An Optimal Station Association Policy for Multi-Rate IEEE 802.11 Wireless LANs

Murad Abusubaih and Adam Wolisz
Technical University Berlin
Telecommunication Networks Group
Einsteinufer 25
10587 Berlin, GERMANY
abusubaih@tkn.tu-berlin.de

ABSTRACT

In wireless local area networks (WLANs) often a station can potentially associate with more than one Access Point (AP). In IEEE 802.11, the station simply associates to the AP from which it has received the strongest signal during the scanning process. However, this may result in a significant load imbalance between several APs since some of them might be highly loaded while others are lightly loaded or even idle. Moreover, the multi-rate flexibility provided by several IEEE 802.11 variants can cause low bit rate stations to negatively affect high bit rate ones and consequently degrade the overall network throughput. Therefore, a relevant question is how to optimally distribute stations among APs so as to maximize the overall network performance. This paper presents a centralized optimal association policy for IEEE 802.11 WLANs. We first derive the optimal solution for stations association. Then, we evaluate the effectiveness of the solution through the results obtained from Lingo optimization and NCTUns simulation packages.

Categories and Subject Descriptors

C.4.1 [**Computer Systems**]: Performance of Systems;
C.2.1 [**Computer Communications Networks**]: Network Architecture and Design - *Wireless Communication*

General Terms

Performance, Management

Keywords

Association, Access Point Selection, IEEE802.11, WLANs

1. INTRODUCTION

The proliferation of wireless users and the promise of converged voice, data and video technology is expected to open new numerous opportunities for WLANs [1] in the networking market. Due to decreasing cost of equipments (wireless access points (APs) and wireless network cards) and fixed broadband connections (digital subscriber lines), WLANs have become the preferred access technology in homes, offices and hot-spot areas (like airports and meeting rooms). Although originally several solutions for WLANs have been competing, today virtually all WLANs are based on the IEEE 802.11 standard.

Currently, an IEEE 802.11 station (STA) has to first select (and associate with) an AP before it can access data transmission services. This process can be performed either actively or passively and is referred to as scanning. In active scanning a STA sends a "Probe Request" frame and the AP replies with a "Probe Response" frame. The frame exchange is repeated over all supported channels, such that the STA has a list of APs at the end of the scanning process. Alternatively, in passive scanning a STA hops over all supported channels and listens to "Beacon" frames which are periodically transmitted by APs. After scanning (either actively or passively), a STA always associates to the AP from which it has received the strongest signal. Afterwards, it stays associated until the STA is powered down or the AP shuts down its service.

This intuitive association scheme can cause problems especially in multi-rate WLANs. In principle, the advantages of multi-rate protocols have been shown in [2]: Usually, a mobile STA with a relatively low signal to noise and interference ratio (SNIR) chooses a low transmission rate to balance its frame error rate. However, the 802.11 medium access control (MAC) protocol provides "per frame fairness". It means that in the long term STAs have the same chance to access the medium and send their frames (all STAs should transmit with an equal average frame rate over a longer time horizon). As the time duration required to transmit a frame with a low transmission rate is much longer than the duration for the same frame size with a higher transmission rate, a low transmission rate STA will occupy the channel for longer time. This phenomenon degrades the throughput of high rate STAs if they are associated to the same AP. Heusse et al. [3] have shown that if a STA with a transmission rate of

11 Mbps shares the channel with a STA at a transmission rate of 1 Mbps, the throughput of the 11 Mbps STA is about the same as that of the 1 Mbps STA (assuming equal flow characteristics of each STA as well as the saturation mode).

Obviously the rather "simple" selection policy currently implemented in IEEE 802.11 WLAN cards can lead to problems in dense WLANs with many STAs and several APs [4, 5]. Some APs will become highly loaded while others are lightly loaded or even idle. In addition, low rate STAs will significantly degrade the throughput of high rate STAs. From our point of view these system characteristics call for four issues:

- A decentralized AP selection policy implemented at the station to enable it to initially select a "fairly good" AP that provides a sufficient rate while the station is not degrading rates of other stations too much. Such selection policy can be based on information about the cell status received via AP beacons or probe response frames.
- A centralized WLAN management policy which finds the optimal association and redistributes already associated stations among APs.
- A mechanism to facilitate information exchange between communicating APs in order to collect information required for the central redistribution of stations.
- A mechanism to support a transparent re-association of stations if a central policy decides so.

This paper contributes to the development of solutions for the above listed issues with a centralized optimal STA-AP association policy. Unlike other published work in this direction, the proposed policy uses more realistic model and a metric that encapsulates several important cell and connection parameters. In order to evaluate the effectiveness of the presented policy, we have conducted extensive experiments using a Non-Linear Optimization Solver as well as simulation tools. The paper also compares the outcome of the centralized association policy with the results of our decentralized policy published in [6]. Our investigations have shown that the centralized policy could better utilize the WLAN resources and improve the QoS. The implementation aspects of the proposed policy are also discussed.

The remainder of this paper is organized as follows: Section 2 discusses the related work. Section 3 derives the optimal solution for the station association problem and describes the basic assumptions. Section 4 discusses the implementation aspects of the proposed policy. Finally, we evaluate the performance of the policy in Section 5 before we conclude the paper in Section 6.

2. STATE OF THE ART

The legacy AP selection policy implemented in today's IEEE 802.11-based WLAN cards has initiated research activities in an area commonly referred to as âĂİload balancingâĂİ. Equal maximum physical rate (for example 11Mbps in IEEE802.11b) has been assumed in many of the research work in this area. The main target of load balancing is basically to utilize the capacity of the WLAN more efficiently and improve the QoS by distributing users over multiple cells (A tutorial discussion of load balancing in packet switched networks is provided in [7]). Actually, many decentralized as well as centralized approaches have been proposed to tackle the problem of load balancing. The decentralized approach is also referred to as *AP selection*. The major question among the work in this area has been how to model the load most realistically in a WLAN cell. For example, in [8] it has been proposed to simply characterize the AP load by the number of stations associated to it. While this is easy to implement, the multiple rates provided by several IEEE 802.11 variants and the fact that users have different traffic loads counteract this load metric. A decentralized approach to load balancing has been proposed by Ekici et al. in [9]. With this approach, each station decides independently on its association. However, the authors suppose in their study that the achieved goodput per station equals the transmission rate which is not the case in general. The recent paper of [13] addresses another decentralized AP Selection. With this scheme, a STA associates with the AP that provides the best service considering the connection data rate as well as the number of users accommodated by the AP. Kumar and Kumar [10] have presented a simple mathematical model for the multiple rate effect and the consequence for centralized, optimal load balancing. Although the authors consider the multi-rate effect, again the goodput per terminal is assumed to equal STA's physical transmission rate. A further centralized solution with a simplified load characterization can be found in [11]. A heuristic decentralized solution for online STA-AP association which is also based on the model of [10] has been proposed recently in [12] for two AP networks. In our paper in [6], we have proposed and investigated a new decentralized AP selection policy that bases AP selection on the STA's effective throughput and its impact on other STAs throughput, which are already associated to an AP of a cell. The effective throughput is computed based on an estimation of the average time required to transmit a frame successfully over the wireless channel. Through simulation examinations, we have shown that the policy performs better than the legacy selection policy currently implemented in IEEE802.11 devices. Moreover, we have recommended that STAs decentrally and periodically re-evaluate their current association and check whether the current association is still the best one or not. A more common assumption in the previous work is that STAs are always active (i.e they are always transmitting or receiving data packets). This means that a low rate STA always has the same influence on high rate STAs regardless of its activity level which is not realistic. Therefore, a solution might avoid, for example, associating a high rate STA to an AP that accommodates low rate STAs even if the low rate STAs are idle. Moreover, it introduces unnecessary overhead by moving low rate STAs that are not harmful (not very active) to other cells.

In this work we are interested in exploring a centralized policy that optimally assigns STAs to APs so as to maximize the network performance considering not only STAs' frame times but also their activity levels. Usually, a central entity has a global view on the network status. Hence, it is expected to improve the WLAN performance at the cost of signaling and processing overhead.

3. SYSTEM MODEL

Let us consider an area that is covered by an Infrastructure WLAN with N APs indexed by the set $A = \{1, 2, 3, .., N\}$. We assume that APs operate over different channels and provide communication services to M STAs indexed by the set $S = \{1, 2, 3, .., M\}$. Denote the set of STAs currently associated to AP a as S_a. Practically, STAs may use different services and have different loads. Hence, some of them might not be active all the time. To model this fact, we introduce a factor α_s to represent the activity level of STA s relative to other STAs (i.e activity levels are normalized with respect to their sum). Note that the activity level is independent from the physical transmission rate of a STA. We assume that each AP can estimate the activity of each STA s it accommodates during an observation time interval as will be explained in the next section. Let $x_{a,s} \in \{0, 1\}$ denotes the decision variable if STA s is associated to AP a. Furthermore, let $c_{a,s} \in \{0, 1\}$ denotes the principle connectivity between AP a and station s, meaning that if $c_{a,s} = 1$ then station s can connect to AP a employing one of the 802.11 rates.

In [10], they have proposed to associate STAs to APs based on the association that maximizes the total throughput computed as:

$$D = \sum_{a \in A} \frac{Y_a}{\sum_{j \in S_a} \frac{1}{R_j}} \tag{1}$$

where Y_a is the number of users associated to AP a and R_j is the physical rate of STA j.

In [6], we have derived a more realistic model for the average throughput $G_{a,s}$ of a STA s if it associates to an AP a as follows:

$$G_{a,s} = \frac{L_s}{\sum_{j \in S_a} t_{a,j}} \tag{2}$$

where $t_{a,j}$ is the average time that STA j requires to successfully transmit a frame when communicating via AP a. Hence, $t_{a,j}$ depends on the current rate and packet error rate of the connection. L_s is the frame length in bits. It is clear that other STAs associated to AP a reduce the throughput of STA s. Actually the amount of reduction should not only depend on their corresponding frame times but also on their individual activity levels. Thus, we re-write equation (2) as follows (incorporating the activity level of station j as well):

$$G_{a,s} = \frac{L_s \alpha_s}{\sum_{j \in S_a} \alpha_j t_{a,j}} \tag{3}$$

The total throughput of AP a is given as:

$$W(a) = \sum_{s \in S_a} \frac{L_s \alpha_s}{\sum_{j \in S_a} \alpha_j t_{a,j}} \tag{4}$$

and the aggregate WLAN throughput is given as:

$$D_{\text{Total}} = \sum_{a \in A} W(a) \tag{5}$$

Now, our objective is to find the assignment matrix $\mathbf{X}$ that maximizes the WLAN throughput (i.e the total APs' throughput). With this, we can write the optimal association model as follows:

$$\begin{aligned}
\max_{X} \quad & \sum_{a \in A} W(a) \\
\text{s.t.} \quad & x_{a,s} \le c_{a,s} && \forall a, s \in A \times S \\
& \sum_{a \in A} x_{a,s} = 1 && \forall s \in S \\
& \sum_{s \in S} \alpha_s = 1 && \forall s \in S \\
& W(a) = \sum_{s \in S_a} \frac{L_s \alpha_s}{\sum_{j \in S} \alpha_j t_{a,j} x_{a,j}}
\end{aligned} \tag{6}$$

- $x_{a,s} \le c_{a,s}$: Assures that associations between APs and STAs are only performed if possible due to the connectivity information.
- $\sum_{a \in A} x_{a,s} = 1$: Assures that each STA s is associated to precisely one AP.
- $\sum_{s \in S} \alpha_s = 1$: Sums the normalized activity levels of all STAs to 1.

In order to motivate the importance of considering the activity level as a parameter in the optimal association problem, we provide a ***simple example:***

Consider two APs and three STAs. Assume that the average frame time of STA s simply equals $1/R_s$ seconds, where R_s is the corresponding physical rate in Mbps. Let us assume that the three STAs have the following normalized activity levels $\alpha = \{0.45, 0.05, 0.5\}$ and each one can associate to any AP. Consider the following possible associations:

Table 1: Total APs' Throughput in Mbps for two different Associations

Assoc.	AP1	AP2	D_{Total}
A1	$R_1 = 1$,$R_3 = 11$	$R_2 = 1$	**2.92**
A2	$R_1 = 1$	$R_2 = 1$, $R_3 = 11$	**6.21**

From table I, it is clear that the second association (**A2**) achieves better aggregate throughput than the first association. However, ignoring the activity levels (i.e assuming $\alpha_s = 1/M = 1/3, \forall s \in \{1, 2, 3\}$), the two associations are considered to achieve the same throughput.

3.1 Special Case

The optimization model in equation (6) is hard to be solved analytically due to the nonlinearity and binary variables. For simplicity, we consider and analyze a special case where every STA can join any AP and all STAs associated to AP a have the same average frame time T_a, (i.e. $t_{a,j} = T_a, \forall j \in S_a, \forall a \in A$). This case could apply to a dense WLAN with many APs where STAs could connect to an AP at the same rate. As in [10] and [14], we introduce the logarithmic utility function $\mathbf{ln(.)}$ which grants high throughput with some fairness among the STAs. We also assume equal frame lengths and drop the parameter L_s. We are interested in finding out how the STAs should be distributed among APs.

A simplified optimization model could be written as:

$$\begin{aligned} \max \quad & \sum_{a \in A} F(a) \\ \text{s.t.} \quad & \sum_{s \in S} \alpha_s = 1 \\ & F(a) = \sum_{s \in S_a} \alpha_s \ln \left[\frac{1}{T_a \sum_{j \in S_a} \alpha_j} \right] \end{aligned} \tag{7}$$

which is equivalent to minimizing the following objective function:

$$\begin{aligned} \min \quad & \sum_{a \in A} \sum_{s \in S_a} \alpha_s \ln \left[T_a \sum_{j \in S_a} \alpha_j \right] \\ \text{s.t.} \quad & \sum_{s \in S} \alpha_s = 1 \end{aligned} \tag{8}$$

Now, we apply the Lagrange multipliers methodology to solve the above model. The Lagrangian function is given as:

$$F(\alpha_1, \alpha_2, .., \alpha_M, \lambda) = \sum_{a \in A} \sum_{s \in S_a} \alpha_s \ln \left[T_a \sum_{j \in S_a} \alpha_j \right] + \lambda \left[\sum_{s \in S} \alpha_s - 1 \right] \tag{9}$$

Differentiating (9) w.r.t to each α_s and setting the result equal to zero, we have:

$$\ln \left[T_a \sum_{j \in S_a} \alpha_j \right] + \frac{\alpha_s}{\sum_{j \in S_a} \alpha_j} + \lambda = 0 \tag{10}$$

simplifying and re-arranging variables, we obtain:

$$\sum_{j \in S_a} \alpha_j = \frac{1}{T_a} e^{-(\frac{\alpha_s}{\sum_{j \in S_a} \alpha_j} + \lambda)} \tag{11}$$

Summing both sides over $a \in A$ and noting that $\sum_{s \in S} \alpha_s = \sum_{a \in A} \sum_{j \in S_a} \alpha_j = 1$, we have:

$$\sum_{j \in S_a} \alpha_j = \frac{1}{T_a \sum_{b \in A} \frac{1}{T_b}} \tag{12}$$

Note that the left-hand side of (12) represents the total activity levels that should be assigned to AP a.

If the activity level is equal for all STAs associated to AP a (i.e $\alpha_j = \alpha_a, \forall j \in S_a$), then:

$$Y_a = \frac{\sum_{b \in A, b \neq a} Y_b \alpha_b}{\alpha_a (T_a \sum_{b \in A} \frac{1}{T_b} - 1)} \tag{13}$$

where Y_a is the number of STAs that should associate to AP a.

The following results can be drawn from the above analysis:

1. The number of STAs that any AP should accommodate depends on the average frame times as well as the activity levels of the STAs to be associated to this AP.
2. When $\alpha_s = \alpha, \forall s \in S$, $\forall a, b \in A$, then equation (13) reduces to:

$$Y_a = \frac{M}{T_a \sum_{b \in A} \frac{1}{T_b}} \tag{14}$$

which means that the number of STAs that should be associated to an AP is proportional to the STAs average frame times. When $T_a = T, \forall a \in A$. Then :

$$Y_a = \frac{M}{N}. \tag{15}$$

which means that STAs should be evenly distributed among the APs. The sub-results in equations (14) and (15) are in accordance with the conclusions of [10].

As an illustration: Assume the WLAN has two APs, **AP 1** and **AP 2**. The STAs can associate to **AP 1** with average frame time $T_1 = \frac{1}{11Mbps}$ and to **AP 2** with average frame $T_2 = \frac{1}{5.5Mbps}$. If the STAs to be associated to **AP 1** have equal activity levels of $\alpha_1 = 1/12$ and those to be hosted by **AP 2** of $\alpha_2 = 1/6$. Then:

$$\frac{Y_1}{Y_2} = \frac{1}{T_1 \sum_{b \in A} \frac{1}{T_b} - 1} . \frac{\alpha_2}{\alpha_1} = 4 \tag{16}$$

which means that the number of STAs to be hosted by **AP 1** should be four times greater than the number of STAs to be accommodated by **AP 2**.

4. IMPLEMENTATION ASPECTS

In this section we discuss the implementation aspects of the proposed policy. Thanks to the 802.11k [15] standard, where each STA provides it's AP the connectivity information with all APs in it's vicinity. Since the Carrier Sense Multiple Access (CSMA) provides per frame fairness, each STA will have the chance to use the channel. Therefore, it is possible for each AP to estimate the activity levels of all STAs it accommodates by observing the in/out frames during some time interval. Clearly, a central entity is needed to process the current WLAN status information and find the optimal association vector. APs feed the status information to the central entity which could be a central management switch that connects all APs as proposed in the literature. However, such solution could imply high unnecessary signaling and processing overhead since most likely STAs will be able to join APs in their neighborhood and not anywhere. Alternatively, a cluster of neighboring APs might cooperate and a semi-central entity could be one of them. Such solution applies to managed WLANs in many organizational deployments such as hotels, airports, and centrally managed hotspots. In order to facilitate such cooperation between APs, an Inter-AP protocol is required. Any AP shall be able to trigger this protocol and request other APs in it's neighborhood to submit their status information, find and distribute the optimal association vector to them. The AP could trigger this protocol based on a threshold value that reflects the characteristics of the physical rates of the frames transmitted and received by the AP during an observation time interval T. We refer to this value as the *Rate Index*(RI) which could be computed as follows:

$$RI = \frac{1}{R_{max} \times T} \sum_{i=R_{min}}^{R_{max}} R_i * T_i \tag{17}$$

where R_{min} and R_{max} are the minimum and maximum supported physical rates respectively. R_i is the physical rate of i, T_i is time duration the AP spends transmitting and receiving frames at R_i, and finally T is the total observation time period. It is clear that RI becomes small as the time that the AP spends exchanging frames employing low physical rates increases.

5. PERFORMANCE EVALUATION

In order to investigate the performance gain of our proposed centralized policy, we have conducted extensive experiments using the versatile optimization package, Lingo from Lindo systems [16]. Then we have used Lingo to solve the optimal association problem in a simulation scenario developed with the NCTUns 3.0 [17] simulation package. We do not consider the processing time and the Inter-AP coordination protocol overhead and leave the specification and analysis of the protocol for future work.

5.1 Simulation Scenario and Metrics

The conducted simulation experiment was comprised of four APs. APs are assigned different channels and placed 250m apart from each other. 30 stationary FTP STAs appear at different points in time and at different places. APs and STAs employ 802.11b. All STAs utilize CBR TCP with packet length of 1000 bytes and different loads generated with the Jugi's Traffic Generator (jtg) [18]. The sessions terminate at the wired part of the network at a single server. The latency for packets between APs and the server was set to 10μs. The cables connecting the APs to the server (via an 802.3 switch) have a 100 Mbps bandwidth.

APs and STAs employ same transmission power of 18dB. Depending on the distance between AP and STA, the wireless channel is attenuated more or less severely. However, we assume that radio signals are not only attenuated by path loss, but are also affected by fading due to multi-path propagation. In order to accurately model these effects, a path loss component as well as a Rayleigh-distributed fading component is considered. The fading impact is regenerated for every frame transmission per station. An internal fading process of the NCTUns simulation tool is used which takes as parameter a variance coefficient. For the path loss, we have used a two-ray ground reflection model with the received power $P_{\rm rx}$ given as:

$$P_{\rm rx} = \frac{P_{\rm tx} G_{\rm tx} G_{\rm rx} h_{\rm tx} h_{\rm rx}}{d^2} \qquad (18)$$

where $P_{\rm tx}$ is the transmit power in mW, $G_{\rm tx}$,$G_{\rm rx}$ denote the transmitter and receiver antenna gains respectively and set to 0 dBi. $h_{\rm tx}$ and $h_{\rm rx}$ are the antenna heights of transmitter and receiver considered to be 1m and d is the distance between them.

At power up, STAs select their APs using the legacy 802.11 selection policy based on the received signal strength. Stations choose their transmission rates depending on the perceived power and try to assure a bit error rate (BER) less than 10^{-5}. This rate remains constant during the simulation, i.e. no rate adaptation mechanism has been implemented.

APs estimate the activity levels of STAs by counting their corresponding in/out frames over a time window of 3 seconds. They also collect the connectivity information from STAs. At almost half of the simulation time (i.e. 150 seconds), a script running on the switch connecting APs invokes the optimizer which in turn finds the association decisions and distributes them to the APs. Then APs instruct the STAs which require to join other APs to re-associate to their new APs. The simulation was run for 30 independent times each of 350 seconds. In each run STAs were randomly relocated in the coverage area.

As the throughput of the whole system needs to be maximized, every AP measures its throughput at every second. The sum of the four APs throughputs is the metric of interest, which is denoted as *aggregate throughput* now on.

5.2 Lingo Results

In order to investigate the necessity of considering the STA's activity level in the optimal association policies, we firstly compare numerically the aggregate throughput of the WLAN achieved with our policy and the optimal policy of [10] which ignores the STA's activity level. The default local solver of Lingo optimizer has been used to solve both models. The physical rates and the activity levels of the STAs have been randomly selected. We have used 300 instances (50 instances for each number of APs N $\in \{2, 3, 4, 5, 6, 7\}$). Figure 1 depicts the aggregate throughput obtained from both policies for 60 samples where each sample is the average value of 5 instances. The figure shows that the performance of our policy is better than the one proposed in [10]. The results also show that the difference in performance increases as the number of APs increases which indicates that the policy should be efficient in dense WLANs where a STA can easily hear multiple APs during the scanning process.

A legitimate question that arises here is: How the differences in the STAs activity levels affect the difference in the performance of the two policies? To answer this question, we have evaluated the performance of both policies with five APs for 10 different cases that vary from high difference in the activity levels to zero difference. The similarity index γ that was firstly introduced in [19] is used. It is given by:

$$\gamma = \frac{(\sum_{s=1}^{M} \alpha_s)^2}{M \sum_{s=1}^{M} \alpha_s^2} \qquad (19)$$

where M is the number of STAs. γ takes a value between 0 and 1 and it's value approaches 1 as the activity levels of STAs become very similar.

Figure 2 plots the percentage of improvement of our optimal association policy over the policy of [10] for 10 different values of γ. Each plotted value corresponds to an average over 40 independent runs that differ in the transmission rates that STAs experience from APs. The figure reveals that the difference in performance becomes small if γ goes above 0.7.

5.3 Simulation Results

In this subsection we present the results of the conducted simulation experiments. Figure 3 plots the performance of the optimal association policy. The figure also depicts the performance of our dynamic decentralized AP selection policy published in [6] where low rate STAs try to maximize

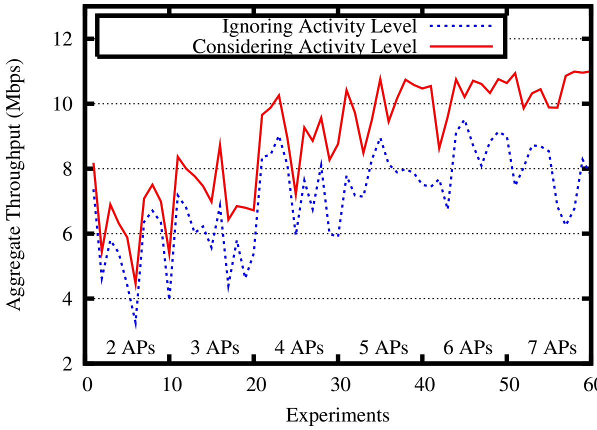

Figure 1: Lingo Results: Performance of Optimal Association with and without activity level consideration for different number of APs

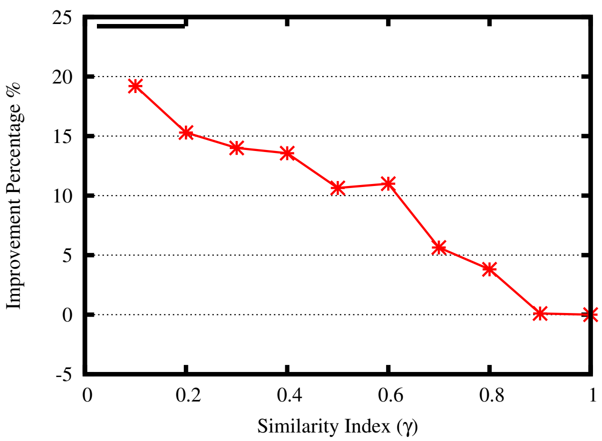

Figure 2: Lingo Results: Percentage of Improvement of the Optimal Association with activity level consideration for 10 different values of the similarity index γ

their throughput but minimize their impact on high rate STAs and periodically re-evaluate their association. The results show that more gain in the throughput performance is achieved with the optimal association policy. With dynamic decentralized selection, the throughput performance of the legacy selection (RSSI-based) has been improved by 16.54%. Almost the same improvement has been achieved with the centralized policy of [10]. However, the optimal association policy proposed in this paper has improved the legacy selection by about 25.67%. This indicates that our policy utilizes WLAN resources more efficiently than the centralized policy in [10] and our decentralized one in [6].

6. CONCLUSIONS

The currently implemented selection policy in IEEE802.11 based WLAN cards is not efficient. It leads to imbalance load on APs. Additionally low rate stations bring down the throughput of high rate stations if they associate to the same AP resulting in WLAN resource wastage. This paper presents an optimal centralized policy for station association in IEEE802.11 WLANs. The policy considers the STAs' frame times as well as their activity levels. The paper also discusses the implementation aspects of the proposed policy. The results obtained from both the Lingo Non-Linear Solver and simulation experimentation have shown significant improvement of WLAN performance.

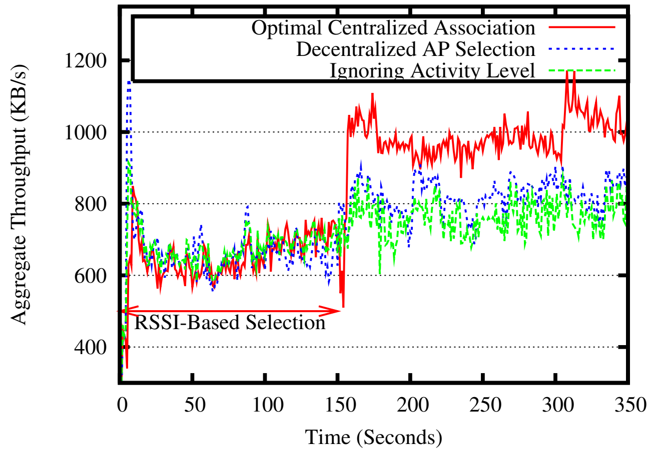

Figure 3: Simulation Results: Performance of Optimal Association and Decentralized Dynamic Selection, 4 APs and 25 STAs

7. ACKNOWLEDGMENTS

The authors gratefully acknowledge the helpful discussions with Dr.-Ing. James Gross on the Association issue in WLANs. The first author would like also to thank the German Academic Exchange Service (DAAD) for granting him a scholarship to pursue his PhD studies at the Technical University Berlin.

8. REFERENCES

[1] IEEE Std. 802.11-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Reference number ISO/IEC 8802-11:1999(E), IEEE Std. 802.11, 1999 edition.

[2] G. Holland and N. Vaidya and P. Bahl. A Rate - Adaptive MAC Protocol for Multi-Hop Wireless Networks. *In Proceedings of ACM/IEEE MOBICOM*, Rome, Italy, July, 2001.

[3] M. Heusse and F. Rousseau and G. Berge-Dabbatel and A. Duda. Performance Anomaly of 802.11b. *In Proceeding of the IEEE INFOCOM'03,* San Francisco, CA, March, 2003.

[4] W. Arbaugh and A. Mishra and M. Shin. An Empirical Analysis of the IEEE 802.11 MAC Layer Handoff Process. *ACM SIGCOMM Computer Communication Review,* March, 2003.

[5] Y. Bejerano and R. Bhatia. MIFI: A Framework for Fairness and QoS Assurance in Current IEEE 802.11 Networks with Multiple Access Points. *IEEE INFOCOM,* 2004.

[6] M. Abusubaih, J. Gross, S. Wiethoelter, and A. Wolisz. On Access Point Selection in IEEE802.11 Wireless Local Area Networks. *In Proceedings of 6'th IEEE International Workshop on Wireless Local Networks, WLN'06*, Tampa, FL, USA, November 2006.

[7] G. Bianchi and I. Tinnirello. Channel-dependent Load Balancing in Wireless Packet Networks. *Wireless Communications and Mobile Computing*, Number 4, pp43-53, 2004.

[8] A. Sang and X. Wang and M. Madihian and R. Gitlin. Coordinated Load Balancing Handoff/Cell-Cite Selection and Scheduling in Multi-Cell Packet Data Systems. *Proceedings of ACM/IEEE MOBICOM*, Philadelphia, PA, USA, 2004.

[9] O. Ekici and A. Yongacoglu. Predictive Association Algorithm for IEEE 802.11 WLAN. *In Proceedings of IEEE International Conference on Information and Communication Technologies (ICTTA)*, April, 2006

[10] A. Kumar and V. Kumar. Optimal Association of Stations and APs in an IEEE 802.11 WLAN. *In Proceedings of National Conference on Communications (NCC)*, February, 2005

[11] G. Fanglu and C. Tzi-cker. Scalable and Robust WLAN Connectivity Using Access Point Array. *In Proceedings of the 2005 International Conference on Dependable Systems and Networks (DNS'05) Vehicular Technology Conference 2004-Fall (VTC2004-Fall)*, 2005

[12] G. Kasbekar and P. Nuggehalli and J. Kuri. Online Client-AP Association in WLANs. *In Proceedings of the 2005 International Conference on Dependable Systems and Networks (DNS'05) Vehicular Technology Conference 2004-Fall (VTC2004-Fall)*, April, 2006.

[13] O. Ekici and A. Yongacoglu. A Novel Association Algorithm for Congestion Relief in IEEE 802.11 WLANs. *In Proceedings of the International Wireless Communications and Mobile Computing Conference*, July, 2006.

[14] A. Tang and J. Wang and S. Low. Is Fair Allocation always Inefficient. *In Proceedings of IEEE INFOCOM*, Hong Kong, March, 2004.

[15] *IEEE 802.11k Radio Resource Measurement, IEEE Draft 2.0*, February 2005.

[16] *Lingo User's Guide, LINDO Systems, Inc., Chicago, Il*, 2004.

[17] *http://nsl.csie.nctu.edu.tw/nctuns.html*.

[18] http://www.cs.helsinki.fi/u/jmanner/software/.

[19] D. Chiu and R. Jain. Analysis of the Increase and Decrease Algorithms for Congestion Avoidance in Computer Networks. *Journal of Computer Networks and ISDN Systems*, vol. 17, no. 1, pp1-14, June, 1989.