Dynamic Load Balancing through Association Control of Mobile Users in WiFi Networks

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Abstract —*With the development of IEEE 802.11 MAC (Medium Access Control) protocols, efficient utilization of wireless local area networks (WLANs) has become a very important issue. In typical IEEE 802.11 networks, the association between mobile users (MUs) and access point (AP) is based on the signal strength information. As a result, it often results in the extremely unfair bandwidth allocation among MUs. In this paper, we propose a distributed association algorithm to achieve load balancing among the APs. The proposed algorithm gradually balances the AP loads for the available multiple bit rate choices in a distributed manner. We analyze the stability and overhead of the proposed algorithm, and show the improvement of the fairness via computer simulation. Additionally, we have implemented a prototype on a testbed to prove its feasibility.*[1]

Index Terms — Distributed algorithm, WLANs, AP selection, association algorithm, fairness, and load balancing.

I. Introduction

Within last decade, due to the success of IEEE 802.11 MAC (Medium Access Control) standards or well-known as WiFi, the wireless local area networks (WLANs) have been deployed pervasively in many places such as homes, offices, and campuses. The increasing popularity of WLANs has led to a substantial increase in the density of WiFi access points (APs) deployed publicly. On the other hand, as already found in [1], the mobile users (MUs) are more likely to geographically cluster around several specific APs in the network. Due to the anarchy nature of WLANs, the MUs choose its associated AP based on the information collected by probing when they roam into the network. Under this context, the potential of the network might not be fully explored.

Comparing with wired line, the wireless channel is notorious for its instability owing to fading and losses. To be adaptive to the dynamic nature of wireless medium, data rate adaptation mechanisms such as Auto Rate Fallback (ARF) [2] or Receiver Based Auto Rate (RBAR) [3] are widely deployed for current WiFi products. However, it is well-known that 802.11 MAC has an "anomaly" that the throughput of high data rate MUs in good channel condition is down-equalized to that of the lowest data rate peer in the network. In this way, the data rate information is required to guide load balancing schemes.

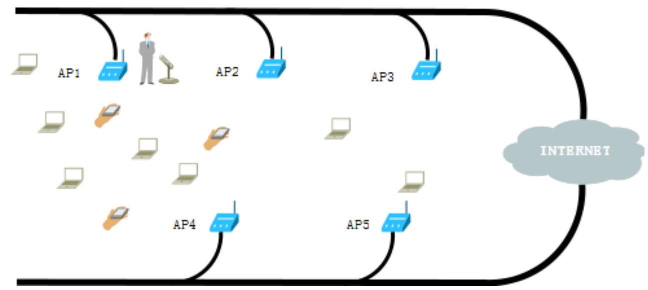

Fig. 1. A typical WiFi network to emulate the conference scenario.

Based on the discussion above, we can let the MUs be associated with the right APs to balance the loads [4]. However, the default best-RSSI(receiving signal strength indicator)-based AP selection scheme which does not provide any fair sharing functionality will lead to unbalanced traffic load distribution. This is because bad MU-AP associations result in severe unfairness and even poor overall performance. Moreover, the association scheme is required to consider the feature of dynamic rate adaptation. We use one typical scenario shown in Fig. 1 to illustrate the problem mentioned before. In this example, most of the MUs are gathering around the AP1 to hear the presentation in a conference room. Thus, AP1 is heavy-loaded and the capacities of other APs are almost wasted.

There have been a number of research efforts on this special issue. Generally, they can be divided into two categories: centralized optimization and distributed heuristic methods. Till now, most of the optimal AP association algorithms for IEEE 802.11 WLANs use the centralized approach that collects information from the entire network, and then derive an optimal configuration based on complex computation. Such an approach is not scalable due to the NP-hard nature of the problem, and requires a separate processing infrastructure for performing the centralized computations. On the other hand, the distributed heuristic schemes are more flexible and they do not require the management center. However, some of the distributed AP selection schemes do not consider the multiple data rate information or propose non-practical solutions that use the specific features not available in normal IEEE 802.11 standards.

To fill the gap between the theoretical studies and the practical issues for the association study in WiFi networks, we propose a new distributed heuristic algorithm to achieve load balancing by incorporating the multi-rate information. Owing

[1] This work was supported by the Basic Research Program of the Korea Science and Engineering Foundation (KOSEF) under Grant No. (R01-2006-000-10556-0).

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Contributed Paper
Manuscript received January 14, 2008 0098 3063/08/$20.00 © 2008 IEEE

to the duality relationship between AP load and MU throughput, the proposed scheme can be effectively realized in current WiFi products for networking. It is only required to add one additional field in the AP beacon and probing packets. Also, some low complexity operations should be inserted in the MUs. Moreover, we analyze its stability and overhead. Finally, we have not only evaluated the performance of the proposed scheme for realistic scenario with mobility pattern by the numerical simulator but also implemented a prototype on small-scale testbed to prove its feasibility.

The rest of this paper is organized as follows. Section II describes the latest related work and the basics of IEEE 802.11 MAC protocols. Section III defines the system model and problem statement. Section IV introduces the proposed AP selection scheme and analyzes its stability and overhead. Section V shows the evaluation results and we finally draw the conclusion in Section VI.

II. Related Work and IEEE 802.11 Basics

A. Related Work

Most of the fine-grained for association control are based on centralized optimization techniques. Before applying the complex computation, researchers formulate the original problem for different fairness criteria, such as max-min fairness, proportional fairness, and etc. In [5], Bejerano *et al.* formulate the problem of AP selection for max-min fairness of MU throughput based on integer linear programming and solve it by relaxation and approximation. In [6], Kumar *et al.* have studied AP selection for proportional fair sharing relying on optimization software. Recently, Kasbekar *et al.* have proposed an iteration algorithm based on an auxiliary Discrete Time Markov Decision Chain (DTMDC) to find a stationary optimal policy [7]. These centralized schemes usually assume that all information about the network is already known beforehand to provide more accurate results. However, it is not practical to let one control center collect all the information inside the network and distribute the association commands to the MUs.

On the other hand, there are some distributed schemes proposed for AP selection. In [8], Fukuda *et al.* propose a distributed selection scheme that balances the load according to the number of MUs associated with the APs. They, however, did not incorporate the multi-rate information. Recently, Takeuchi *et al.* and Siris *et al.* propose distributed fair algorithms by incorporating the multi-rate information [9], [10]. To give more priority to high-rate associations, their proposed scheme is dependent on the specific features of not-yet-deployed IEEE 802.11e.

B. IEEE 802.11 Protocols

Till now, two access methods have been defined in IEEE 802.11 MAC: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). In this study, we only concentrate on DCF due to overwhelming deployment. The DCF is based on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol which provides two access schemes, the basic scheme and the request to send/clear to send (RTS/CTS) scheme. In the basic scheme, a pair of source and destination MUs only exchange data frames and acknowledgement (ACK) frames, while the RTS/CTS scheme adds an RTS/CTS dialog preceding the data frame to reduce the probability of collision. If the channel is sensed to be idle for a time interval equal to the DCF inter-frame space (DIFS), the MU simply transmits the packet. Otherwise, the MU continues to sense the channel until it is sensed idle for a period of DIFS. The detailed diagram of the frame and delay sequence is shown in Fig. 2.

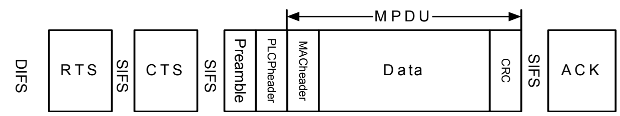

Fig. 2. Frame and delay sequence diagram for CSMA/CA and RTS-CTS.

DCF adopts an exponential backoff scheme. A backoff counter is chosen uniformly in the range [0:CW-1], where CW is size of the contention window. At the first packet transmission attempt, CW is set to a value CWmin, which denotes the minimum contention window size. After each unsuccessful transmission, CW is doubled until a predefined maximum size (CWmax) is reached. The backoff counter is decremented once every time slot, as long as the channel is sensed idle. The counter is frozen when a transmission is detected, and reactivated when the channel is sensed idle again for more than a DIFS period of time. When the backoff counter reaches zero, the MU gets the right to transmit. On the other hand, the collision occurs when there are two or more stations transmitting at the same time. Since CSMA/CA does not rely on a station to detect a collision by hearing its own transmission, an ACK is transmitted by the destination station to signal successful packet reception. If the ACK is not received, the MU assumes that the transmitted frame is not received and reschedules the packet transmission according to the backoff process.

As for the association procedure for the roaming MU, when a MU moves inside the WLANs, it starts gathering information on the APs present in the vicinity by broadcasting probe messages. The MU can receive responses from multiple APs, which is based on some implementation-dependent policy. Then, the MU sends Association Request to one of the APs. After the AP receives the association request successfully, it will reply with Association Reply. When the new station receives the Association Reply message it changes its status from a new station to a registered station. After the establishing the association, the AP still keeps sending beacon packets periodically.

III. System Model and Problem Definition

For the sake of simplicity, we assume that the neighboring APs are configured with different non-overlapping channels like most other existing AP selection studies. Since there are total 11 non-overlapping channels in IEEE 802.11a WLANs, the network manager can achieve this by careful frequency planning. The set of APs and MUs are denoted as A and U, respectively. We let the set of associated MUs be $U_a \subseteq U$ for AP a and the set of APs that can provide service for MU u as $A_u \subseteq A$. We use r to denote the physical data rate of MU, where $r_{ua} > 0$ means that MU u can be served by AP a with a valid data rate in the predefined bit rate set of IEEE 802.11, and $r_{ua} = 0$ means MU u is out of the transmission range of AP a. The length of data packet is assumed to be identical in the scenario. We use L to denote this packet length. Finally, we assume that the traffic is saturated unidirectional UDP (user datagram protocol) packets with the same packet length throughout the network.

Although the network overall performance is usually studied in the domain of MU throughput, the corresponding domain, AP load, is naturally highly correlated. Here, we extend the definition of AP load from [5], where the AP load y_a on AP a is defined as the aggregate period of time that takes AP a to provide a unit of traffic volume to all associated users $u \in U_a$.

According to the characteristic of IEEE 802.11, "performance anomaly" in [11], we can derive that the saturated throughputs of MUs are identical and can be approximated by the inverse value of AP load [12]. Formally, the relationship between AP load y_a of AP a and the MU throughput θ_u for all the MUs associated with AP a is

$$\theta_u = \frac{L}{y_a}(\forall u \in U_a). \qquad (1)$$

To avoid the complexity of the throughput model proposed in [12], we utilize an approximated transmission time model based on the throughput model proposed in [13] for practical implementation. According to IEEE 802.11 MAC standards, the time required to transmit one packet from MU $u \in U_a$ can be roughly calculated by

$$d_{ua} = DIFS + BO(m_a) + DATA_u + SIFS + ACK + RTS + CTS + 2SIFS$$

where $DIFS$, $SIFS$, ACK, RTS, and CTS are the constant time period defined by the IEEE 802.11 MAC standard. $DATA_u$ is the amount of time to transmit one data packet including the preamble time $Preamble$ and MAC overhead H_{mac}:

$$DATA_u = Preamble + \frac{L + H_{mac}}{r_{ua}}.$$

Additionally, we use the function $BO(m_a)$ to denote the amount of time slots for backoff before transmitting one data packet.

$$BO(m) = \begin{cases} \dfrac{2^m (CW_{\min}+1)-1}{2} t^{slot} & 0 \le m \le 6 \\ \dfrac{CW_{\max}}{2} t^{slot} & m > 6 \end{cases}$$

where t^{slot} is the interval for one time slot in MAC operation and the number of retrials required to transmit one packet is denoted by $m_a = 1/p_c$. Here, p_c is the collision probability given in [15]. Finally, the load of AP a can be denoted as

$$\theta_u = \sum_{u \in U_a} d_{ua}.$$

The original association problem is normally tackled from the domain of MU throughput as achieving different fairness criteria (max-min fairness, proportional fairness) among the MUs. As given in [5], the nonlinear integer formulation to achieve max-min fairness can be approximated by solving a set of linear programming problems. However, the full process is centralized, where it requires a separate processing infrastructure to perform the centralized computations, collect the network status information, and distribute the association commands. On the other hand, the distributed algorithms are friendlier for the latest trend of ubiquitous networking since they are adaptive to the dynamic wireless environment. Instead of directly solving the fair throughput allocation by adopting linear programming technique all at once, the distributed algorithm can be based on gradually balancing the load periodically. Since this load information of APs can be notified during the probing operation and periodical beaconing in IEEE 802.11, we can design the proposed distributed heuristic algorithm by dynamically switching the MU association to balance the loads, which equivalently solves the original association problem.

IV. Distributed Association Algorithm

In this section, after exploring the details of distributed AP selection algorithm for APs and MUs, we also analyze the stability and overhead of the proposed algorithm.

A. Association Algorithm for APs and MUs

By exchanging information among MUs and APs, the proposed association scheme can be summarized as Algo. 1 as shown in Fig. 3.

Algorithm 1 Association algorithm for each AP and MU.

Periodical operation on each AP a **with interval** T_Ω**.**

1. Periodically update its AP load by Eq. (2).

Periodical operation on each MU u **with interval** T_Δ**.**

1. Exchange the probing packets with AP.
2. Calculate the estimated AP load by Eq. (3).
3. **if** u is a newly MU joining the WLAN **then**
4. The MU u selects the AP as $argmin_{a \in \mathcal{A}_u} \tilde{y}_a(t)$.
5. **else** /* u *is already associated with AP* a */
6. **if** switching to a' lead to $y_a(t) - y_{a'}(t) > \delta$ **then**
7. MU u switches the association to a'.
8. **end if**
9. **end if**

Fig. 3. The distributed algorithm for load balancing in WLANs.

In legacy IEEE 802.11 standard, the management packets from the AP do not contain any field indicating the AP load information. To realize the proposed scheme, it is required to add one additional field to the beacon and probing packets. Moreover, due to the dynamic nature of the wireless network and the mobility of MUs, the APs should keep updating the AP load by iterative moving average as

$$y_a(t + T_\Omega) = \alpha y_a(t) + (1-\alpha) \sum_{u \in U_a(t)} d_{ua}(t), \qquad (2)$$

where T_Ω is the fixed updating interval and $0 \le \alpha \le 1$ is the weighting parameter to tradeoff previously estimated AP load and current value.

If a MU is not associated with any AP in the network, it immediately scans all channels by sending probe request messages and receives response packets from the available APs. By detecting the respective RSSI levels to the APs, each MU can determine the most suitable physical data rate for transmitting packets. The proposed AP selection strategy is to let each MU choose the AP with least estimated load by supposing that it will be associated with all available APs. That is, if the newly joining MU u can be served by a subset of APs $A_u \in A$, the estimated AP load on $a \in A_u$ supposing the association of MU u with AP a will be updated as

$$\tilde{y}_a(t) = y_a(t) + d_{ua}(t) \qquad (\forall a \in A_u). \qquad (3)$$

Then the MU will select an AP as $argmin_{a \in Au} \tilde{y}_a(t)$. After the MU joins the WLAN, it will keep periodically (with period T_Δ) detecting the load information from the neighboring APs and change its association if the AP loads can be further decreased. This operation is not only necessary to reduce the effect introduced by the joining order of MUs but also required for the MU to be adaptive to the dynamic wireless environment and topology changes. The period T_Δ, configured to be more than 10 seconds, is much longer than the load updating period T_Ω on the AP.

B. Association Algorithm for APs and MUs

In dynamic WLANs, the association of MUs should vary with the network conditions. However, it is not intuitively obvious that the proposed distributed algorithm is self-stabilizing for static networks. That is, MUs continually looking to balance the AP loads will eventually converge to a stable result in static topology. Here we can show that indeed this process does stabilize.

Theorem 1: For a fixed population WLAN with APs and static MUs that implement the above distributed association algorithm with $\delta = 0$, the switching operations of the MUs in Algo. 1 reaches a stable state where MUs cease changing associated APs[2].

Proof: The core part of the proof is that a monotonic property of global lexicographic ordering [15] decrement holds whenever one MU switches its association. Lexicographic order, a concept borrowed from economics, can be used to compare the extent of fairness between two vectors. Given two vectors A and B; the method to determine the lexicographic order is to compare the corresponding values index by index after sorting the original vectors. According to Algo. 1, assuming one MU switch from AP a to AP b, the AP loads of them are denoted as y_a, y_b, y'_a, and y'_b , respectively. Straightforwardly, we will have $y_b < y_a$, $y'_b < y_a$, and $y'_a < y_a$, where the lexicographic order has been decreased. Since the lexicographical order can not be infinitely decreased, we can conclude that the Algo. 1 will stop after finite number of operations.

[2] $\delta = 0$ is the loosest condition to activate the switching operation.

The introduced overhead by the proposed algorithm on the AP is straightforwardly low. On each MU, the most time consuming operation is the periodically probing process in every T_Δ seconds. However, this probing process only takes around 300ms according to measurements. Comparing with the interval T_Δ, the overhead is almost negligible.

V. PERFORMANCE EVALUATION

In this section, we first introduce the numerical evaluation based on the developed simulation program. The program is able to simulate dynamic and large-scale topology to clearly show the achievable benefits of the proposed scheme. We then provide NS2 [16] simulation results for a medium-size topology with suddenly roaming clients. Finally, we also explain our prototype implementation on a testbed built with normal computers.

To measure the performance, we use total throughput $\sum_{u \in U} \theta_u$ as the metric to measure the overall efficiency and Jain's fairness index [17]

$$\frac{(\sum_{u \in U} \theta_u)^2}{|U| \sum_{u \in U} \theta_u^{\,2}}$$

to denote the degree of load balancing in the network.

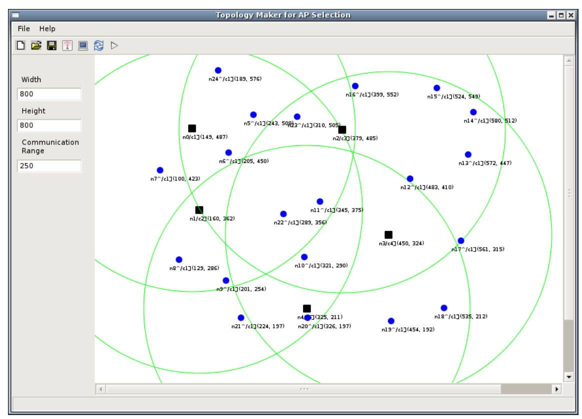

Fig. 4. The snapshot of developed numerical simulator.

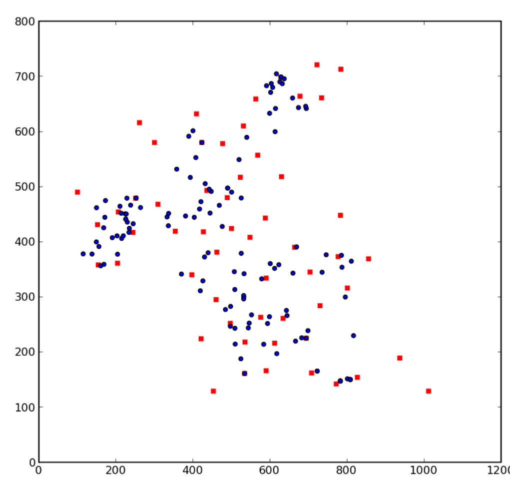

Fig. 5. A realistic scenario with measured mobility for numerical simulation. The red squares denote the APs and the blue circles denote the MUs at the beginning of simulation.

A. Numerical Simulation for Realistic Scenario

In order to evaluate the proposed scheme for large-scale topologies, we have developed a discrete-event simulator based on SimPy [18], which is a Python framework for discrete-event simulation applications. Users can manually place the APs and MUs in the GUI (Graphic User Interface). The generated scenario can also be saved and loaded for future use. The snapshot of the program interface is captured and shown in Fig. 4. To accelerate the simulation, the complex behavior of IEEE 802.11 MAC is simplified and the throughput is calculated by the throughput model given in [12]. We use a set of measured trace files provide by [19], which collected the 20 minutes measurement data by capturing the realistic mobility patterns of the MUs in the campus of Dartmouth University. From the measurement results, we pick up 56 APs and 126 MUs with their mobility placed in a rectangle topology of size 1100×1000m2 as shown in Fig. 5.

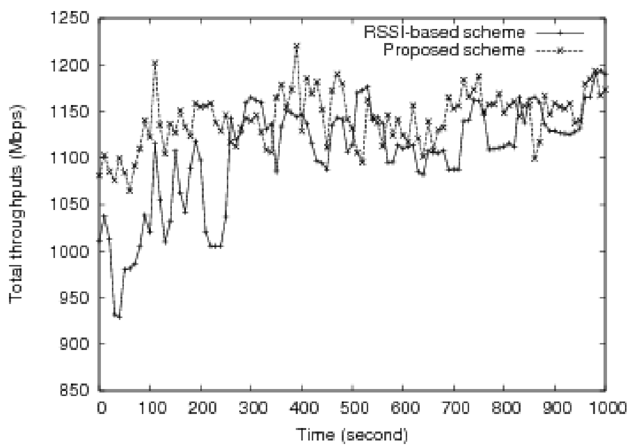

Fig. 6. The throughput difference between RSSI-based scheme and proposed scheme w.r.t simulation time for the realistic topology shown in Fig. 5.

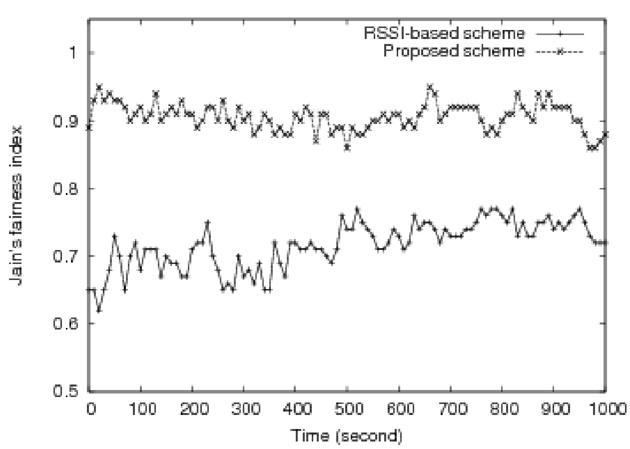

Fig. 7. The Jain's fairness value difference between RSSI-based scheme and proposed scheme w.r.t simulation time for the realistic topology shown in Fig. 5.

According to Fig. 6 and Fig. 7, we can observe that the total throughput achieved by the proposed scheme is generally the same or sometimes higher than that of the default RSSI based scheme. However, the value of fairness metric has been apparently (between 20%-30%) improved after applying the proposed scheme. On the other hand, we also find that it mostly takes only one probing and reassociation operation for the MUs to reach a steady state when they move around in the topology.

B. Packet Level Simulation

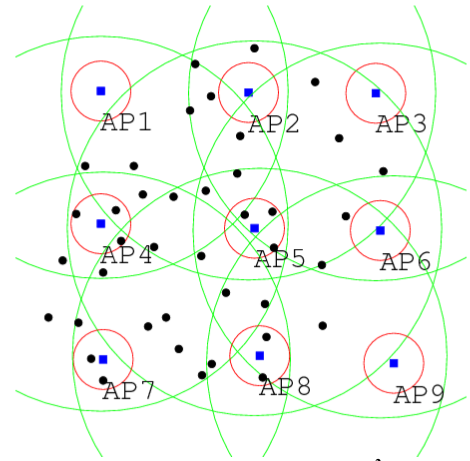

Fig. 8. A WLAN scenario with 9 APs in 600×600m^2 for NS2 simulations. The MUs in the inner circle of the AP have the maximal data rates and the MUs out of the outer circle can not communicate with the AP. Neighboring APs are configured with different non-overlapping channels. At a specific time, 10 MUs suddenly arrive around AP1 simultaneously.

To confirm the results from numerical evaluation, we have also modified the NS2 which is a comprehensive packet level simulation package to simulate medium-size wired and wireless network. To show the importance of incorporating data rate information for association control, we have also implemented the association scheme by considering only the number of associated clients proposed by Fukuda *et al.* in [8]. Here, we run the simulation for a scenario (9 APs and 40 MUs) with 10 MUs suddenly roaming around AP1 as shown in Fig. 8. Moreover, either UDP or TCP traffic is applied separately for this scenario. We configure UDP traffic with 2Mbps constant bit rate. The TCP traffic is set as NewReno version with FTP application. The simulation results are collected as shown in Table I.

According to the table, the proposed scheme not only shows better average throughput but also significantly increases fairness index value (sometimes even twice) than that of the RSSI-based scheme. The Fukuda's scheme generally achieves similar or even lower average throughput by comparing with RSSI-based scheme but with fairest throughput distribution due to lacking of consideration of the bit rate information. Since the observations are valid before and after the MU's arriving, it also shows the stability of the proposed scheme in dynamic environment. Combined with the numerical evaluation results, we can conclude that the proposed scheme is a good tradeoff to balance fairness (load balancing) and efficiency (total throughput) in the network.

TABLE I
COMPARISON FROM NS2 SIMULATIONS FOR SCENARIOS SHOWN IN FIG. 8.

	Before MUs' arriving				After MUs' arriving			
	Average throughput (Kbps)		Fairness index		Average throughput (Kbps)		Fairness index	
	UDP	TCP	UDP	TCP	UDP	TCP	UDP	TCP
Rssi-based scheme	147.77	144.66	0.54	0.59	137.74	131.84	0.53	0.58
Fukuda's scheme	159.62	146.51	0.95	0.95	141.82	128.89	0.91	0.94
Proposed scheme	187.57	174.19	0.81	0.85	159.84	147.63	0.79	0.87

C. Prototype Implementation

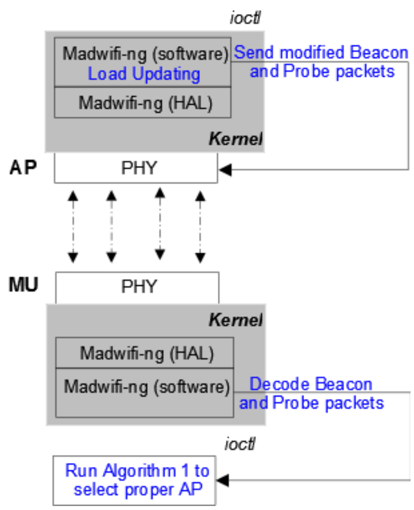

Fig. 9. The diagram to illustrate the implementation of the prototype based on Madwifi-ng. The modified part is shown in blue color.

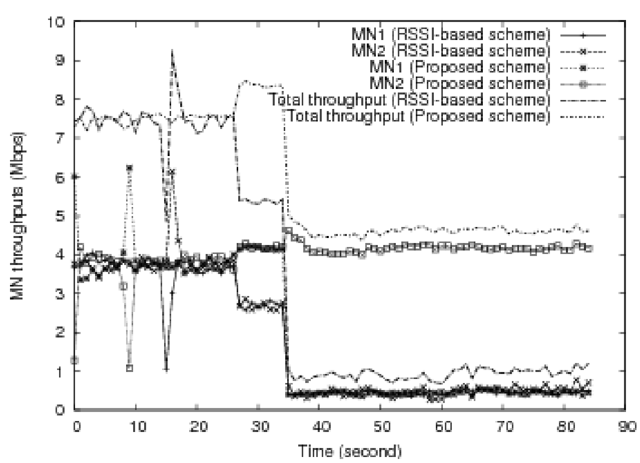

Fig. 10. The measurement results to compare the performance difference between the default RSSI-based scheme and the proposed scheme.

In order to prove the feasibility of the proposed scheme, we also have modified MadWifi-ng wireless driver [20] to implement a prototype. The WLAN testbed is built with normal desktop and laptop computers. The wireless adapters installed on them are based on Atheros chipset that is supported by MadWifi-ng in Linux. On the AP side, an additional field is added in the beacon and probing packets to announce its load periodically. While on its client side, the MUs repeat the probing with a rather longer interval. The decision to switch the association among APs is executed by a program written in script language. The data rate to transmit packets is estimated by the RSSI value detected on the MU. Finally, the whole prototype is implemented under IEEE 802.11b standard. The modification of the original Madiwifi-ng and the component added is illustrated in Fig. 9.

In the experiment, we configured two Dell laptops as MUs (MU1 and MU2) and two Dell Desktops as APs (AP1 and AP2), respectively. At beginning, the two MUs were placed together around AP1 and farther from AP2 so that both of them will be associated with AP1. Then, MU1 began to move away from AP1 and AP2, but can still get better service from AP1. The respective throughputs and total throughput were measured and shown in Fig. 10. For default association scheme, the two MUs will not change their association even when the throughput of MU2 was drastically reduced due to the low quality link between MU1 and AP1. Straightforwardly, this result is not preferred by us. On the other hand, if the proposed scheme is enabled for the same scenario, MU2 can detect the load increment on AP1 and then switch to AP2 to get better service.

VI. CONCLUSION

In this paper, we have explored the load balancing scheme to guarantee the throughput fairness among the MUs. To achieve this, we have proposed a distributed and self-stabilized association scheme for the MUs in the multi-rate WLANs. The proposed scheme gradually balances the AP loads in a distributed manner. With extensive simulations, we can observe that it can significantly improve, or sometimes nearly double, the extent of throughput fairness among the MUs with low overhead. To show the feasibility of the proposed scheme, we have implemented a prototype on normal computers by modifying open source wireless driver software package.d Our research is oriented for practical WiFi products and can be implemented with small additional modification to achieve apparent load balancing in deployed WLANs.

REFERENCES

[1] D. Kotz and K. Essien, "Analysis of a campus-wide wireless network," in *Proc. ACM MOBICOM*, Sep. 2002.

[2] A. Kamerman and L.Monteban, "WaveLAN-II: a high-performance wireless LAN for the unlicensed band," *Bell Lab Technical Journal*, pp. 118–133, 1997.

[3] M. Lacage, M. H. Manshaei, and T. Turletti, "IEEE 802.11 rate adaptation: A practical approach," in *Proc. ACM MSWiM*, Venezia, Italy, Oct. 2004.

[4] A. Balachandran, P. Bahl, and G. M. Voelker, "Hot-spot congestion relief in public-area wireless networks," in *Proc. ACM SIGCOMM Comput. Commun. Rev.*, 2002, pp. 32(1):59–59.

[5] Y. Bejerano, S.-J. Han, and L. E. Li, "Fairness and load balancing in wireless LANs using association control," in *Proc. ACM MOBICOM*, Sep. 2004, pp. 315–329.
[6] A. Kumar and V. Kumar, "Optimal association of stations and APs in an IEEE 802.11 WLAN," in *Proc. India NCC*, Jan. 2005.
[7] G. K. Kasbekar, J. Kuri, and P. S. Nuggehalli, "Online association policies in IEEE 802.11 WLANs," in *Proc. IEEE WiOpt*, Apr. 2006.
[8] Y. Fukuda, A. Fujiwara, M. Tsuru, and Y. Oie, "Analysis of access point selection strategy in wireless LAN," in *Proc. IEEE VTC*, 2005.
[9] S. Takeuchi, K. Sezaki, and Y. Yasuda, "Access point selection strategy in IEEE 802.11e WLAN networks," in *Proc. IEEE WCNC*, 2006.
[10] V. A. Siris and D. Evaggelatou, "Access point selection for improving throughput fairness in wireless LANs," in *Proc. 10th IFIP/IEEE Symposium on Integrated Management*, May.
[11] M. Heusee, F. Rousseau, G. Berger-Sabbatel, and A. Duda, "Performance anomaly of 802.11b," in *Proc. IEEE INFOCOM*, 2003.
[12] K. Medepalli and F. A. Tobagi, "Throughput analysis of IEEE 802.11 wireless LANs using an average cycle time approach," in *Proc. IEEE GLOBECOM*, Nov. 2005.
[13] E. Garcia, D. Viamonte, R. Vidal, and J. Paradells, "Achievable bandwidth estimation for stations in multi-rate IEEE 802.11 WLAN cells," in *Proc. IEEE WoWMoM*, 2007.
[14] G. Bianchi, "Performance analysis of the IEEE 802.11 MAC protocol," *IEEE JSAC*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
[15] B. Radunovic and J. L. Boudec, "A unified framework for max-min and min-max fairness with applications," in *Proc. 40th Annual Allerton Conference on Communication, Control, and Computing*, 2002.
[16] Network Simulator 2. http://www.isi.edu/nsnam/ns/.
[17] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," *DEC Research Report TR-301*, Sep. 1984.
[18] SimPy. http://simpy.sourceforge.net/.
[19] CRAWDAD. http://crawdad.cs.dartmouth.edu/index.php.
[20] Madwifi-ng. http://madwifi.org/.

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