Association Management for Data Dissemination over Wireless Mesh Networks

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***Abstract*— It is critical to optimize the broadcast traffic load in mesh networks to enable multimedia broadcasting services, which is an emerging application. This paper studies the problem of optimizing the broadcast traffic load in a mesh-network. Traditionally, users associate with access points (APs) based on the strongest signal strength. We propose the concept of multi-association, where the AP for unicast traffic and the AP for broadcast traffic are independently chosen by exploiting multiple coverage that are typical in mesh networks. Our focus in this paper is on the problem of selecting the AP for broadcast traffic to reduce the load. We propose a novel cost metric based on ETT and the number of nodes in range of the APs, that is advertised in the beacons from the APs. Users periodically scan and associate with the AP with the lowest cost metric. The proposed approach reduces the number of APs that handle the broadcast traffic. This results in heavy reduction in control and data packet overhead, leading to higher packet delivery rate and video quality measured in terms of PSNR. This also helps improve the delivery ratio of unicast traffic. We compare the performance of our approach with the traditional signal strength based association using extensive simulations and real experiments in the Kansei indoor testbed at OSU that consists of 180 802.11b devices.**

I. Introduction

Mesh Networking is emerging as a promising technology that brings Wireless LANs to the masses at a reduced deployment cost. In Mesh-networks APs (access points) communicate with other APs over wireless channels. The absence of wired Ethernet connections, makes it easier to deploy Mesh-networks, and reconfigure them when APs need to be physically relocated. In new network deployments, re-configuration is often critical due to lack of accurate initial usage pattern models and also due to changing usage patterns often associated with new technologies. Public deployments of mesh networks are already operational in several cities including Philadelphia, Las Vegas, and Urbana-Champaign (cuwireless.net). The upcoming WiMAX (wimaxforum.org) products that can provide up to 70 Mbps and 31 miles range, are expected to provide a tremendous boost to the Mesh-networking technology. Various types of WLANs, such as city-wide WLANs[1], in-building WLANs, and temporary WLANs, can all benefit from the Mesh-network technology.

While unicast services are essential for providing Internet access to individual users, broadcast services are needed to disseminate local news, visitor's information, TV channels, or other multimedia information. The need for supporting efficient broadcasting services in the access network has become increasingly important with the emergence of various applications such as real time multi-party conferencing, scientific data visualization, and presentation broadcasting at conferences and lectures.

The challenges in supporting multimedia services over Mesh-networks are manifold. First, traditional signal strength based user-to-AP association leads to an inefficient broadcast tree resulting in network overload in the mesh. The key reason is the unawareness of other participating users during association. Second, coordination for computing an efficient broadcast tree will incur overhead that needs to be minimized. And third, users and APs may have multiple radios that can operate in different modes (infrastructure vs. peer-to-peer) and on different channels, and an optimal configuration (channel, mode etc.) is needed for efficient operation.

Although industry [1], [2] and academia are both beginning to acknowledge the potential of Mesh-networks, prior research on Mesh-networks [3], [2], [4], [5], [6] has primarily focused on unicast traffic. Related research on multicasting [7], [8], [9], [10], [11], [12] and broadcasting [13], [14], [15] in ad-hoc networks are not directly applicable to mesh networks due to the following two key differences. First, in contrast to ad-hoc networks where all nodes communicate over the same channel, in mesh-networks, nearby APs are configured in different channels in order to reduce interference. Second, unlike in ad-hoc networks, the user-to-user links are not used in typical deployments of mesh networks. Instead, users can associate and communicate only via the APs. Issues of security and accounting have posed practical challenges in using user-to-user links. Third, the mesh formed by the APs is static and always connected, with the users possibly moving between APs. This contrasts with ad-hoc networks where typically all nodes are mobile, which can also result in network partitions. These limitations of prior research and the growing demand for multimedia dissemination services over public access networks, forms the basis of our work.

Our solution leverages highly overlapping coverage areas that provide multiple choices for APs to associate with. In Mesh-networks the wireless connectivity between neighboring APs naturally leads to highly overlapping coverage regions.

[1] The city of Chaska, Minnesotta provides WLAN coverage in a 15 sq miles area since Oct 2004 (www.chaska.net).

Moreover, a high density of APs is necessary for supporting a large number of users with high throughput connections. As MAC layer broadcast packets are always transmitted at the lowest data rate in the IEEE 802.11 family of protocols, users can benefit from the multiple choices of APs for receiving the broadcast traffic. Thus, it is not necessary for a user to associate with the AP with the strongest signal (that can support the highest possible data rate) for the broadcast traffic.

We assume that each user is equipped with a single radio and each AP is equipped with two radios. In the AP one radio is used for communication with other APs and the other radio is used for communication with the users. The channel for AP-AP communication is set to be different from the AP-user channels. The AP-user channels are statically allotted to minimize interference.

In this paper we study the problem of optimizing the broadcast traffic load in the mesh using the novel concept of multi-association, where users maintain distinct associations for unicast and broadcast traffic. We use the AP with the best signal strength for unicast traffic, but other metrics such as unicast traffic load [16] can also be used to select the unicast AP. For reducing the broadcast traffic load, users select the AP for broadcast services independently of the AP selected for unicast traffic. The selected broadcast APs can be connected to the AP with the backbone access (Main AP or MAP) using any ad-hoc multicast routing protocol. As the multicast structure construction is not the focus of the paper, we choose to connect the selected APs to the MAP using a tree, only for purposes of simplicity. The tree construction and maintenance uses the mechanisms of MAODV [17], but any other multicast routing protocol can be used as well.

Our focus is on the problem of selecting the broadcast AP for association that leads to optimal broadcast traffic load in the network. For efficient selection of broadcast APs, we propose a metric that is periodically advertised by each AP. Users greedily select the AP with the lowest metric for broadcast services. Our contributions in this paper are as follows:

- We formalize the problem of efficient association for data dissemination over Mesh-networks. We prove that the problem is NP-hard by showing a reduction from the Steiner tree problem.
- We propose the multi-association concept and a novel metric that optimizes the broadcast traffic load in the mesh.
- We present a heuristic based distributed protocol based on our metric.
- Using simulations in *ns2* we evaluate the performance of our approach and compare it with the traditional approach that uses signal strength based association. The key metrics are the size of the tree and the quality of received MPEG video measured using PSNR (Peak Signal-to-Noise Ratio).
- We have implemented the distributed approach and compared its performance with the traditional signal strength based approach, on an indoor testbed of 180 nodes with 802.11b radio.

The rest of the paper is organized as follows. Section II defines the problem, the notations, and the terminology used in the paper. Dual AP management framework is described in Section III. The distributed approach of the problem is discussed in Sections IV. Section V presents a detailed evaluation of our approach and comparison with signal strength based approach using simulations. The results from the testbed experiments are presented in Section VI. Section VII summarizes relevant related work. Finally, Section VIII concludes the paper.

II. Terminology and Problem Definition

We represent the connectivity between the users and the access points using a graph $G = (V, E)$, where V (same as $V(G)$) is the set of nodes (users and access points) and E (same as $E(G)$) is the set of edges. E consists of edges connecting users to access points in range, and between access points that are in range of each other. E does not include user-to-user edges as we do not consider ad-hoc communication between the users. V can be partitioned into the set of users, V_u, and the set of access points, V_a. We assume that one of the APs, called the main AP (MAP), has a connection to the backbone Internet and acts as a gateway to the rest of the APs. Although we study the performance of multiple MAPs in our simulations, the discussion in the rest of the paper assumes a single MAP for simplicity.

As mentioned in Section I, our goal is to optimize the broadcast traffic load in the network. One of the well known metrics for load is defined as the Expected Transmission Time (ETT) [18]. Although in general the expected transmission time between two nodes can be asymmetric, the definition of the ETT metric as given in [18] is symmetric. With a symmetric definition of ETT, we restrict our discussion to undirected graphs in this paper. To account for a possibly asymmetric definition of ETT, the research presented in this paper can be extended for directed graphs. We define the problem of constructing the tree for optimizing the broadcast load, and name it the Mesh Steiner Tree (MESH-ST) problem. The following definition assumes that MAC layer unicast is used for transmissions between the APs and MAC broadcast is used for the last hop transmission from the AP to the users. Unicast transmissions in the wireless backbone ensures high reliability and broadcast transmissions on the last hop are used for low overhead for serving multiple users. Other combinations of unicast and broadcast transmissions on the tree links can be used (with appropriate modifications to the definition of MESH-ST), but are not studied in this paper. The definition of the Steiner tree and our definition of the MESH-ST problems are as follows:

- **Steiner Tree (ST):** Given an undirected graph G with nonnegative edge costs and whose vertices are partitioned into two sets, Required nodes and Steiner nodes, ST is a minimum cost tree in G that contains all the required nodes.

- **Mesh Steiner Tree (MESH-ST):** Given a graph G with two vertex partitions V_a and $V_u = V(G) - V_a$, and a node $MAP \in V_a$, MESH-ST is a least cost tree (cost $Cost_{MESH-ST}(T)$ is defined below) with the MAP as the root and the nodes in V_u as its leaves. The cost $c(v)$ of each node v is the ETT for broadcast from that node to all its associated users, and the cost $c(e)$ of each edge e is the ETT for unicast over that edge. Let $E_{non-leaf}(T)$ be the set of non-leaf nodes in a tree T, and let $V_{leaf-nbr}(T)$ be the set of nodes in tree T that are connected to a leaf node using a tree link. The cost of the tree T is defined as follows.

$$Cost_{MESH-ST}(T) = \sum_{e \in E_{non-leaf}(T)} c(e) + \sum_{v \in V_{leaf-nbr}(T)} T \quad (1)$$

The first term accounts for the unicast transmissions on the AP-AP links and the second term accounts for the broadcast transmission on the last hop from the AP to the user(s).

There are two main differences between ST and MESH-ST. The Mesh Steiner Tree requires the nodes in V_u to be leaf nodes, and the cost function includes weights of some vertices rather than edge weights over the leaf-edges. In spite of these differences, in the following theorems we show that the ST problem is reducible to the MESH-ST problem and vice-versa, thus proving that it is also an NP-hard problem See Appendix for proofs of the theorems.

Theorem 1: [Lower bound] MESH-ST is at least as difficult as ST.
Theorem 2: [Upper bound] MESH-ST is at most as difficult as ST.

Theorem 1 establishes the NP-hardness of the MESH-ST problem. Theorem 2 shows that the problem can be modeled as a ST problem.

We can transform the problem with multiple MAPs to a problem with single MAP by *fusing* the nodes corresponding to the MAPs.

Although the MESH-ST problem is reducible to the ST problem, ad-hoc multicasting solutions that typically approximate a Steiner tree computation, are not directly applicable due to reasons discussed in Section I. The key challenge is in designing a protocol that can efficiently compute the broadcast-AP to associate with such that it can lead to a tree with the optimal broadcast load. The selected APs (rather than the end-users) can then be connected using any ad-hoc multicast protocol. Ad-hoc multicast protocols have been well studied in the literature [17], [11], Our focus in this paper is instead on the algorithm for selecting the broadcast-APs for association.

III. AP MANAGEMENT FRAMEWORK

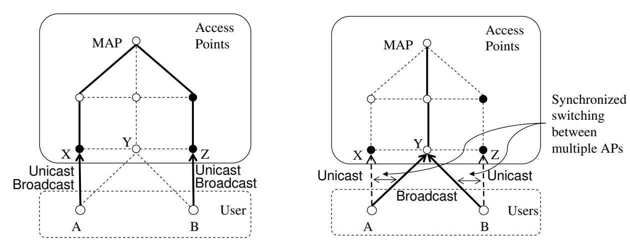
We propose an AP management framework for simultaneous support of higher quality broadcast and unicast services. The framework is characterized by dual-AP association, dual-traffic cycles, and Time-based AP switching.

- **Dual-AP association:** Users receiving broadcast services maintain two independent associations with APs: one for unicast (unicast-AP) and the other for broadcast(broadcast-AP).
- **Dual-traffic Cycles:** Time is partitioned into cycles consisting of separate unicast and broadcast periods.
- **Synchronized AP Switching:** Users receiving broadcast services switch between the unicast AP and the broadcast AP at the end of the respective periods.

The unicast-AP selection can be based on the traditional strongest signal based selection or other techniques for optimizing or balancing unicast load [16]. The unicast AP selection is orthogonal to our work and any scheme can be used.

A. Dual-AP Association

In current mesh-networks, users associate to the AP with the best signal-strength. Figure 1(a) shows an example where user A selects AP X and user B selects AP Z. Both unicast and broadcast data are received from the AP with which the user associates. Consider the proposed approach (Figure 1(b)) where each user simultaneously maintains two associations: one for unicast traffic and the other for broadcast traffic. Observe that for unicast communications the selection of the APs remains unchanged, but the broadcast traffic is now received by both the users through AP Y.



(a) Traditional Association (b) Multi-association

Fig. 1. Unicast and Broadcast Communication. Highlighted links carry broadcast traffic. Arrows on links between users and APs represents associations.

The IEEE 802.11 family of protocols supports multiple transmission rates with various modulation schemes. For unicast traffic, the best transmission rate is selected based on the observed channel condition [19]. For broadcast packets it is difficult for the sender to estimate the worst channel quality among all the potential receivers. So, broadcast packets are always transmitted at the lowest data rate in IEEE 802.11 family of protocols. For example IEEE 802.11b uses 1 Mbps, as opposed to the highest rate of 11 Mbps, for the broadcast packet transmission rate with BPSK modulation. Users can therefore select from a set of APs without compromising the broadcast quality. As discussed in Section I highly overlapping coverage areas are common in mesh networks. The separation of the unicast-AP and the broadcast-AP in our framework makes it possible to leverage the wider choice of broadcast-APs to optimize the broadcast traffic load.

B. Dual-traffic Cycles

Users switch in time between the unicast AP and the broadcast AP during the unicast and the broadcast periods, respectively, as shown in Figure 2. APs use the broadcast period for broadcast traffic transmission and the unicast period for unicast traffic transmission. The cycle length, T_c, consists of broadcast period, t_b, and unicast period, t_u. We denote the ratio of t_b to T_c by α. Therefore, $t_b = \alpha T_c$ and $t_u = (1-\alpha)T_c$. T_c and α can be configured by the network provider and can be advertised in the beacons. The effect of these parameters are studied using simulations in Section V-A. Although the broadcast and unicast periods are separate, as discussed later in the section, there is no wastage of bandwidth if there are not enough packets for the broadcast period.

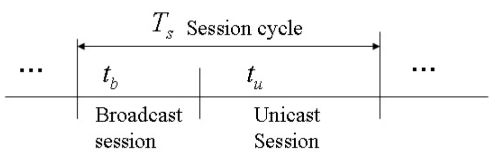


Fig. 2. Broadcast and unicast session.

Users synchronize with the APs based on beacons advertised at the beginning of the broadcast periods. In each broadcast period, each AP determines whether to transmit the beacon or not based on a certain probability, p_{beacon}. Probabilistic beaconing avoids the problems of synchronized beacon collision if nearby APs happen to use the same channel. An alternate solution is to operate in the PCF mode and use probabilistic transmissions of the PCF beacons for synchronization. As PCF periods are required to alternate with DCF periods, the unicast-broadcast cycles can be limited to the DCF periods. In addition to user-AP synchronization, APs also need to synchronize with nearby APs to allow users to dynamically switch between them in each cycle. Protocols such as [20], [21] can synchronize nearby APs. Large cycle length (of the order of a few 100 ms) can be used to limit the impact of clock inaccuracies at the cost of increased latency.

C. Synchronized AP Switching

The users and APs switch between unicast and broadcast modes at fixed intervals. Each AP needs to maintain two queues - one for the unicast packets and other for the broadcast packets. At the beginning of the broadcast period, users switch to their respective broadcast APs and the APs start to transmit packets from their broadcast queues. Switching to a broadcast-AP requires switching the transceiver to the channel corresponding to that AP. If an AP runs out of broadcast packets during the broadcast period, it sends unicast packets to user nodes that are associated with that AP in the broadcast period. After the broadcast period, the users switch back to the unicast-AP (switch the channel of the transceiver to that of the unicast-AP) and during the unicast period, packets are transmitted only from the unicast queue at the APs. Users are allowed to transmit packets to the APs in both unicast and broadcast periods. However, the broadcast packets (always transmitted in the broadcast period) from the APs are given higher priority over upstream unicast packets. This prevents underutilization when APs do not have any downstream data (broadcast or unicast) during the broadcast period. If an AP or a user is still in the process of transmitting a unicast packet at the beginning of the broadcast session, they complete the transmission before switching sessions. Unicast-only users and users who associate with the same AP for both unicast and broadcast traffic do not have to undergo any synchronized switching.

IV. Distributed Solution

In this section, we propose a distributed heuristic based solution for computing the broadcast association that results in low broadcast traffic load in the network. The goals for the design of the distributed solution are as follows:

- The number of total APs (TAP) for data broadcasting in the tree should be optimized.
- The number of selected APs (SAP) for the last hop data broadcasting should be optimized.
- If an AP has to be in the tree then it should be preferred for association over selecting a new AP that is currently not serving the broadcast data.

We propose a metric that is advertised in the beacons from the APs. The user associates with the AP with the lowest metric as opposed to the best signal strength. To meet the above design goals we propose the following mechanisms in our solution:

- **Associate to an AP that has smallest ETT to the current tree:** The APs that have low ETT will reduce the load due to transmissions between the APs.
- **Associate with APs supporting more users:** The APs that have a large number of users in range have a higher potential for serving a large number of users. Selecting a AP that has the largest number of users is motivated by the greedy algorithm for minimum set cover algorithm [22]. The greedy algorithm for approximating a minimum set-cover, at each step, simply chooses the covering set with the maximum number of leftover elements. So APs with more users in range must be preferred.
- **Associate to an AP that has a** ***special user*** **that is in range of a single AP:** If a user has only a single choice for association, then the corresponding AP is required to be part of the broadcast tree. If other users realize this necessity of the AP, they can be assured that by joining this AP the tree size will not increase.

A. Metric Computation and AP Selection

Each AP needs to compute a metric to advertise. Let $CETT_i$ be the cumulative ETT to the nearest node in broadcast tree from the AP_i, and N_i be the number of users in range of AP_i. The cost metric C_i of AP_i is defined as follows:

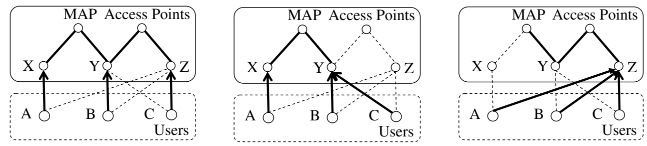
$$C_i = w_i(\beta CETT_i + (1-\beta)\frac{1}{N_i}),\ where \quad (2)$$

$$w_i = \begin{cases} \epsilon, & \text{AP i has one or more special users} \\ 1, & \text{otherwise} \end{cases} \quad (3)$$

where ϵ is a very small number in the range [0,1] but close to 0, and β is a tunable parameter also in the range [0,1]. Equation 2 gives a tradeoff between the load of AP-AP channel and AP-user channel. These two terms correspond to the two terms of Equation 1. The first term of Equation 2 is the sum of transmission times along the hops to the tree. This reflects the resource consumption in the AP-backbone network. The second term is used to minimize the number of SAPs and thus the resource consumption in the AP-user network. w_i is set to a small value (ϵ) when APs have special users. This reduces the cost of such APs, thus making it highly likely to be selected by other users. The $CETT_i$ is computed using a proactive routing algorithm like DSDV that runs in the AP-backbone. We used the ETT calculation method introduced in [18]. N_i is computed by APs based on periodic scanning messages from users. Note that users periodically scan in all channels to select the best unicast-AP and best broadcast-AP for association.

The cost metric and the associated broadcast-AP selection process has three properties: *tree-preserving*, *self-reordering* and *self-convergence*. First, note that the users periodically scan the channel and collect the cost metrics of neighboring APs. Then, they change their broadcast-AP to the minimum cost metric AP. However, once a user selects an AP, the $CETT_i$ of the selected AP becomes zero as the AP joins the broadcast tree. Thus, at the next scan, the user receives smaller cost metric from that AP, which forces the user to stick with the current AP. This tree-preserving property reduces the overhead of tree maintenance. Second, when a user can hear two or more APs that are already part of the tree, their cost metrics are likely to be lower than that of non-tree APs because of zero $CETT_i$. Then, the user (re)selects an AP with the largest number of users among the in-tree APs. This *self-reordering* property attempts to optimize the number of selected APs in the tree, resulting in reduction of the total broadcast load in the network. Third, the users that associate with the same AP in several scan iterations do not change their associations for longer intervals unless the link to the AP breaks. This *self-convergence* property results in stabilization of the tree and optimization of tree maintenance overhead.

Consider the example shown in Figure 3. Assume that the ETT for broadcasting from all APs are the same, and the ETT over each AP-AP link is also the same. When traditional signal strength based association is used, three APs are selected for broadcasting to the users and all five APs are selected in the broadcast tree. Figure 3(b) shows that if $c(e) >> c(v)$, then MESH-ST selects the least number of APs to be in the tree. As a result only three APs are selected in the tree, two of which have associated users. Figure 3(c) shows that if $c(e) << c(v)$, then MESH-ST selects the least number of APs with associated users. So it selects one AP with associated users to minimize the MESH-ST metric (Equation 1) which is joined to the MAP using a tree involving four APs. We observe that based on the computed ETT metrics, the tree may be very different from the tree obtained by traditional association.



(a) Traditional (b) MESH-ST ($c(e) >> c(v)$) (c) MESH-ST ($c(e) << c(v)$)

Fig. 3. Broadcast Communication. The arrows represent the associations for broadcast data. The solid lines indicate the links on which data is transmitted.

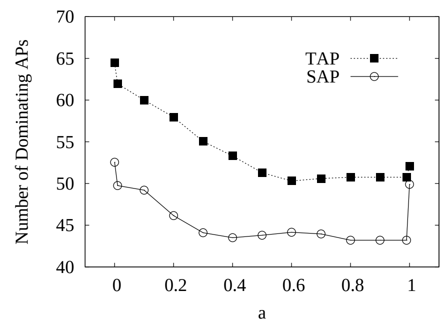


Fig. 4. Broadcast tree size with respect to β. The number of APs is 100 and distance of each AP is 90m with 100m radio range. The number of user is 50 with random way-point mobility model and $2m/s$ speed.

The total number of APs (TAP) in the broadcast tree is an indicator of the first term of Equation 1. The number of selected APs (SAP) effects the contribution of the second term in Equation 1. So it is critical to reduce the number of TAPs as well as SAPs. Figure 4 shows the average number of TAPs and SAPs with respect to β. The number of TAPs is lowest for $\beta \geq 0.6$ and the number of SAPs is lowest for $\beta \geq 0.3$. So for $\beta \geq 0.6$ we obtain a low value for both TAPs and SAPs, which will lead to a low value of $Cost_{MESH-ST}$. Moreover we observe that the TAPs and SAPs are insensitive to the exact value of β for $\beta \geq 0.6$. An interesting observation is that as β approaches 1, the number of SAPs and TAPS remains similar, but for $\beta = 1$, the number of TAPs and especially SAPs is much higher than their lowest values. This shows that both the terms $CETT_i$ and $\frac{1}{N_i}$ are critical to the metric. For a very high value of β such as 0.99, the initial selection of the AP is based on $CETT_i$. After an AP is selected, the $CETT_i$ term becomes zero for that AP for subsequent scans, and the AP selection becomes dependent on the term $\frac{1}{N_i}$.

B. Limited Users per AP

Our discussion so far has assumed that an unlimited number of users can associate with an AP. But in reality, the number of users per AP is often bounded. A typical limit is 32 users for most 802.11 based APs. Our protocol can be easily extended to support limited number of users. A simple extension involves a flag in each beacon message. The flag is set only when the AP is already associated with the maximum number of users allowed. If a user decides to associate with an AP which is already serving its maximum allowable number of users, the AP would reply back to the user's association message indicating so, thus forcing the user to associate with another AP. Another way is to advertise progressively higher costs when APs start to get saturated. These approaches have an impact on the number of users that get starved (rejected by all neighboring APs as they are saturated).

C. Channel Scan Optimizations

The proposed cost metric based distributed association algorithm needs reliable and up-to-date metric collection from all neighboring APs of a user. To get the cost metric, the user can perform active or passive scan. The active scan mechanism actively collects cost metrics by switching channel and sending PROBE messages. The PROBE message and extended BEACON messages may suffer from the queuing delay at the queue in the interface and backoff time at the MAC layer. The active scan delay causes delay and drop of data packets as the user cycles through different channels. Thus, the performance of active scan is critical to the overall performance.

For efficient active scan, we use several optimizations: priority queuing, MAC layer call-back, and MAC initialization with channel switching. First, the PROBE and BEACON messages have higher priority than other data packets and are queued in front of the interface queue. This reduces the queuing delay of PROBE and BEACON messages. Note that other data packets in the queue should not be sent to the currently scanned channel. Next, active scan should know when the PROBE messages are actually sent out after delays at the MAC layer. Since there may be working timers in the MAC such as backoff timer, defer timer, and NAV timer, the PROBE message cannot be sent out within a given time. To learn the time of transmission of the PROBE message, we use a MAC layer callback. When the MAC sends out the PROBE message, it calls an active scan handler to indicate the successful transmission. Then, the active scan algorithm waits for a BEACON within the timeout period. Finally, active scan initializes the MAC status after switching channels, since it is not necessary to keep the old status of MAC in the new channel. Active scan module stops MAC timers, and initializes state variables. These methods increase the reliability of active scan.

V. PERFORMANCE ANALYSIS

In this section we report on performance studies of the proposed cost metric based distributed algorithm (COST) using simulations in the Network Simulator ns2 [23]. For the simulation, we implement a simple tree management mechanism for the selected AP by users to 'JOIN' and 'PRUNE' to the tree. We also implement a dual AP management scheme that switches from the unicast AP to the broadcast AP, periodically.

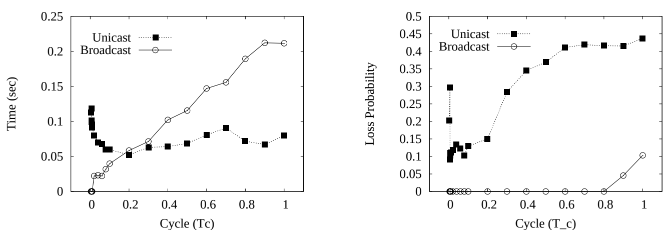
We first discuss the impact of cycle length on the performance to select the proper T_c III-B. Then, we compare the performance of the proposed DA algorithm with the signal strength based association algorithm (SS). SS mechanism acts like our DA except it selects AP based on the signal strength. For performance evaluation, video is streamed to all users over a wireless mesh network. The metrics of evaluation are: the constructed tree size (SAP, TAP), the transmission load that is the average time taken for serving broadcast traffic in the network, the number of control messages to compute and maintain the broadcast tree, the number of data packets transmitted in the tree. The quality of received video is measured by average PSNR (Peak Signal to Noise Ratio).

Our study is mostly based on the multi-channel configuration. The highlights of our evaluation for the three components of our study are as follows:

1) *Impact of cycle length* We observe that the longer traffic cycle increases the transmission delay and the high packet losses and shorter traffic cycle decreases throughput.
2) *Video Quality achieved* We observe from the simulations that DA has the lower number of APs selected in the backbone, smaller transmission load, and average delay, resulting in highest average PSNR. The video quality observed in DA is much better than the video quality observed in SS.
3) *User Density* We observe that the increase in the user density results in a increase in the number of APs in tree.
4) *AP Density* We observe that the increase in the AP density results in a decrease in the number of APs in tree.
5) *User Speed* We observe that the speed of users does not change the number of APs in tree.

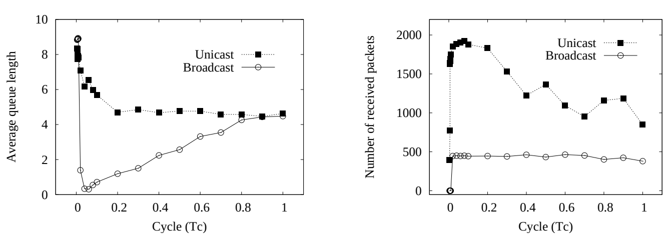
For our simulations we use a grid topology of 10×10 APs. The distance between neighboring APs, D, is 90m and radio propagation range of AP is 100m, unless mentioned otherwise. We use a single MAP in our simulation. Users are uniformly distributed in the area and move randomly according to the random way-point model. We used a maximum speed of 10 m/s with 1 sec pause time for the random way-point model for all experiments, unless mentioned otherwise. The users associate with APs using active scanning. We use the quarter common intermediate format (QCIF, 176×144 pixels/frame) sequence "Foreman" (first 300 frames from the original 30 fps sequence) encoded at 10 fps. The encoder generates a stream with a bit rate of 48 Kbps. In a multi channel scenario, each user has a single wireless interface and each AP has two wireless interfaces: backbone interface and local subnet interface. APs communicate with each other through the backbone interface. The backbone interface of all APs share a single channel. APs communicate with users via the local subnet interface. The neighboring APs are configured in such a way that they are on different channels on the local subnet interface. We assign 13 channels to the local subnet interfaces of APs. In the single channel scenario, APs and users have one wireless interface and they share a single channel. In the dual channel scenario, the AP has two wireless interfaces and the user has a single wireless interface. The APs operate in IEEE 802.11b infrastructure mode. Although we configure the bandwidth of the wireless channel to be 11Mbps, the broadcast data is transmitted at 1 Mpbs. Priority queuing is being used to give higher priority to the control packets as compared to the data packets.

A. Impact of the length of cycle on performance



(a) Average delay (b) Loss probability

Fig. 5. (a) Average packet delay and (b) packet loss probability with respect to the cycle length, T_c with α as 0.5 and queue length as 20 packets.



(a)Queue length (b) Throughput

Fig. 6. (a) Queue length and (b) the number of received data with respect to the cycle length, T_c with α as 0.5 and queue length as 20 packets.

In this section, we examine the impact of cycle length ,T_c, on the performance of packet transmission in MAC layer. To operate the dual AP association, it is required to select accurately the T_c, since it affects the performance of MAC transmission. Note that α can be determined based on the amount of broadcast traffic. We set $alpha$ as 0.5, for simplicity. We simulate two AP and one user who associate with one AP for unicast traffic and the other for broadcast traffic. Two unicast flow are configured to test the dual association scheme: one is from the unicast AP to the user and the other is backward flow. Each unicast flow generate CBR traffic with 1Mbps rate. Broadcast traffic generates CBR traffic with 400Kbps rate. Packet size of both traffic type is 1kbyte. The length of interface queue is 20 packets. Note that when a traffic session is switched, the packet that waits for transmission in the MAC is pushed back to the interface queue and the MAC state is initialize.

Figure 5 shows the transmission delay and the length of interface queue at the AP. The delay of unicast traffic decreases as the T_c increases from 4ms to 200ms. This is because of decreased switching-cost. Whenever the sessions are altered, the packet in the MAC goes back to the queue which causes queueing delay of the packet. However, the T_c increases 700ms, the delay at the queue increases. If the T_c increases, we can see the packet overflow in the queue as shown in Figure 5 (b). We can observe that loss probability is increasing when T_c exceed 300ms. Note that the input traffic of unicast is high. Figure 6 (a) shows the average length of queue, where the queue length decreases when T_c increases. However, the queue length becomes stabilized because of increased losses. The through, the number of received packet, shows similar pattern. The throughput is low at a short T_c and shows good performance between 100ms and 200ms. Because of low traffic rate and enough bandwidth (α=0.5), the average delay, queue length, and the loss probability increases slowly. However, at the high T_c, the transmission delay of broadcast packet crosses the unicast packet's because of the low transmission rate.

B. Video quality over Mesh Network

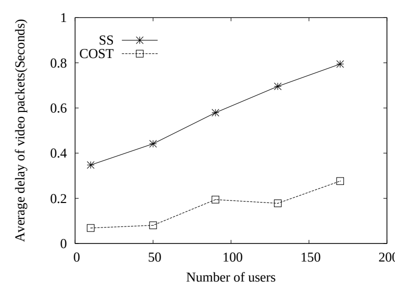


Fig. 7. Average delay of video packets with respect to the number of users.

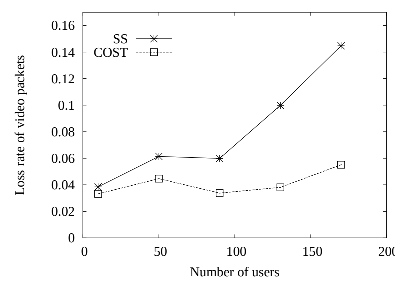


Fig. 8. Average loss rate of video packets with respect to the number of users.

In streaming multimedia applications, multimedia data has to be continuously transmitted to clients over the mesh network where the available bandwidth, delay, and jitter are fluctuating. In traditional wired networks, packet loss and delay are mainly caused by network congestion. The delay, jitter, and loss of packets in the wireless network occurs due to channel interference, signal quality variation and contention of nodes. Various network adaption techniques are proposed where media-server and wireless clients co-operate to adapt to the unreliable wireless channel. To adapt to wireless resource

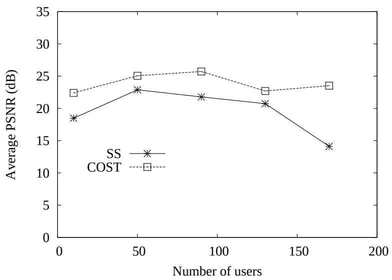


Fig. 9. Average PSNR with respect to the number of users. It is an average value of the PSNR of all frames of all users.

(a)SS (b)COST

Fig. 10. Video quality of sampled video. 13^{th} decoded video frame of 11^{th} user where the number of user is 90.

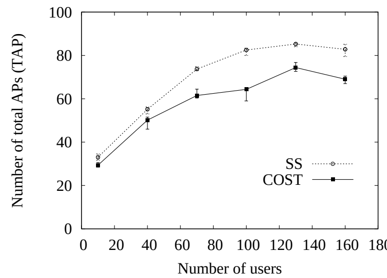
fluctuations, streaming application on the client buffers the packets. The streaming client also sends its status information to the server, which includes the current buffer occupancy, receiving rate, and error rate. The streaming server reacts to the feedback of the streaming client by performing quality adaptation and packet scheduling. A well-designed wireless mesh architecture can reduce the frequency of interference and contention between the nodes and can reproduce a high quality video at the clients.

In our test, we have implemented a simple video streaming server and a client. The server sends encoded video with a variable data rate. The client performs 2 seconds pre-buffering to compensate for the bandwidth fluctuations of the wireless channel. The server and client do not perform forward error correction, ARQ, or rate control with users feedback. However, with these enhanced feature of streaming technologies, higher quality of received video can be achieved.

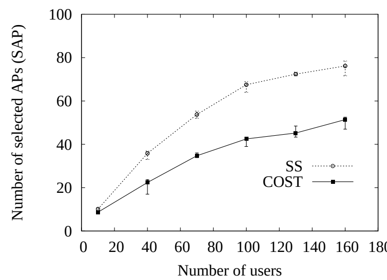
Figure 7 indicates that the average delay increases with the increase in the number of users. This is due to the fact that, with increasing users, more APs are selected in the tree for data dissemination. Hence, there is reduced bandwidth and increased contention at the backbone which results in increased delay. But we can observe that the average delay incurred in COST is 68.2% lower in comparision to SS when the number of users is 170. Also, we observe that average loss rate increases with the x-axis in Figure 8. The average loss rate using COST is 61.9% lower in comparison to SS. It is clear that higher video quality can be achieved, when the packet loss is lower.

The average PSNR of received video is shown in Figure 9. The average PSNR decreases with increased number of users. Even here, we can observe that the COST have 8.3% higer PSNR as compared to the SS. Figure 10 shows the decoded video. We can clearly distinguish that the COST has better video quality than SS.

C. User density



(a) TAP



(b) SAP

Fig. 11. Number of selected APs with respect to the user density.

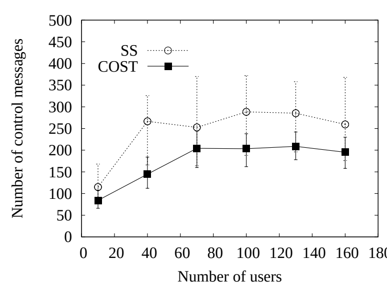


Fig. 12. The number of control messages with respect to the user density.

Figure 11(a) shows the number of TAPs and SAPs with respect to the number of users. As the number of users increases, the number of TAPs also increases. We observe that COST has lower number of TAPs than SS. For the case of 160 users, the number of TAPs for COST is 16.6% than that of SS. Figure 11(b) shows the number of SAPs with respect to the number of users. The SAP of COST is 35% lower than that of SS. The number of TAPs and SAPs of both SS and COST do not fluctuate too much. The min and max are close as shown in Figure 11. However, if we see Figure 12, the number of control messages to maintain the tree of the SS is much larger than that of COST. This shows that the COST method is more stable than SS. The average number of control messages for COST is 25% lower than that of SS for 160 users. However, the variation (between min and max) for SS is much bigger than that of COST. In case of SS, frequent changes of

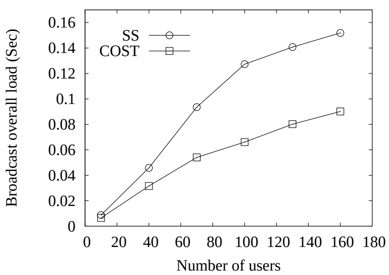
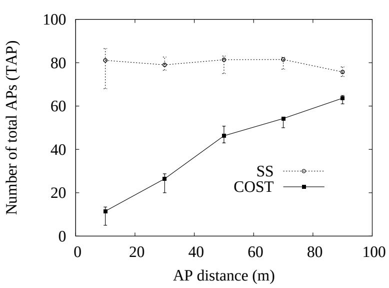


Fig. 13. Average broadcast load. Fraction of broadcast transmission per second of all APs in a mesh network.

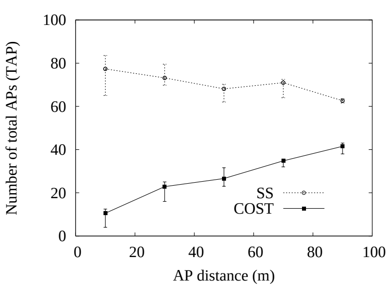
associated AP results in higher control messages in addition to the poor performance of the tree for broadcast services.

Figure 13 depicts the broadcast load in terms of the normalized transmission time of the mesh network spent by broadcast traffic. At an average APs of the SS consume 150ms per second to transmit broadcast traffic when the number of users is 160. However, at the same traffic load, APs of the COST use only 90.9ms per second to deliver the broadcast packets. It is clear that unicast users can utilize the rest of broadcast time. Broadcast load of COST is 40% lesser than that of SS.

D. AP Density



(a) TAP



(b) SAP

Fig. 14. The number of APs in tree with respect to the AP density(AP distance). Number of users are 100.

Figure 14 shows the number of TAP and SAP versus the distance between adjacent APs. As the density of APs decreases, which means the distance between adjacent APs increases in a grid network, the number of SAPs and TAPs increase. In the denser AP topology lesser number of APs are needed to cover users in our approach. The number of TAPs and SAPs of SS looks constant as the AP density varies.

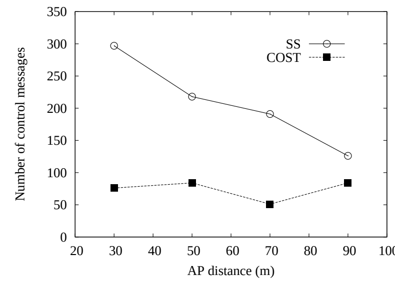
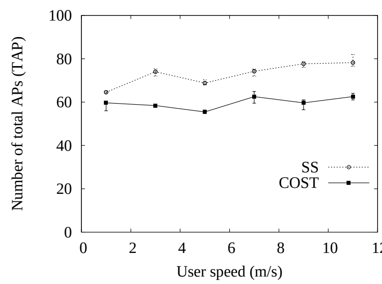


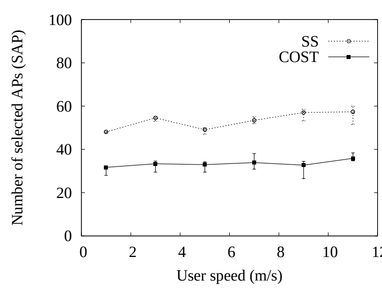
Fig. 15. The number of control messages with respect to the AP density(AP distance).

Figure 15 shows the number of control messages to maintain the broadcast tree. In the SS, the number of control messages increases as the AP density increases, since a user will change its an associated AP even with small movement. However, the number of control messages of COST decreases as the AP density increases, since it keeps the currently selected AP even with large movement compared to SA. The number of control message of COST have 74.4% lesser than that of SS.

E. User speed



(a) TAP



(b) SAP

Fig. 16. The number of APs in tree with respect to the user speed (m/s). Number of users are 70.

The movement of users causes changes in user-AP association. However, active movement of user can increases the chance of selecting a new AP and removing an old AP for user. Figure 16 shows the number of TAPs and SAPs versus the user speed. We can observe the small change of the number of TAPs and SAPs as user speed increases. Figure 17 shows that the number of control message increases as the user speed increases. The COST has 58.1% lesser control message than

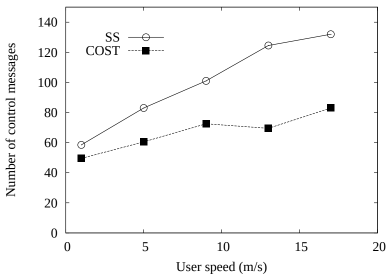
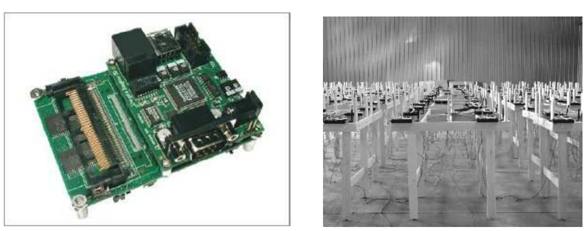


Fig. 17. The number of control messages with respect to the user speed (m/s). Number of users are 70.

that of SS. The increase of control messages represents the increase of tree change.

VI. Testbed Evaluation

In this section we present the results obtained by implementing and testing our protocol on an indoor testbed of 180 Stargate (Figure 18) nodes. The nodes are arranged in a 15×12 grid, with an inter-node separation of about 3 feet. The Stargate is a 32-bit hardware platform running Linux, which has a PCMCIA wireless interface and an Ethernet interface. An IEEE 802.11b card is used in each node for testing our protocols. The Ethernet interface of all the Stargates are connected together through hubs and switches to a central server, which is used to control the experiments. The Ethernet network is used to load programs, start-stop experiments, and monitor them, while the nodes use their wireless interface to run the protocols.



(a) Stargate node (b) Indoor testbed

Fig. 18. A Stargate node and Testbed.

Alternate nodes in alternate rows are made Access Points (AP) and the rest of the nodes are made users (U). With this configuration, the network had 52 Access Points (AP) and 128 Users (U). The range of the 802.11 wireless cards can be dynamically configured by changing the power level of the card and also by enforcing a logical topology on the Stargates. For our experiments we varied the logical range from 7 feet to 19 feet, in steps of 3 feet and studied the total number of APs in the tree. The protocols were developed and tested using a software system known as Emstar [24].

Figure 19 shows the comparison of the size of the tree for the traditional Signal Strength based approach and our distributed cost based approach. We observe that as we increase the range of all the nodes the number of nodes in the tree decreases for our approach. With increased range, each user has more APs to choose from. Our distributed approach attempts at minimizing the number of selected APs, which is clearly seen in the figure. In SS, increasing the transmission range increases the choices for each user, but the best AP (closest and with highest signal strength) does not change. Hence, we observe that our approach can reduce the size of the tree and the mesh network traffic by up to 70% in the tested scenarios.

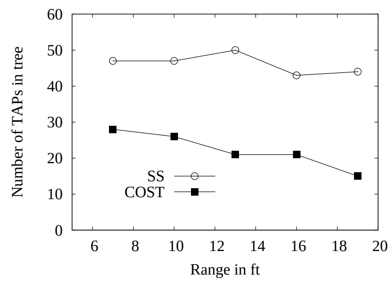


Fig. 19. The number of TAPs with 52 APs and 128 users.

Figure 20 compares the delivery ratio obtained in SS and the cost based approach. We can observe that the delivery ratio obtained in the cost based approach is upto 76% higher than that of the signal strength based approach. Given the same interference pattern in the network, the increased delivery ratio of the cost based approach could be attributed to reduced collision because of lesser number of APs in the tree formed using cost based approach in comparison to SS. Its critical to note that on an average, SS achieves a delivery ratio of 50% which is too low for the reconstruction of the video file that is being transmitted. In contrast, the cost based approach on an average achieves a delivery ratio of 80%. The decreasing trend in the delivery ratio for SS with increasing range is because of unreliable long links that are formed at the backbone. This effect although observed for the cost based approach is offset by the benefits of the reduced tree size

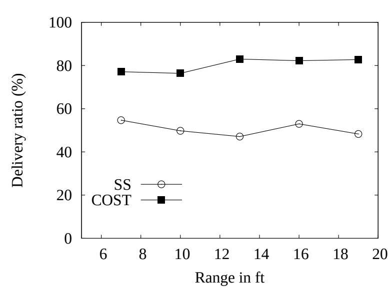


Fig. 20. Delivery ratio with respect to range.

Figure 21 plots the normalized load for both SS and cost based approaches. We measure load in terms of the total number of packet transmissions. The Normalized load is the load of the network normalized over the delivery ratio. As it can be observed, the normalized load for the cost based approach goes down as the range increases. This is because lesser number of packets are being broadcast in the network and more packets are being received due to decreased collision. In SS, the network load goes up with increase in range due increased collision and reduced delivery ratio.

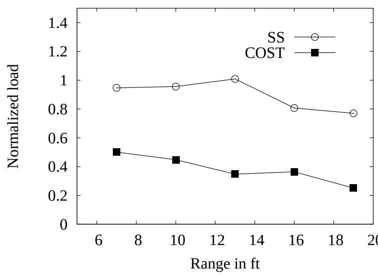


Fig. 21. Normalized Load with respect to range

VII. Related Work

In this section, we outline related work in the areas of mesh networking, controlled association in 802.11 networks, and sub-structure computation in ad-hoc networks.

Providing connectivity to large communities using wireless back-haul networks, also known as mesh networks, has lately received a lot of attention [1], [2]. Several companies including Mesh-networks, Firetide, Strix, and BelAir Networks have various products based on the concept of mesh networking.

In [25], the authors present a software based solution called Multinet, that facilitates simultaneous connections to multiple networks by virtualizing a single wireless card. In conjunction with the idea provided in Multinet, our solution consisting of multiple wireless cards can be modified to a solution that uses a single wireless card.

In [3], authors have explored the problem of fairness across flows between the APs in a Mesh Network. The APs are referred to as Transit Access Points (TAPS). The authors propose a fairness model and an approach at layer 2 for providing fairness. The critical relationship between fairness and aggregate throughput is captured by their reference model. This work is orthogonal to our work as it only pertains to unicast traffic.

The problem of channel assignment and multi-radio operation has lately received attention from Meshdynamics Inc. and also reported in [6]. In [6], authors propose a multi-channel wireless mesh network architecture, called Hyacinth, that equips each mesh network node with multiple 802.11 network interface cards (NICs). Authors propose distributed local information based algorithms for channel assignment and routing, and show that using 2 NICs the network throughput can be improved by a factor of 6 or 7.

The problem of unicast reliability in mesh networks is addressed in [5]. The authors consider the problem of maximizing the reliability of connections in mesh networks against multi-link failure scenarios.

In 802.11 networks user nodes often use the signal strength as the key metric in selecting the AP. Recent work [16] has explored the idea of association control to balance the network load and provide max-min fairness among users. The authors prove that balancing the network load is equivalent to achieving the max-min fairness. Although our objective is different from [16], in the presence of unicast flows load-balancing and fairness will make the MESH-ST problem more challenging.

The idea of constructing backbones or sub-structures in ad-hoc networks to limit the number of transmissions has been explored by several protocols. The concept of MCDS has been used in designing various routing protocols for ad-hoc networks [26], [27]. The importance of constructing and maintaining an MCDS in an ad-hoc network has spurred research on finding better approximation algorithms [28], [29].

VIII. Conclusion

In this paper we studied a novel technique for association that reduces the load for broadcast traffic in mesh-networks. We propose the concept of multi-association, where the AP for unicast traffic and the AP for broadcast traffic are independently chosen by exploiting multiple coverages that are typical in mesh networks. We propose a cost metric based on ETT and the number of nodes in range of the APs, that is advertised in the beacons from the APs. Users periodically scan and associate with the AP with the lowest cost metric. Using extensive simulations and experiments on an indoor testbed of 180 802.11b devices we evaluated the performance of our approach. We observed that the load can be reduced and the performance of both unicast and broadcast data services can be significantly improved using our approach.

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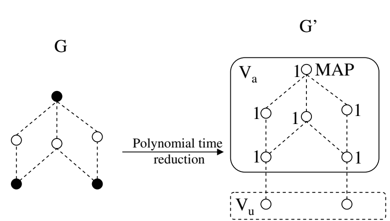
APPENDIX. A

Theorem 1: [Lower bound] MESH-ST is at least as difficult as ST.

Proof: We present a reduction from an arbitrary instance of the ST problem to an instance of the MESH-ST problem. Let G be the graph with a set of required nodes R in the ST problem. We construct the new graph G' by modifying G as follows. Let $MAP \in R$ be an arbitrary required node. Create a new node v' for each required node v in R except the MAP. Join v and v' with an edge. All the newly added nodes constitute V_u and the old nodes constitute V_a. The weight of all nodes in V_a is unity. We claim that when the leaf edges are deleted from the solution Z' to MESH-ST(G'), we obtain a solution Z to ST(G).



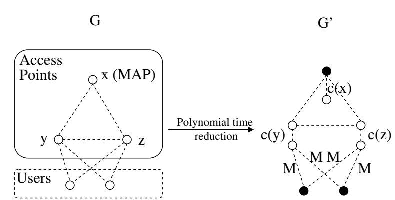
(a) ST(G) (b) MESH-ST(G')

Fig. 22. Reduction from ST to MESH-ST. The highlighted nodes are the required nodes for the Steiner tree problem.

It is easy to see that by removing the leaf edges from a tree, we still obtain a tree. We now prove that if there exists a solution to ST(G) that is smaller than Z, then it leads to a contradiction, thus completing the proof. The Steiner tree does not include the cost of any nodes. But Z' includes the cost of $|V_u|$ nodes. Therefore, $Cost_{Steiner}(Z) = Cost_{MESH-ST}(Z') - |V_u|$. Let us assume that there exists a solution Y to ST(G), such that $Cost_{Steiner}(Y) < Cost_{Steiner}(Z)$. By augmenting Y with the edges connecting the nodes in V_u, we obtain a tree in G' whose $Cost_{MESH-ST}$ is $Cost_{Steiner}(Y) + |V_u| < Cost_{Steiner}(Z) + |V_u| = Cost_{MESH-ST}(Z')$. As the new tree's cost is lower than $Cost_{MESH-ST}(Z')$, it contradicts the optimality of Z'. **QED.**

Theorem 2: [Upper bound] MESH-ST is at most as difficult as ST.

Proof: We present a reduction from an arbitrary instance of the MESH-ST problem to an instance of the ST problem. Let G be the graph with an instance of the MESH-ST problem. We split each node $v \in V_a$ into v_1 and v_2. All edges incident from V_u on v are now incident on v_2 and the other edges are incident on v_1. A new edge is added between v_1 and v_2 with a cost equal to $c(v)$. The weight of all the edges incident on V_u are M, where M is a very large number (larger than the sum of weights of all AP-AP edges). The MAP and the nodes in V_u are the required nodes in the new graph G'. We claim that the solution Z' to ST(G') represents a solution to MESH-ST(G). The corresponding solution Z for MESH-ST(G) excludes the newly added links.



(a) MESH-ST(G) (b) ST(G')

Fig. 23. Reduction from MESH-ST to ST. The highlighted nodes are the required nodes for the Steiner tree problem.

Note that due to the high cost on the edges to the required nodes in $ST(G')$, only the minimum number of such edges will be selected in Z'. This guarantees that all nodes in V_u will be leaf nodes in Z'. We now prove that if there exists a solution to MESH-ST(G) that is smaller than Z, then it leads to a contradiction, thus completing the proof. As $Cost_{MESH-ST}$ does not include the cost of the leaf edges, $Cost_{MESH-ST}(Z) = Cost_{ST}(Z') - M|V_u|$. Let us assume that there exists a solution Y to MESH-ST(G), such that $Cost_{MESH-ST}(Y) < Cost_{MESH-ST}(Z)$. By adding the corresponding newly added links to Y, we get a tree in G' with a cost of $Cost_{MESH-ST}(Y) + M|V_u| < Cost_{MESH-ST}(Z) + M|V_u| = Cost_{ST}(Z')$. As the new tree's cost is lower than $Cost_{ST}(Z')$, it contradicts the optimality of Z'. **QED.**