Design and Implementation of CLASS: a Cross-Layer ASSociation Scheme for Wireless Mesh Networks

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Abstract—In the IEEE 802.11 standard, a Mobile Station (MS) associates to an Access Point (AP) which has the best Received Signal Strength Indication (RSSI) value during its scanning. However, in 802.11-based wireless mesh networks, the conditions of the access link (e.g., traffic load of associated stations, and the frame error rate between the MS and the Mesh Router (MR)) and the conditions of the mesh backhaul (e.g., end-to-end latency, and asymmetric uplink and downlink transportation costs) have significant impact on the network performance of the MS after its association. In this work, we propose a cross-layer association scheme for wireless mesh networks. The end-to-end airtime cost is used to determine the MR to associate with, which comprises the access link airtime cost and the backhaul airtime cost. Our experimental results on a Linux-based testbed show that the proposed association scheme is capable of providing the mobile stations with the best end-to-end network performance after their association.

Index Terms—wireless mesh networks, WLAN, association, airtime cost, network performance

I. INTRODUCTION

IEEE 802.11 based multi-hop Wireless Mesh Networks (WMNs) comprise of Mesh Routers (MRs) that connect together using wireless radio links to form large-scale metropolitan-sized wireless broadband networks. According to the functions of an MR, it can be a Mesh Access Point (MAP) providing AP services in addition to mesh services, a Mesh Point (MP) only without client access, and/or an Internet GateWay (IGW) connecting the WMN to the Internet [1]. Different from the traditional 802.11 WLANs, the backhaul of WMNs is fully wireless.

In the IEEE 802.11 standard, a Mobile Station (MS) associates to an Access Point (AP) which has the best Received Signal Strength Indication (RSSI) value during its scanning. The previous works [2]–[5] have revealed that such a strongest signal strength (SSS) [5] based association scheme is unable to provide MSs with the best network performance, and have tried to optimize the AP selection in WLANs based on the access link conditions. Recent research work [6] has argued that the backhaul transportation latency should also be considered for the association in WMNs, and has used the airtime cost defined in the 802.11s draft [1] to evaluate both the access link quality and the backhaul performance for the association. However, the traffic load of the candidate MRs, the effective access link bandwidth after the association of the new MS, the impact of various packet size, and the asymmetric backhaul transportation costs on uplink and downlink have not been considered in that backhaul-aware association scheme.

In this work, we propose a Cross-Layer ASSociation scheme for wireless mesh networks, called CLASS. The end-to-end airtime cost is used to determine the MR to associate with, which comprises the access link airtime cost and the backhaul airtime cost. The access link airtime cost is determined by the channel access overhead, protocol overhead, dominant packet size, frame error rate, and the expected available bandwidth after the new MS associates to the MR. The expected available bandwidth is calculated based on both the current traffic load of an MR and the expected traffic load generated by the new MS, which infers if the MR will be saturated after accepting that MS. The backhaul airtime cost is a weighted average of the uplink airtime cost and the downlink airtime cost, depending on the application traffic pattern of the MS (e.g., dominant downlink traffic of Video-on-Demand or dominant uplink traffic of video surveillance).

Previous works [6]–[8] on the association in WMNs are all implemented and evaluated in simulations. In our work, the implementation of CLASS is based on the off-the-shelf Wi-Fi devices and the open-source Madwifi driver [9]. Each node (either an MR or an MS) in the WMN testbed is running a Cross-Layer Service Middleware (CLSM) module, which collects association-related metrics from the modified Madwifi driver and returns them to the association daemon running in the user space. Unlike the previous works [6]–[8], CLASS is independent from the routing protocol for the mesh backhaul and its routing metric.

The remainder of this paper is organized as follows. Next section will discuss the related works. In Section III, we will describe the proposed association scheme. The implementation of CLASS is described in Section IV, followed by the performance evaluation in Section V. Finally, we summarize our work in Section VI.
II. RELATED WORK

In the literature, many works have tried to improve the association scheme used in the IEEE 802.11 standard. In the approach proposed by Mhatre and Papagiannaki [2], a client measures the receive signal strength of beacon messages from all the APs operating on the current channel and its overlapping channels, and chooses the AP based on the varying trends of these signals. Vasudevan et al. estimated the potential bandwidth of an AP based on the delay incurred by 802.11 beacon frames from that AP, and used this metric to determine the AP for a client to associate with [3]. Lee et al. also used the estimated available bandwidth as the association metric, which is proportional to the expected number of successfully transmitted data frames at a unit transmission attempt [4]. In the automatic AP discovery and selection system proposed by Nicholson et al., a client scans for all available unencrypted APs, associates to each of them, and evaluates the quality of each AP’s connection [5].

The association schemes in [2]–[5] are proposed for 802.11 based WLANs. Athanasiou et al. proposed a cross-layer association scheme for WMNs, which combines channel conditions of the client access channel and the backhaul routing metric of RM-AODV [6]. Their approach relies on the routing metric of the routing protocol. Makhlouf et al. also considered both the access link airtime cost and the network backhaul airtime cost in their network-assisted association scheme [7]. In their simulations, they found that the impact of packet size on the total association cost is significant. However, the association schemes proposed in [6], [7] did not consider the actual traffic load of a candidate MAP when they evaluated the quality of the access link of that MAP. In the association scheme proposed by Luo et al. [8], the quality evaluation of the access link considered the traffic load, however, their scheme did not consider the channel access delay, protocol overhead and the packet size in either access channel quality calculation or backhaul expected transmission time (ETT) calculation.

Our proposed association scheme considers the frame error rate and airtime cost for different packet size categories, and the potential available bandwidth after the client association based on the predicted traffic load. CLASS uses the airtime cost to measure the backhaul performance of an MR, and is independent from the routing protocol running on the backhaul and its routing metric. The backhaul performance measurement considers the uplink and the downlink separately to support the applications which have significant asymmetric uplink and downlink transportation costs.

III. THE CROSS-LAYER ASSOCIATION SCHEME

In this section, we first discuss the association metric used by CLASS. Then we present the association procedure.

A. Association Metric

\[ TC_{i,a} = (1 - \alpha)AC_{i,a} + \alpha BC_{a} \]  

(1)

We choose the airtime cost introduced in the 802.11s draft [1] as the association metric for CLASS. However, as shown in Equation 1, the airtime cost used in CLASS \((TC_{i,a})\) is the end-to-end total airtime cost from MS \(i\) to the IGW via MR \(a\) (i.e., the whole wireless path), which includes the access link airtime cost \(AC_{i,a}\) between MS \(i\) and MR \(a\) and the backhaul airtime cost \(BC_{a}\). MS \(i\) will associate to MR \(a\) if \(TC_{i,a}\) is the lowest among the airtime costs of all candidate MRs. The tunable parameter \(\alpha (0 \leq \alpha \leq 1)\) weighs the influence of \(AC_{i,a}\) and \(BC_{a}\), and is set as 0.5 in our experiments in Section V. In our future work, we will build the empirical model for \(\alpha\) using the statistical Design of Experiments (DOE) [10] to further improve the accuracy of the association decision.

1) Access Link Airtime Cost Calculation:

\[ AC_{i,a} = (O_{ca} + O_{p} + \frac{B_{i}}{R_{avl}^{i}}) \frac{1}{1 - e^{p}_{i}} \]  

(2)

Equation 2 shows the access link airtime cost between MS \(i\) and MR \(a\), where \(e^{p}_{i}\) is the frame error rate between MS \(i\) and MR \(a\), \(R_{avl}^{i}\) is the available bandwidth that MS \(i\) can acquire from MR \(a\), and \(B_{i}\) is the dominant packet size in bit of the traffic generated by MS \(i\) (e.g., H.323 video conference has some typical packet length.) \(O_{ca}\) and \(O_{p}\) are channel access overhead and protocol overhead respectively, which are constant values defined in the 802.11s draft [1]. The calculation of \(e^{p}_{i}\) is shown in Equation 3, where \(N_{original}\) is the number of original unicast data packets transmitted by MS \(i\), \(N_{retries}\) is the number of data packet retries, and \(N_{dropped}\) is the number of unicast data packets dropped.

\[ e^{p}_{i} = 1 - \frac{N_{original} - N_{dropped}}{N_{original} + N_{retries}} \]  

(3)

In CLASS, each MR monitors the transmission time and the receive time during a time duration \(T\). When MS \(i\) calculates \(AC_{i,a}\), it can get the channel idleness ratio from MR \(a\) as follows, where \(t_{j}\) and \(t_{k}\) are the transmission time (including backoff, retransmission, etc.) of Packet \(j\) and the receive time of Packet \(k\).

\[ \lambda_{a} = \frac{T - (\sum_{j=1}^{N_{sent}} t_{j} + \sum_{k=1}^{N_{received}} t_{k})}{T} \]  

(4)

When \(AC_{i,a}\) is bigger than the expected latency of MS \(i\) (as shown in Equation 5 where \(R_{i,a}\) is the data rate at the physical layer between MS \(i\) and MR \(a\), and \(R_{req}^{i}\) is the bandwidth requirement of applications on MS \(i\)), the access link of MR \(a\) is saturated. Previous research has shown that under saturation the associated MSSs of an MR fairly share the bandwidth with an upper bound shown in Equation 7 where \(C_{a}\) is the set of existing clients of MR \(a\) [11]. By comparing \(\lambda_{a}\) of MR \(a\) with \(\lambda_{a}^{c}\) (in Equation 6), MS \(i\) can determine if the access link of MR \(a\) will be saturated after its association and estimate the available bandwidth using Equation 7.

\[ (O_{ca} + O_{p} + \frac{B_{i}}{\lambda_{a}R_{i,a}}) \frac{1}{1 - e^{p}_{i}} \geq \frac{B_{i}}{R_{req}^{i}} \]  

(5)

\[ \lambda_{a}^{c} = \frac{B_{i}}{R_{i,a}[(1 - e^{p}_{i}) \frac{B_{i}}{R_{req}^{i}} - (O_{ca} + O_{p})]} \]  

(6)
\[ R_{\text{avl}}^i = \begin{cases} \lambda_a R_{i,a} & \lambda_a \geq \lambda'_a \\ \frac{1}{\sum_{j \in C_{a,l}} T_{j,a}} & \lambda_a < \lambda'_a \end{cases} \] (7)

2) Backhaul Airtime Cost Calculation: Equation 8 shows the backhaul airtime cost of an MR measured in CLASS, which includes both the uplink backhaul airtime cost (in Equation 9) and the downlink backhaul airtime cost (in Equation 10) between that MR and the IGW. In CLASS, the frame error rate of each backhaul link is tracked by the modified driver for various packet size categories (small, medium and large packet sizes in current implementation). CLASS is independent from the routing protocol, and in some routing protocols the uplink routing path may be different from the downlink one.

\[ BC_a = (1 - \beta)BC_{\text{uplink}} + \beta BC_{\text{downlink}} \] (8)

\[ BC_{\text{uplink}} = \sum_{k=1}^{\text{HopCount}_{\text{uplink}}} (O_{ca} + O_p + \frac{B_i}{R_k}) \frac{1}{1 - e^{pt_k}} \] (9)

\[ BC_{\text{downlink}} = \sum_{k=1}^{\text{HopCount}_{\text{downlink}}} (O_{ca} + O_p + \frac{B_i}{R_k}) \frac{1}{1 - e^{pt_k}} \] (10)

B. Association Procedure

In CLASS, an MS will scan all AP channels and acquire the airtime cost information from each discovered MR. When a non-IGW MR receives the Association Information Request message from the MS, it will send the IGW a Backhaul Airtime Request message attached with its own uplink backhaul airtime cost. And the IGW will send back the initiating MR that message with the accumulated uplink backhaul airtime cost and its downlink backhaul airtime cost. Any intermediate MR between the initiating MR and the IGW will update the uplink backhaul airtime cost and the downlink backhaul airtime cost contained in the message respectively when this message passes it. Finally, the initiating MR sends the metrics of its access link and the separate uplink and downlink backhaul airtime costs to the MS. The MS will associate to the MR with the lowest total airtime cost.

IV. IMPLEMENTATION DETAILS

We have implemented a prototype version of CLASS for Linux. We modified the Madwifi driver [9] to support CLASS functions on the MS and the software-based MR. The architecture of CLASS on either the MR or the MS includes the modified driver running in the kernel space, the daemon running in the user space, and a cross-layer service middleware. In the following, we will elaborate on the implementation details of CLASS.

A. The Cross-Layer Service Middleware (CLSM)

The Cross-Layer Service Middleware (CLSM) is a general platform that provides the applications running in the user space with the data from the lower layers in the networking stack and the ability to change the configurations of lower-layer protocols. The motivation to build such a platform is to facilitate the data request of applications and hide the implementation details of the lower layers. For instance, the MAC-layer protocol of an 802.11 based wireless card can be maintained by the Madwifi driver, HostAP driver or other driver depending on the chipset of that card. Applications running in the user space such as the CLASS daemon need not know any information of the specific driver and can get the information of the MAC and physical layers from CLSM.

CLSM accesses the networking protocols/modules in the kernel space using ioctl calls of Linux, and provides the applications with two types of interfaces: local APIs are available to local applications; a listening server on TCP/IP sockets is waiting for the requests from the applications running on remote machines (or local applications). Upon the request of the applications, CLSM will return the metrics acquired from the lower layers (e.g., the number of original unicast data packets transmitted, the number of data packet retransmits, and the number of unicast data packets dropped), and/or calculate some comprehensive metrics (e.g., frame error rate) based on those metrics.

B. Implementation of CLASS on the MR

As shown in Figure 1, the modified Madwifi driver on the MR keeps tracking the access link conditions (e.g., packet transmission time) and the backhaul conditions (e.g., the number of data packet retries of each packet size category during a time interval). The driver also checks each received data packet to identify the Association Information Request message from an MS or the Backhaul Airtime Request message from its neighboring MRs. The driver will extract the information from those messages, signal the CLASS daemon to handle the received request, and swap data with the daemon through a raw socket. Both the Backhaul Airtime Request message and the Association Information Response message of the MR are generated and transmitted using raw socket.

C. Implementation of CLASS on the MS

The Madwifi driver on the MS is running in the Monitor Mode during the association process of CLASS. Thus, the CLASS daemon generates the Association Information Request message and the probing data packets (for measurement of $e_{pt}$) using raw socket so that they can be transmitted in the Monitor Mode. The probing data packets will be acknowledged by the MR in case of successful reception, although they will not be delivered to the upper layer since the MS is not associated. The CLASS daemon switches channels using ioctl call, and fetches data from the modified Madwifi driver through a raw socket. The authentication and association of the MS are also handled by the daemon using raw socket when the candidate MR has been determined by CLASS. After the MS is associated with the MR, the Madwifi driver will be switched into the Managed Mode for regular communications.
V. Performance Evaluation

In this section, we compare the performance of CLASS with the strongest signal strength based association scheme (denoted as “SSS” here) and the backhaul-aware association scheme proposed in [6] (denoted as “Ath07” here), in terms of the end-to-end performance of the MS via the MR selected by each association scheme.

A. Experiment 1: Investigate the impact of packet size on airtime cost

The objective of this experiment is to investigate the impact of packet size on airtime cost and the selection of the right MR which provides the MS with the best end-to-end performance. Figure 2(a) shows the testbed used in this experiment. In the testbed, the three MRs (MR1, MR2 and MR3) use 802.11a for the backhaul and the three non-overlapping channels (Channels 1, 6 and 11) of 802.11g for their client access channels, respectively. MR3 is also an IGW, and is connected to a server on the Internet via ethernet. An existing client node associated with MR1 generates the background traffic for the experiment, which is 10Mbps UDP flow from the client node to the server with 8224-bit packet size. The AP channel data rate of MR3 is fixed as 9Mbps. The packet size of the probing packets varies from 100 bytes to 1400 bytes as well as the packet size of the UDP flow generated by the new MS.

In the experiment, the received signal strength of MR1,
MR1 and MR3 by the MS are -31dBm, -40dBm and -48dBm. Thus, SSS selects MR1 for the MS all the time. Ath07 only considers the constant testing frame size (8224-bit) in the calculation of airtime cost, and the airtime costs calculated by Ath07 for MR1, MR2 and MR3 are 1446µs, 594µs and 554µs, respectively. Thus, MR3 is selected by Ath07 all the time.

According to our measurement, the AP channel data rate of MR2 is 48Mbps and the backhaul channel data rate between MR2 and MR3 is also 48Mbps in the experiment. Figure 2(b) shows the total (end-to-end) airtime cost of each MR measured by CLASS for various packet sizes. MR1 always has the highest airtime cost since its access link is under high traffic load and it has the biggest hop count from the IGW (MR3). When the packet size is relatively small (i.e., 100 bytes and 250 bytes), MR3 has the lowest airtime cost because the advantage of 0 backhaul airtime cost (directly connected to the Internet) overwhelms the disadvantage of a lower AP channel data rate. When the packet size raises to 500 bytes and above, the advantage of higher AP channel data rate overpowers the disadvantage of higher backhaul airtime cost. Hence, MR2 has the lowest total airtime cost for the medium and large packet sizes (i.e., 500 bytes, 1000 bytes and 1400 bytes).

Figure 2(c) shows the throughput of the UDP session between the MS and the server on the Internet generated by the tool of Iperf [12]. From Figure 2(c), we can see that MR1 selected by SSS always provides the lowest throughput to the MS. MR3 selected by Ath07 provides the MS with the highest throughput for the small packet size, but does not for the medium and large packet sizes. CLASS considers the impact of packet size on the airtime cost. Thus, the MR selected by CLASS for each packet size provides the highest throughput to the MS in our investigation.

B. Experiment 2: Investigate the impact of traffic load on airtime cost

In this experiment, we investigate how the traffic load on the access link of an MR impacts on the airtime cost of that MR. In the testbed shown in Figure 3(a), MR1 has two client nodes which have a 10Mbps UDP flow between them. MR3 has a client node which has a 20Mbps UDP flow to the server, and MR2 also has a client node associated but its traffic load is negligible. In this experiment and Experiment 3 in the next subsection, the packet size for both the background traffic and the traffic of the new MS is 8224 bits, in order to exclude the packet size impact which differentiates the performance of Ath07 and CLASS. The data rates of the AP channel and the backhaul channel of each MR and client are set in Auto Mode. The transmission power of MR1 is tuned so that the received signal strength of MR1 at the new MS is always the highest among all MRs. That is, SSS always chooses MR1 for the MS to associate with.

Figure 3(b) shows the access link airtime cost, the backhaul airtime cost, and the total airtime cost of Ath07 and CLASS for various MRs. The airtime cost of Ath07 and the airtime cost of CLASS cannot be compared with each other since they are calculated in different ways. The measurement of the access link airtime cost in Ath07 does not consider the actual traffic load of an MR. Thus, MR3 is selected by Ath07 since its backhaul airtime cost is zero, which results in the lowest total airtime cost among the three MRs. CLASS takes into account the traffic load on the AP channel, and thus determines that MR2 is the best choice for the MS to associate with. Figure 3(c) shows the throughput of the UDP session between the MS and the server when it associates with various MRs. The experimental result shows that the MR selected by CLASS provides the MS with higher throughput than the MRs selected by other schemes, indicating the traffic load consideration in CLASS is significant to the correct association decision for the MS.

C. Experiment 3: Investigate the impact of asymmetric uplink and downlink backhaul transportation costs on airtime cost

The objective of this experiment is to investigate the impact of asymmetric uplink and downlink backhaul transportation costs on airtime cost. Figure 4(a) shows the topology of
the testbed used in this experiment. The WMN testbed here comprises of 6 MRs. MRs 1, 2, 4 and 5 are MAPs, and MR3 and MR6 are MP only. The backhaul of MRs 1, 2 and 3 is running on Channel 40 of 802.11a, and the backhaul of MRs 4, 5 and 6 is running on Channel 60. Thus, two non-overlapping backhaul branches are connected to the Internet for this WMN. MR1 has a client node which has 10Mbps uploading UDP traffic to the server, and MR2 has a client node which has 10Mbps downloading UDP traffic from the server. The traffic pattern of the new MS is the downloading UDP traffic from the server, such as the Video-on-Demand traffic.

Figure 4(b) shows the access link airtime cost, the backhaul airtime cost, and the total airtime cost of Ath07 and CLASS for various MRs. Because Ath07 only considers the uplink routing cost for the backhaul airtime cost and the uploading traffic of the MR1-MR2-MR3 branch is higher than that of the MR4-MR5-MR6 branch, MR1 (2 hops from IGW) and MR2 (1 hop from IGW) have higher airtime cost than MR4 and MR5 in the measurement of Ath07, respectively. CLASS evaluates the backhaul airtime cost of each MR based on the traffic pattern of the MS, and assigns 0.9 to β in this case. Thus, different from the conclusion of Ath07, MR1 and MR2 have lower airtime cost than MR4 and MR5, respectively. MR2 is selected by CLASS for the lowest total airtime cost, and provides the MS with the highest throughput as shown in Figure 4(c). Hence, considering the asymmetric uplink and downlink backhaul transportation costs in the airtime cost measurement is important to identify the correct MR which provides the MS with the best end-to-end performance.

VI. SUMMARY AND FUTURE WORK

In this paper, we presented a comprehensive description, including the implementation details and an experimental performance evaluation of CLASS, a cross-layer association scheme for WMNs. The key attribute of CLASS is that it considers the importance of the traffic load of the access link, the dominant packet size of the client traffic, and the asymmetric uplink and downlink backhaul transportation costs in the measurement of airtime cost, the metric used for the association decision. The experimental results show that CLASS is able to identify the MR which provides the MS with the best end-to-end performance. In our future work, we will investigate the α value of the end-to-end airtime cost calculation using the statistical DOE methodology. Next, we will evaluate CLASS on our on-campus testbed, which comprises 13 Soekris-board based mesh routers running our customized Debian Linux (Kernel 2.6.26).

REFERENCES

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