Dynamic Association in IEEE 802.11 Based Wireless Mesh Networks

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***Abstract*—In this paper, we propose a dynamic association mechanism that takes load balancing, link quality and association oscillation avoidance into consideration. The metric introduced in this association mechanism measures the real-time traffic load through channel based load detection and suits both coordinated and uncoordinated wireless mesh networks. Because of the random characteristics of wireless links and the variability of network conditions, dynamic re-association should be involved. To avoid association oscillation during re-associations, we introduce oscillation avoidance schemes, which consist of periodic client station (STA) scan and re-association threshold. We further evaluate our dynamic association mechanism through simulations in the context of IEEE 802.11 based wireless mesh networks.**

I. Introduction

In recent years, Wireless Mesh Networks (WMNs) [1], [2], [3] are emerging as a promising technology for next generation wireless networks. To acquire the advantages of WMNs, many existing standards are revisited to include mesh capabilities. In particular, the IEEE 802.11 standard is extended and multi-hop wireless backbone takes the place of traditional wired backbone. All these are introduced in IEEE 802.11s [4].

In the IEEE 802.11 standard [5], Received Signal Strength Indicator (RSSI) based association policy is defined for Wireless Local Area Networks (WLANs). STAs simply choose the access point (AP) that has the highest RSSI to associate with. This policy, however, does not consider many important factors such as link quality and load balancing in wireless networks, which may lead to poor network performance [6]. Other association mechanisms either emphasize link quality [7] or focus on load balancing [8], [9]. Few of them consider these two factors jointly. Furthermore, none of them detect the real-time traffic load.

In WMNs, a multi-hop wireless backbone is introduced. All traffic among STAs or between STAs and other networks is routed through this wireless backbone. Therefore, in addition to the scenario where the access links between STAs and mesh access points (MAPs) may be bottlenecked, the multi-hop wireless backbone could also be the bottleneck. Based on this observation, several cross-layer association mechanisms have been devised for WMNs [10], [11], [12]. In WLANs, especially in WMNs, wireless links fluctuate randomly and network conditions such as traffic requirements and node mobility may vary with time. To address the time-varying network status, dynamic re-association should be involved. In the research works introduced above, some indeed mention re-association, but there is no elaborate study, especially on association oscillation avoidance mechanisms. Several efforts [13], [14] also study the convergence and steady state performance of association using game theory. However, the questions of how to avoid association oscillation and to accelerate network convergence speed still require further specific study.

In this paper, we propose a dynamic association mechanism that jointly takes load balancing, link quality and association oscillation avoidance into consideration. The metric introduced in the association mechanism measures the real-time traffic load through channel based load detection and suits both coordinated and uncoordinated WMNs. Because WMNs extend WLANs with a multi-hop wireless backbone, our dynamic association mechanism also considers the association cost of the end-to-end backbone route in the context of 802.11 based WMNs, just as several previous works. Using our association mechanism, hot-spot MAPs which are heavy loaded due to association with many STAs can be alleviated, thus improving performance. To avoid association oscillation during re-associations, we introduce oscillation avoidance schemes, which consist of periodic STA scan and re-association threshold. In this way, our dynamic association mechanism characterizes the random network conditions in a real-time fashion and optimizes the association continuously.

The rest of the paper is organized as follows. Section II introduces the system model. In section III, our dynamic association mechanism is elaborated. In section IV, the association mechanism is evaluated through elaborate simulations. Finally, we conclude our work in section V.

II. System Model

Assume an IEEE 802.11 based WMN which is connected to the Internet through wired cables as shown in Fig. 1. It consists of MAPs, mesh points (MPs) and STAs. MAPs and MPs self-organize to form a multi-hop wireless backbone that is responsible for relaying traffic among STAs or between a STA and the Internet through some gateway MAPs. Client STAs associate with MAPs to gain network access and become part of the whole mesh network. Each STA is equipped with a single wireless network interface. MAPs and MPs can be equipped with multiple interfaces. In MAPs, one interface acts as access interface for communications between MAPs and STAs, while other interfaces act as relay interfaces in

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the backbone. Interfaces in MPs are solely for traffic relay purpose. The access and relay interfaces can either apply different radio technologies or just adopt the same radio technology but operate on different channels. Access interfaces in neighboring cells can operate either on the same channel or on different channels, corresponding to uncoordinated and coordinated WMNs.

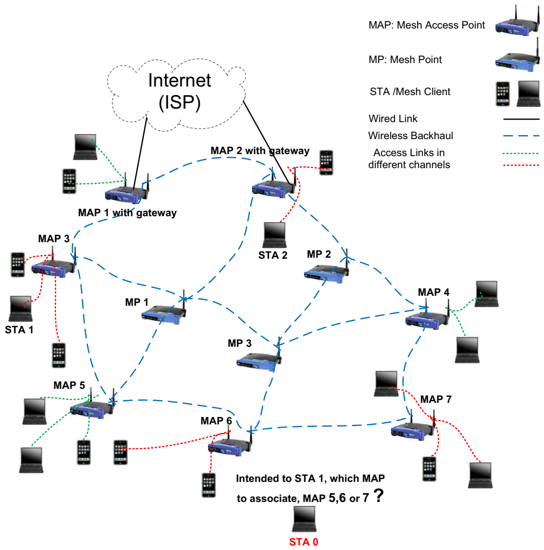


Fig. 1. System model for association in IEEE 802.11 based WMNs.

III. Dynamic Association Mechanism

To improve network performance of IEEE 802.11 based WMNs, we propose a dynamic association mechanism based on a cross-layer association framework, which is defined as

$$A_{a,i}^{\mathrm{WMNs}} = \omega_1 A_{a,i} + \omega_2 R_a^{\mathrm{Backbone}}, \tag{1}$$

where $A_{a,i}^{\mathrm{WMNs}}$ is the total association cost of STA i if associating with MAP a, $A_{a,i}$ is the association cost of the access link between STA i and MAP a, R_a^{Backbone} is the backbone route cost from MAP a to the destination MAP, ω_1 and ω_2 ($\omega_1 + \omega_2 = 1, 0 \le \omega_1, \omega_2 \le 1, \omega_1 = 0.55, \omega_2 = 0.45$ in our implementation) are the weights assigned to the access link and the backbone route. This dynamic association mechanism jointly takes traffic load balancing, link quality and association oscillation avoidance into consideration. During the (re-)association procedure, a STA chooses the MAP with the minimum total association cost. All the STAs periodically trigger the dynamic re-association procedure to cope with changing network conditions.

A. Association Cost of the Access Link

The association cost of access links is defined by estimating the expected transmission time of a test frame as

$$A_{a,i} = \frac{s}{B_{a,i}}, \tag{2}$$

where s is the number of bits in the test frame, $B_{a,i}$ is the attainable bandwidth between STA i and MAP a, which can be obtained as

$$B_{a,i} = (1 - e_{a,i})(1 - C_a^t) r_{a,i}, \tag{3}$$

where C_a^t is the moving average of the channel occupancy ratio of the channel that MAP a is operating on at time t, $r_{a,i}$ is the data transmission rate in the access link between STA i and MAP a, and $e_{a,i}$ denotes the packet error rate.

In our association mechanism, the MAPs detect the traffic load (indicated by channel occupancy ratio) on the channel where they are operating and update the channel occupancy ratio periodically, which is described as

$$C_a^t = (1 - p) C_a^{t-1} + p.C_a, \tag{4}$$

where C_a^t and C_a^{t-1} denote the moving average of the channel occupancy ratio on the channel where MAP a operates at detection cycle t and $t-1$, respectively, C_a is the channel occupancy ratio detected by MAP a in the current detection cycle, and p is the channel occupancy ratio updating parameter. MAPs update the channel occupancy ratio smoothly with an updating parameter p ($p = 0.5$ in our implementation). This makes our association mechanism more tolerable to traffic burst and hence mitigate association oscillation. In (4), the current channel occupancy ratio C_a is defined as

$$C_a = \frac{T_{\mathrm{busy}}}{T_{\mathrm{det}}}, \tag{5}$$

where T_{busy} denotes the amount of channel busy time during the detection period T_{det}.

B. Association Cost of the Multi-hop Wireless Backbone

Since this is a cross-layer association mechanism, besides the access links between STAs and MAPs, the association cost of the multi-hop wireless backbone shall also be considered. In IEEE 802.11s, a Hybrid Wireless Mesh routing Protocol (HWMP) is proposed in establishing a multi-hop wireless backbone. The default routing metric is based on airtime cost, which is defined as the amount of channel resources consumed when transmitting a frame over a particular link:

$$C_a = [O_{\mathrm{ca}} + O_{\mathrm{p}} + \frac{B_{\mathrm{t}}}{r}] \frac{1}{1 - e_{\mathrm{pt}}}, \tag{6}$$

where C_a is the airtime cost of the backbone link that MAP or MP a belongs to, r is the data rate, and e_{pt} is the packet error rate. The channel access overhead O_{ca}, protocol overhead O_{p} and test frame size B_{t} are set to be constants. Additionally, there is a need to know which MAP is associated by the destination STA when finding the optimal route to the STA. Hence, Global Association Base (GAB) and Local Association Base (LAB) are introduced in 802.11s. The MAPs could know which MAP is associated by the destination STA through the GAB and LAB. This means the association cost of the multi-hop wireless backbone R_a^{Backbone} is the airtime based routing cost of the optimal route from the source MAP to the intended destination MAP.

C. Procedure of the Dynamic Association Mechanism

The procedure of the dynamic association mechanism is as follows:

1) The STA scans the channels and broadcasts Probe Request frames which contain the address of the intended STA or the Internet portal.

2) The MAPs respond in their Probe Response frames with the backbone routing costs and the channel occupancy ratios.

3) The STA extracts required information from Probe Response frames and calculates the packet error rate and the data transmission rate corresponding to all the candidate MAPs.

4) The STA calculates the total association costs and selects the MAP with the minimum cost to associate with.

5) The STA repeats the previous steps periodically (described as periodic STA scan) and initiates a re-association if $A_{a,i}^{\mathrm{WMNs}} - A_{b,i}^{\mathrm{WMNs}} > T\%.A_{a,i}^{\mathrm{WMNs}}$, where T is the re-association threshold.

The MAPs are responsible for finding the optimal routes, detecting the channel occupancy ratio and informing STAs with all the required information. The STAs initiate the association procedure and make association decisions based on the information from the MAPs. This procedure can be easily extended within the IEEE 802.11 framework.

D. Dynamic Re-association, Association Oscillation Avoidance and Network Convergence

To address variations in both link and network conditions and to ensure continuous optimal network performance, periodic dynamic re-association is introduced in our association mechanism.

During the association procedure, all STAs are non-cooperative and behave selfishly in a greedy way to optimize their own performance. If a newly booted STA associates with a MAP, those STAs which have already associated with that MAP may experience performance degradation. With dynamic re-association, those STAs may find other MAPs having lower association costs and initiate re-associations. These re-associations may trigger further re-associations, with the possibility of creating an association oscillation in the network, and hence degrading network performance. In order to overcome these fatal disadvantages, association oscillation avoidance mechanisms are introduced. As described in step 5) of the association procedure, the STAs will initiate a re-association only when the re-association threshold $A_{a,i}^{\mathrm{WMNs}} - A_{b,i}^{\mathrm{WMNs}} > T\%.A_{a,i}^{\mathrm{WMNs}}$ is satisfied. Furthermore, the STAs will not calculate the association costs of available MAPs in range continuously, but only scan channels at regular intervals. This could also mitigate frequent re-association.

Could networks with dynamic re-association reach a stable state when network conditions vary dramatically? If it could, how soon will the networks converge to the stable state? In [13], the association procedure is modelled as an association game and claims that the entire network converges to a Nash equilibrium within finite time. In our dynamic association mechanism, the re-association threshold also serves to accelerate network convergence speed. Additionally, periodic STA scan also influences the network convergence speed. All these will be discussed in the next section.

IV. System Performance Evaluation

To evaluate the performance of our dynamic association mechanism, we have implemented it using ns2 [15]. In our simulations, the WMN consists of 30 MAPs, 20 MPs and 300 STAs which are randomly distributed in an area of $1000\mathrm{m} \times 1000\mathrm{m}$. One of the MAPs is connected to the Internet through wired cable. In our rate adaptation strategy, we use a simple wireless channel model in which the data transmission rate depends only on the distance between transmitters and receivers. HWMP routing protocol is applied in the multi-hop wireless backbone to relay traffic, which involves 8 cross flows. Each simulation runs for 1000 seconds.

A. Performance of the Association Mechanism

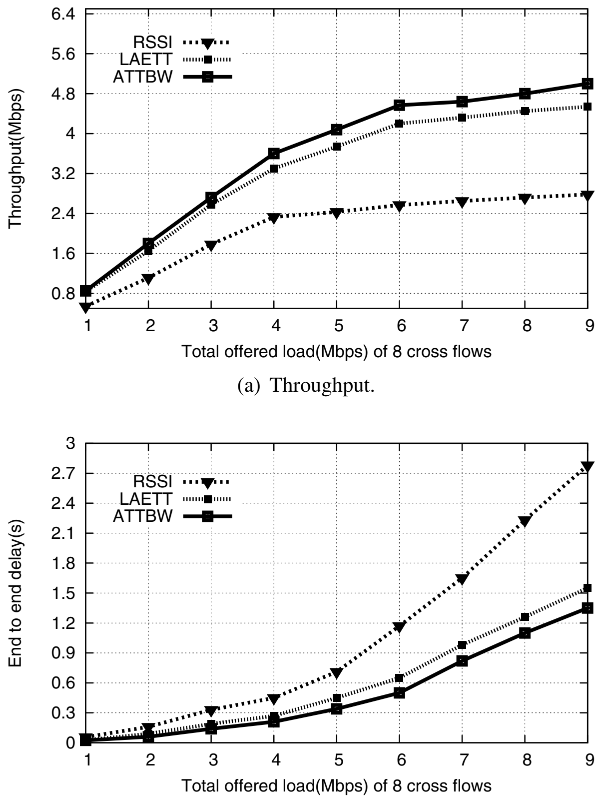
To highlight the advantages of our association mechanism, we compare it with the classical RSSI based association and Load Aware Expected Transmission Time (LAETT) based association mechanism proposed in [11]. At this point, we do not consider dynamic re-associations.

In Fig. 2(a) we see that our association mechanism ATTBW outperforms other schemes in terms of aggregate throughput. Compared with the RSSI based approach, our mechanism improves throughput dramatically by nearly 75%. When the total offered load exceeds 4Mbps, the throughput of the RSSI scheme does not increase much as the load increases, while the other two mechanisms still see considerable increase. Additionally, we are also impressed that ATTBW is superior to LAETT. Hence, association based on real traffic load and link quality is very important.

Fig. 2(b) depicts the average end-to-end packet transmission delay. As expected, our mechanism ATTBW is the best, especially in the high load region. This is of remarkable significance in delay-sensitive applications, such as Voice over IP (VoIP). As total offered load increases, the transmission delay of scheme RSSI increases rapidly. Because our mechanism takes the real-time traffic load of candidate MAPs into consideration, it balances the traffic load and mitigates network congestion, and thus decreases packet transmission delay. We see that when the traffic load becomes heavier, the transmission delay of our mechanism increases much slower than others. These measurements validate that our association mechanism has superior performance. In the following subsection, we focus on dynamic re-association.

B. Dynamic Re-association vs. Static Association

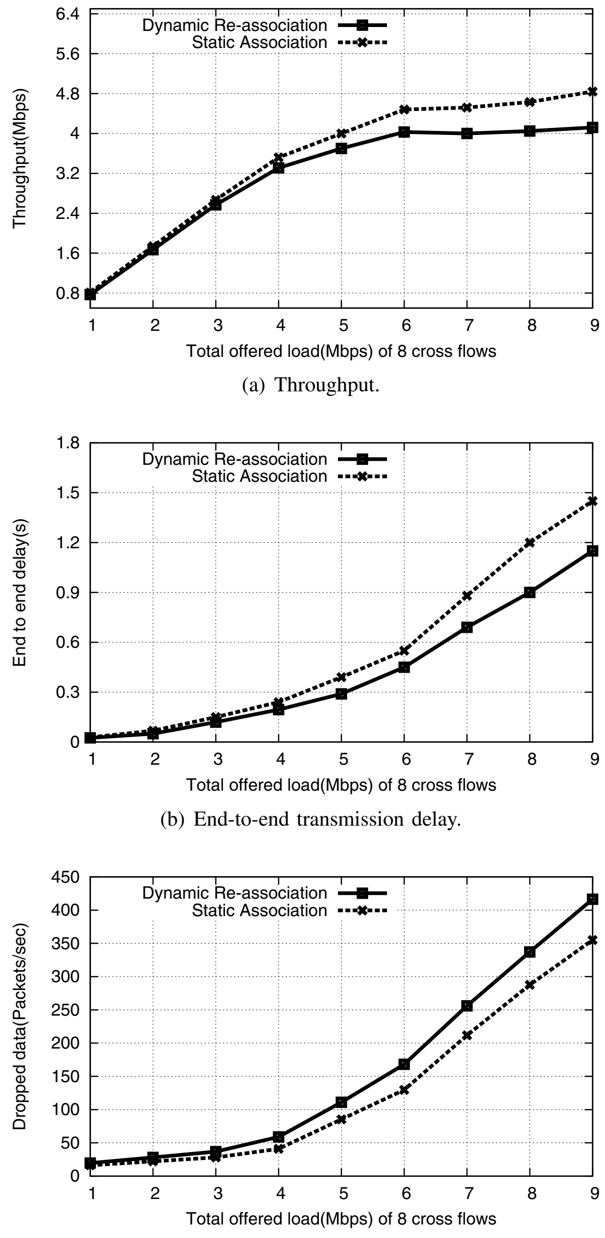
In the previous measurements, we have merely considered static association. To better account for the varying network conditions, we introduce dynamic re-association. We assume that the network traffic is Poisson. During the dynamic re-association procedure, the STAs scan the channels every 4s and re-calculate the total association costs of candidate MAPs. If the MAP with the minimum total association cost is not the MAP the STA is currently associated with, which means, the



(a) Throughput.

(b) End-to-end transmission delay.

Fig. 2. Basic performance evaluation.



(a) Throughput.

(b) End-to-end transmission delay.

(c) Dropped data.

Fig. 3. Dynamic Re-association versus Static Association.

condition $A_{b,i}^{\mathrm{WMNs}} < A_{a,i}^{\mathrm{WMNs}}$ is satisfied, the STA will initiate a re-association and transfer from MAP a to MAP b.

Fig. 3 shows the performance of dynamic re-association compared with static association. Fig. 3(a) reveals surprisingly that dynamic re-association actually degrades network throughput. When the network is heavily loaded, it causes approximately 0.8 Mbps throughput degradation compared to static association. On the other hand, as shown in Fig. 3(b), dynamic re-association outperforms static association in terms of average end-to-end packet transmission delay. The heavier the network is loaded, the better its delay compared to static association. In order to find out the underlying cause of the unexpected behavior in its throughput, we further measure the dropped data of these two mechanisms in Fig. 3(c). We can see that dynamic re-association causes more dropped data, especially when network load is heavy. This more severe data dropping causes throughput degradation directly. We also find that it costs STAs 30 to 40 milliseconds to transfer to another MAP after carefully analysing the simulation trace file. It is the re-association transition time that causes more data dropping. These simulation results indicate that dynamic re-association indeed addresses the fluctuating network conditions better (reducing end-to-end packet transmission delay), but it causes more data dropping due to re-association transition time overhead. Therefore, it is important that we alleviate this re-association time overhead.

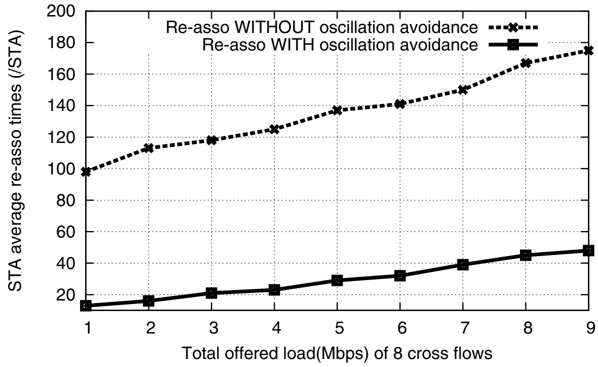
C. Oscillation Avoidance

In the simulation of dynamic re-association described in the previous subsection, no re-association threshold is considered. This means that the STAs will initiate re-association as long as there is another MAP with lower total association cost. As pointed out before, the association of a new STA or re-associations may trigger frequent re-associations leading to association oscillation in the network. Additionally, re-association time overhead will lead to packet dropping. Hence, to reduce packet dropping, we should reduce the frequency of re-associations and avoid association oscillation.

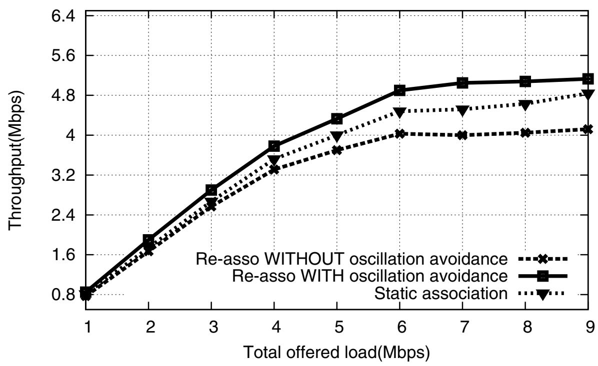
In order to alleviate frequent re-associations as well as to avoid association oscillation and accelerate network convergence speed jointly, we expect that there should be optimal values of re-association threshold and STA scan period. Through a series of simulation studies for numerous re-association thresholds and STA scan periods, we have determined that a re-association threshold of 5% and STA scan period of 4s provide overall optimal performance for the given set of simulation conditions of 8 Poisson traffic flows across the network.

A STA initiates re-association only when there exists another MAP b with a lower association cost, when $A_{a,i}^{\mathrm{WMNs}} - A_{b,i}^{\mathrm{WMNs}} > T\%.A_{a,i}^{\mathrm{WMNs}}$, where T is the re-association threshold. The performances of re-association schemes with and without oscillation avoidance are compared in Fig. 4. Fig. 4(a) depicts STA's average number of re-associations when the total offered traffic load increases in the network. We can see that the re-association threshold for the scheme with oscillation avoidance reduces the number of re-associations dramatically by about 100 per STA.

In Fig. 4(b), we observe that the association mechanism with oscillation avoidance increases the throughout when compared with the mechanism without oscillation avoidance, and also with the static association. Clearly, the combination of a re-association mechanism with oscillation avoidance copes with changing network conditions leading to superior performance.



(a) Average number of re-associations.



(b) Throughput.

Fig. 4. Oscillation avoidance.

V. Conclusion

In this paper, we propose a cross-layer based dynamic association mechanism for IEEE 802.11 based WMNs. It jointly takes link quality and traffic load balancing into account during association. Because of its channel based load detection, it may suit both coordinated and un-coordinated mesh networks. To cope with changing network conditions, dynamic re-association is also incorporated. Furthermore, to reduce frequent re-association and association oscillation triggered by dynamic re-association throughout the network, oscillation avoidance mechanisms such as re-association threshold and STA scan period are therefore introduced. These mechanisms, when carefully configured, also ensure rapid network convergence speed.

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