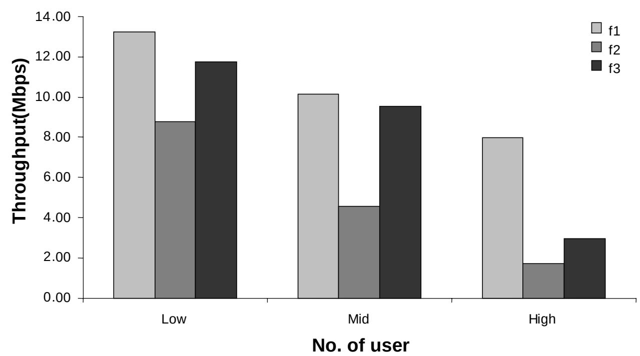

Fig.7 System throughput comparison as the number of users increases

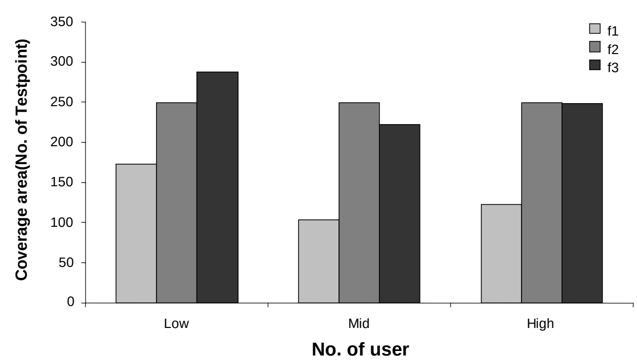

Fig.8 Coverage area comparison as the number of users increases

References

[1] "IEEE standard for information technology- telecommunications and information exchange between systems- local and metropolitan area networks- specific requirements Part II: wireless LAN medium access control (MAC) and physical layer (PHY) specifications," *IEEE Std 802.11g*, 2003, pp. i-67.

[2] Vijay Vazirani, *Approximation Algorithms*, Springer Verlag,2001

[3] F. Cali, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Trans. On networking*, vol. 8, pp.785-799, 2000.

[4] K. N. Sivarajan et al., "Channel assignment in cellular radio," *IEEE Trans Veh. Technol*, p. 846-850, May 1989.

[5] S. U. Thiel, S. Hurley, and D. H. Smith, "Frequency assignment algorithms," Dept. of Computer science, University of Wales Cardiff, UK, Ref. RCCM 070, April 1997.

[6] C.-W. Sung and W.-S. Wong, "A graph theoretic approach to the channel assignment problem in cellular systems," in *Proc. 45th IEEE Veh. Technol Soc. Conf.*, July 1995

[7] R.C. Rodrigues, G.R. Mateus, and A.A.F. Loureiro, "On the design and capacity planning of a wireless local area network," *IEEE/EFEP Network Operations and Management Symposium*, 2000.

[8] C. Prommak and B. Deeka, "On the Analysis of the Optimal Frequency Planning for Wireless Local Area Networks", *The Fourth PSU Engineering Conf. (PEC-4)*, pp. 77-81, December 2005.

[9] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted Coloring based Channel Assignment for WLANs," *Mobile Computing and Communication Review*, vol. 9, number 3, pp. 19-30.

[10] K.K. Leung and B-J.J. Kim, "Frequency Assignment for IEEE 802.11 Wireless Networks," in *Proc. 58th IEEE Veh. Technol Conf. (VTC)*, pp. 1422-1426, Oct 2003.

[11] X. Ling and K. Lawrence Yeung "Joint Access Point Placement and Channel Assignment for 802.11 Wireless LANs," *IEEE Wireless Communications and Networking Conf.*, pp. 1583-1588, 2005.

[12] H. Zhai, X.. Chen, and Y. Fang, " How well can the IEEE 802.11 wireless LAN support quality of service?," *IEEE Trans on wireless communications*, vol. 4, pp. 3084-3094, Nov 2005.

[13] Y. Colletter and P. Siany, *Multi-objective Optimization: Principles and Case Studies (Decision Engineering)*. Springer-Verlag, 2003.