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

Yan He, Dmitri Perkins, and Sritej Velaga
The Center for Advanced Computer Studies
University of Louisiana at Lafayette
Lafayette, LA 70504
{yxh5111, perkins, sxv2719}@cacs.louisiana.edu

***Abstract*— A widely-used association strategy in current 802.11 networks is to allow a Mobile Station (MS) to associate with the 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 a 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 which the MS should associate, comprising 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 highest end-to-end network performance after their association.**

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

I. Introduction

In IEEE 802.11 based Wireless Mesh Networks (WMNs), Mesh Routers (MRs) cooperate using distributed protocols to form a fully wireless multi-hop backhaul. 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 a WMN to the Internet [1].

The IEEE 802.11 standard [2] leaves the association strategy open to the implementers. A widely-used association strategy in current implementations is to allow a Mobile Station (MS) to associate with the Access Point (AP) which has the best Received Signal Strength Indication (RSSI) value during its scanning. Previous works [3]–[6] have revealed that such a strongest signal strength (SSS) [6] 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 [7] argued that the backhaul transportation latency should also be considered for the association in WMNs, and 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.

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 which the MS should associate, comprising 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 backhaul airtime cost and the downlink backhaul 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 [7]–[9] 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 [10]. 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 [7]–[9], CLASS has no constraint with regard to the routing protocol used on the mesh backhaul, and is independent from the routing metric.

The remainder of this paper is organized as follows. The next section discusses the related work. In Section III, we 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.

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II. Related Work

In the literature, many works have tried to improve the strongest signal strength based association scheme which is widely used in current 802.11 networks. In the approach proposed by Mhatre and Papagiannaki [3], a client chooses the AP according to the varying trends of the receive signal strengths of beacon messages. 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 [4]. 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 [5]. 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 [6].

The association schemes in [3]–[6] 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 [7]. 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 [8]. In their simulations, they found that the impact of packet size on the total association cost is significant. However, the association schemes proposed in [7], [8] did not consider the actual traffic load of a candidate MAP when they evaluated the quality of the access link of that MAP, and the frame error rate and the frame retransmission are not considered in [8]. In the association scheme proposed by Luo et al. [9], the quality evaluation of the access link considered the traffic load, however, their scheme did not consider the channel access overhead, protocol overhead and various packet sizes.

Our proposed association scheme considers the frame error rate and airtime cost for various packet size categories, and the potential available bandwidth after the client association based on the predicted traffic load. The proposed scheme uses the airtime cost to measure the backhaul performance of a candidate MR, and is independent from the routing metric. The backhaul performance measurement in our scheme 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

$$TC_{i,a} = (1-\alpha)AC_{i,a} + \alpha BC_a \tag{1}$$

The association metric in CLASS is based on the airtime cost introduced in the 802.11s draft, which reflects the amount of channel resources consumed by transmitting the frame over a particular link [1]. As shown in Equation 1, the association metric in CLASS is the end-to-end total airtime cost ($TC_{i,a}$) 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 α ($0 \le \alpha \le 1$) 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 α using the statistical Design of Experiments (DOE) [11] to further improve the accuracy of the association decision.

1) Access Link Airtime Cost Calculation:

$$AC_{i,a} = (O_{ca} + O_p + \frac{B_i}{R^i_{avl}})\frac{1}{1-e^i_{pt}} \tag{2}$$

$$e^i_{pt} = 1 - \frac{N_{original} - N_{dropped}}{N_{original} + N_{retries}} \tag{3}$$

$$R^i_{avl} = \begin{cases} \lambda_a R_{i,a} & \lambda_a \ge \lambda'_a \\ \frac{1}{\sum_{j \in C_a \cup i} \frac{1}{R_{j,a}}} & \lambda_a < \lambda'_a \end{cases} \tag{4}$$

Equation 2 shows the access link airtime cost between MS i and MR a, where e^i_{pt} is the frame error rate between MS i and MR a, R^i_{avl} is the available bandwidth that MS i can acquire from MR a, and B_i is the dominant packet size in bit of the expected traffic generated by MS i (e.g., H.323 video conference has some typical packet length) or the recorded average packet size in bit of the traffic generated by MS i before. 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^i_{pt} 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.

To calculate the expected available bandwidth R^i_{avl}, we need to measure the current traffic load on the client access channel and determine if the channel will be saturated after the association of MS i. In CLASS, each MR monitors the transmission time and the receive time during a time duration T. When MS i calculates R^i_{avl}, 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.

$$\lambda_a = \frac{T - (\sum_{j=1}^{N_{sent}} t_j + \sum_{k=1}^{N_{received}} t_k)}{T} \tag{5}$$

When $AC_{i,a}$ is bigger than the expected latency of MS i (as shown in Equation 6 where $R_{i,a}$ is the data rate at the physical layer between MS i and MR a, and R^i_{req} 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 MSs of an MR fairly share the bandwidth with an upper bound shown in Equation 4 where C_a is the set of existing clients of MR a [12]. By comparing λ_a of MR a with λ'_a (in Equation 7), MS i can determine if the access link of MR a will be saturated after its association and estimate the available bandwidth using Equation 4.

$$(O_{ca} + O_p + \frac{B_i}{\lambda_a R_{i,a}})\frac{1}{1-e^i_{pt}} \geq \frac{B_i}{R^i_{req}} \quad (6)$$

$$\lambda'_a = \frac{B_i}{R_{i,a}[(1-e^i_{pt})\frac{B_i}{R^i_{req}} - (O_{ca}+O_p)]} \quad (7)$$

2) Backhaul Airtime Cost Calculation: Equation 8 shows the backhaul airtime cost of an MR measured in CLASS, which is a weighted average of the uplink backhaul airtime cost (in Equation 9) and the downlink backhaul airtime cost (in Equation 10) between that MR and the IGW. The weight β is determined by the application traffic pattern of the MS. 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 metric, and in some routing protocols the uplink routing path may be different from the downlink one.

$$BC_a = (1-\beta)BC^a_{uplink} + \beta BC^a_{downlink} \quad (8)$$

$$BC^a_{uplink} = \sum_{k=1}^{HopCount_{uplink}} (O_{ca} + O_p + \frac{B_i}{R_k})\frac{1}{1-e^k_{pt}} \quad (9)$$

$$BC^a_{downlink} = \sum_{k=1}^{HopCount_{downlink}} (O_{ca} + O_p + \frac{B_i}{R_k})\frac{1}{1-e^k_{pt}} \quad (10)$$

B. Association Procedure

In CLASS, an MS will scan all AP channels, and send an Association Information Request (AIR) message to each MAP whose RSSI value is higher than a threshold θ. When a non-IGW MAP receives an AIR message, it will send the IGW a Backhaul Airtime Request (BAR) message attached with its own uplink backhaul airtime cost (for the link to the next hop). The destined IGW will send back the initiating MAP that BAR message with the accumulated uplink backhaul airtime cost and its downlink backhaul airtime cost. Any intermediate MR between the initiating MAP and the IGW will update the uplink or the downlink backhaul airtime cost contained in the BAR message respectively, when that message passes it. After the initiating MAP receives that BAR message, it will send an Association Information resPonse (AIP) message to the MS, which contains the metrics of its access link, and the separate uplink and downlink backhaul airtime costs. Then, the MS will transmit a bunch of probing data packets to that MAP, which are used to measure the frame error rate between the MS and the MAP. Based on this probing result and the metrics in the AIP message, the MS is able to calculate the end-to-end airtime cost which is via that MAP. After measuring the airtime costs for all candidate MAPs, the MS will associate to the one through which the end-to-end airtime cost is the lowest.

IV. Implementation Details

We have implemented a prototype version of CLASS for Linux. We modified the Madwifi driver [10] 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. As shown in Figure 1, CSLM 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).

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 AIR message from an MS or the BAR message from its neighboring MRs. The driver will extract the information from those messages, signal the CLASS daemon to handle the received request, and deliver data to the daemon through a raw socket. Both the BAR message and the AIP 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 MAP discovery and AP channel probing. The CLASS daemon generates the AIR message and the probing data packets (for measurement of e_{pt}) using raw socket. As long as the operating mode is the Monitor Mode, the modified Madwifi driver checks each received unicast data packet to identify the AIP message from the MR. Upon receiving the AIP message, the driver will signal the CLASS daemon to fetch the data via a raw socket. After the MS identifies the best MR for its association, it will switch the Madwifi driver

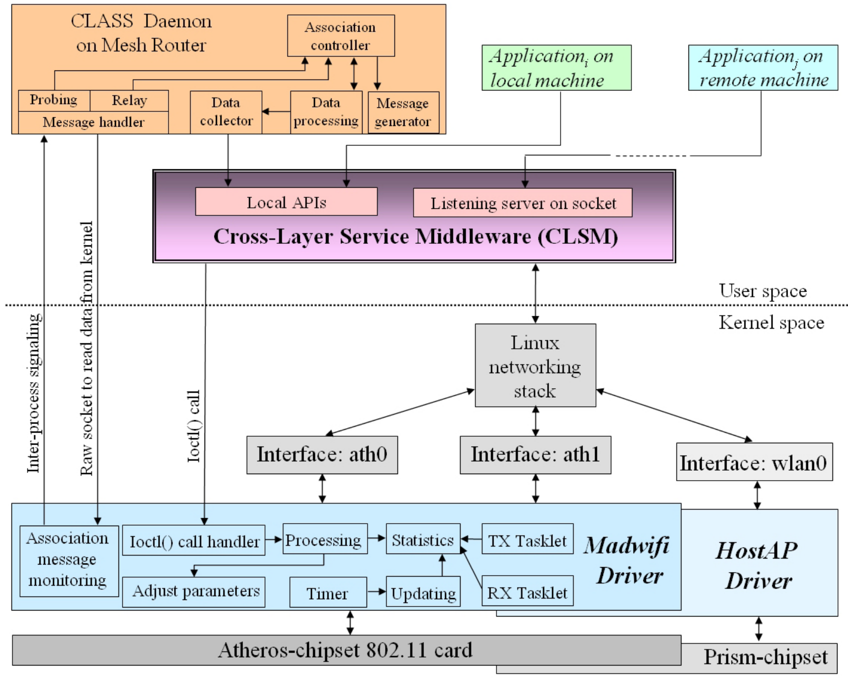


Fig. 1. Architecture of the CLASS implementation on MR

into the Managed Mode for the standard 802.11 association messaging and the subsequent regular data communications. The modified driver records the packet size of each transmitted packet, and updates the average packet size of the traffic periodically, which is useful to future association by CLASS.

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 [7] (denoted as "Ath07" here), in terms of the end-to-end performance of the MS via the MR selected by each association scheme.

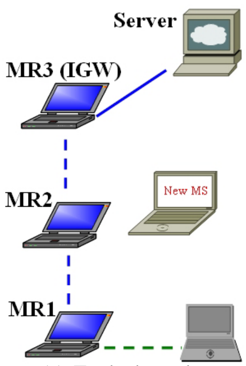
A. Experiment 1: Investigate the impact of packet size on airtime cost

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. The transmission powers of MR1, MR2 and MR3 are tuned in all experiments of this section so that the received signal strength of MR1 at the new MS is always the highest among all MRs.

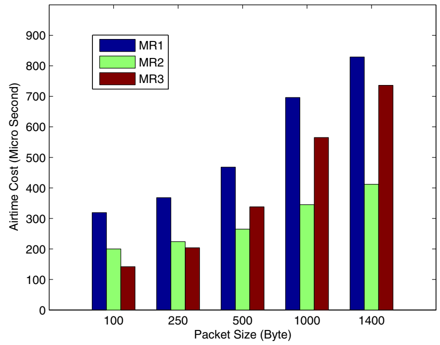
In the experiment, the received signal strengths of MR1, MR2 and MR3 at the MS are -31dBm, -40dBm and -48dBm (the experimental results shown in this section are the average values of five replicates), and the noise level is -95dBm on their client access channels in our measurements. Thus, SSS selects 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 the MS via each MR, measured by CLASS for various packet sizes. The airtime cost via MR1 is always the highest, since the access link of MR1 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), the airtime cost via MR3 is the lowest. The reason is that 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 a higher AP channel data rate overwhelms the disadvantage of higher backhaul airtime cost. Hence, the total airtime cost via MR2 is the lowest for the medium and large packet sizes (i.e., 500 bytes, 1000 bytes and 1400 bytes).

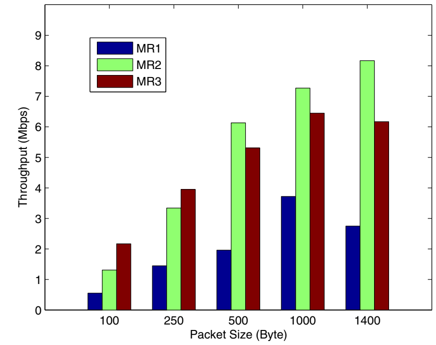
Figure 2(c) shows the throughput of the UDP session



(a) Testbed topology

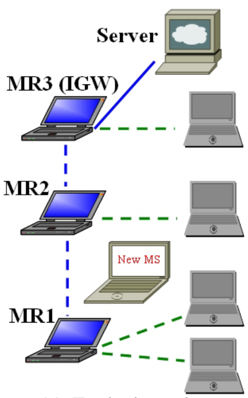


(b) Airtime costs via MRs for various packet sizes

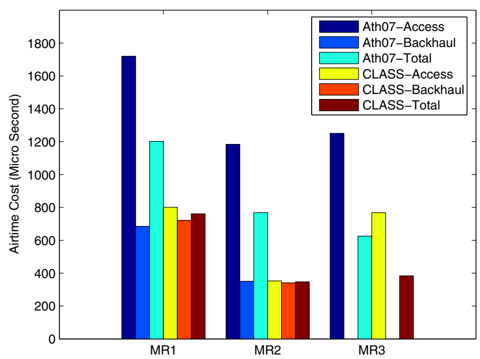


(c) Throughput of the MS via various MRs

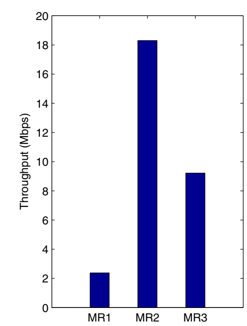
Fig. 2. Experiment 1: Investigate the impact of packet size on airtime cost



(a) Testbed topology



(b) Airtime costs via MRs



(c) Throughput of the MS via various MRs

Fig. 3. Experiment 2: Investigate the impact of traffic load on airtime cost

between the MS and the server on the Internet measured by the tool of Iperf [13]. 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.

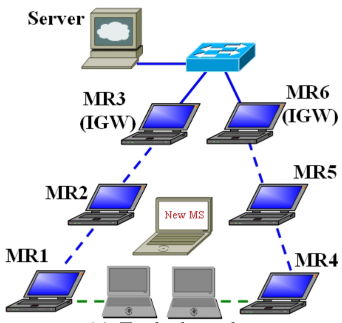
B. Experiment 2: Investigate the impact of traffic load on airtime cost

In this experiment, we investigate how the traffic load on the access link of an MR impacts on the airtime cost of the MS. 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; 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 all clients, the AP channel and the backhaul channel of each MR are set into Auto Mode.

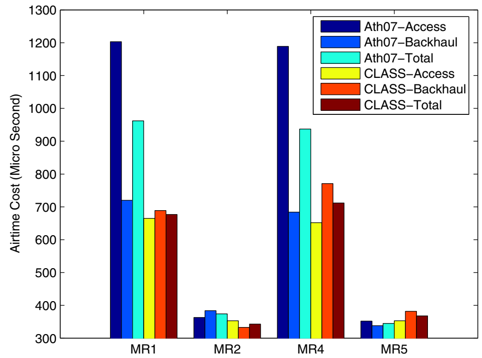
Figure 3(b) shows the access link airtime cost, the backhaul airtime cost, and the total airtime cost of Ath07 and CLASS via various MRs. The airtime cost of Ath07 and the airtime cost of CLASS cannot be compared with each other since they are calculated in different ways. The measurement of the access 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 access link, 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 that by SSS and Ath07, 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

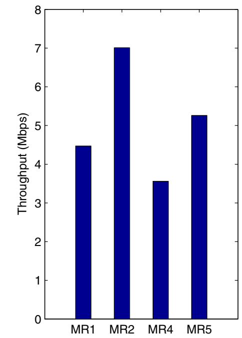
The objective of this experiment is to investigate the impact of asymmetric uplink and downlink backhaul transportation



(a) Testbed topology



(b) Airtime costs via MRs



(c) Throughput of the MS via various MRs

Fig. 4. Experiment 3: Investigate the impact of asymmetric uplink and downlink backhaul transportation costs on airtime cost

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 MR4 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 via 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 the IGW) and MR2 (1 hop from the IGW) bring higher airtime cost to the MS than MR4 and MR5 in the measurement of Ath07, respectively. CLASS evaluates the backhaul airtime cost via 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 bring lower airtime cost to the MS 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 have 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).

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