Optimizing broadcast load in Mesh Networks using Dual-Association

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Abstract— **This paper systematically studies the problem of optimizing the broadcast traffic load in a mesh network. Traditionally, association is based on the strongest signal strength. We propose the concept of multi-association, where the access point (AP) for unicast traffic and the AP for broadcast traffic are independently chosen by exploiting multiple coverages that are typical in mesh networks. Our focus in this paper is on the problem of distributively selecting the AP for broadcast traffic for reducing the load in the mesh network. We propose a novel metric called *normalized-cost* that is advertised in the beacons from APs. We show that by greedily associating with the AP with minimum normalized cost, the broadcast traffic load can be reduced. The proposed approach has 25.4% more APs for broadcast traffic than the optimal number of APs computed by ILP. Simulation results show that the proposed approach reduces the number of APs that handle the broadcast traffic by up to a factor of 6 in comparison to the traditional signal strength based association. This results in 43.7% lower control messages and 54.9% lower broadcast data transmission in backbone network, leading to 21% higher packet delivery ratio.**

I. INTRODUCTION

The last few years have witnessed a tremendous growth in the WLAN market in homes, enterprises and public hotspots. Declining costs of access points (APs), WLAN NICs, and increased support for high bandwidth, has succeeded in enticing the common user. However, the deployment cost of a network of APs is often dominated by the cost of laying cables[1] to provide wired connectivity between the APs. To reduce the deployment cost and design easily deployable wireless access networks, alternate architectures involving wireless-only connectivity between the APs have recently emerged. The terms wireless back-haul networks and Mesh-networks [1] are often used to refer to such networks. A mesh-network has lesser routing overhead than a typical ad hoc network, since the APs are static. Moreover, mesh-networks can make use of channel diversity at last hop, which can lead to improved throughput in comparison to the ad hoc network, which operates on a single channel. Mesh-networks are already operational in several cities including Las Vegas, Philadelphia, 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.

Both unicast and broadcast services need to be supported in wireless Mesh-networks. The need for supporting efficient broadcast services in the access network has become increasingly important with the emergence of various applications like real time multi-party conference, scientific data visualization, and presentation broadcasting at conferences and lectures. Broadcast services can also be used to disseminate local news, visitor's information, TV channels, or other multimedia information.

In current mesh-networks, users associate with the AP providing 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 an alternate solution (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, thus resulting in reduction of broadcast traffic in the mesh. As broadcast packets are always transmitted at the lowest data rate in IEEE 802.11 protocols, the data rate of the broadcast traffic is the same in the two cases. The users and APs need to switch between unicast and broadcast modes at fixed intervals. Time-synchronization for such purposes can be achieved by protocols like NTP. Reduction of mesh traffic enables support for higher quality multimedia data and higher bandwidth for unicast traffic, resulting in increased revenue for the service provider. Deployments in mesh networks typically provide redundant coverage that enables such optimizations. The APs need to be in range of each other for communicating among themselves, and it may result in a highly overlapping coverage reasons. Moreover, a dense deployment of the APs is necessary for supporting more users and providing higher bandwidth. We thus exploit this overlap in coverage as shown in the example above, which also forms the basis of the research presented in this paper.

In this paper we systematically study the problem of optimizing the broadcast traffic load in the mesh using the novel concept of multi-association, where users maintain multiple

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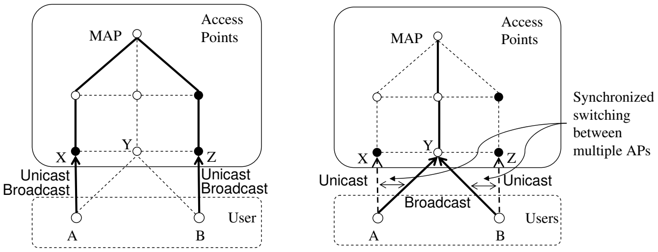
[1] Although Ethernet is inexpensive there is often non-trivial cost of labor, planning, and leasing associated with it especially for large WLAN deployments.



(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.

associations for unicast and broadcast traffic. For unicast, users associate with the AP providing the best signal strength, but other metrics such as unicast traffic load [2] can also be used to select the AP. For reducing the broadcast traffic load, users need to select the AP for broadcast services independently of the AP selected for unicast traffic. These broadcast APs need to connect to the AP with the backbone access (Main AP or MAP) using a sub-graph which can be a tree or a more redundant structure. We choose to connect the selected APs to the MAP using a tree, for purposes of simplicity. For the tree construction and maintenance part of the protocol, any tree based ad-hoc multicasting protocol can be used, since all APs work in single channel. As it is not a contribution of our paper, we do not discuss it further.

Our focus is on the problem of distributively selecting the broadcast AP for association. For efficient selection of broadcast APs, we propose a metric called the *normalized cost*, that is periodically advertised by each AP. Users greedily select the AP with the lowest normalized cost for broadcast services. The normalized cost metric is the cost of joining the current tree normalized with the number of users that will benefit from selecting the AP as a broadcast AP. Our contributions in this paper are as follows:

- We propose the multi-association concept and a novel metric that optimizes the broadcast traffic load in the mesh.
- We simulate the proposed approach in ns-2 [3] and compare it with the two other metrics for the selection of the broadcast AP. We observe that our approach reduces the number of APs in the broadcast tree by up to a factor of 6 in comparison to the traditional signal strength approach, resulting in reduced broadcast traffic load in the mesh.

The rest of the paper is organized as follows. Section II defines the problem, the notations, and the terminology used in the paper. The metric to optimize for efficient selection of the broadcast AP is discussed in Section III. The distributed approach is described in detail in Section IV. Section V presents a detailed evaluation of our approach and comparison with other approaches using simulations. Section VI summarizes the related work. In Section VII, we present a discussion of some important extensions and facets of the problem that we have not addressed in this paper and Section VIII concludes the paper.

II. TERMINOLOGY AND PROBLEM DEFINITION

We define here some graph theoretic notations and terms used in the rest of the paper. Following the notation used in [4], we use $V(G)$ to denote the set of nodes and $E(G)$ to denote the set of edges for a graph G. For a node v, $N(v)$ represents the set of neighbors of v, and $N[v]$ represents the set of neighbors including v itself. Hence $N[v] = N(v) \cup \{v\}$. We summarize some known graph theoretic terms:

- **Dominating Set (DS):** A set of nodes $S \subseteq V$, such that all nodes not in S have an edge connecting them to a node in S. The nodes in S are called dominators.
- **Connected Dominating Set (CDS):** A DS $S \subseteq V$, such that the induced subgraph of S in G, denoted by $G[S]$ is connected.
- **Minimum CDS (MCDS):** The smallest cardinality CDS.

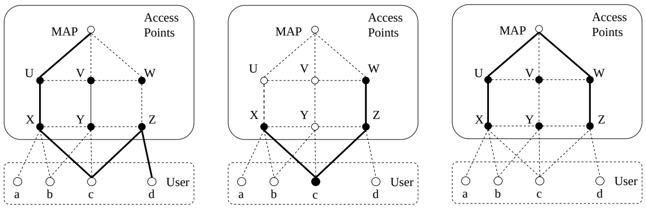
We represent the connectivity between the users and the access points using a graph $G = (V, E)$, where V (same as $V(G)$) is the set of nodes (users and access points) and E (same as $E(G)$) is the set of edges. E consists of edges connecting users to access points in range, and between access points 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. The problem addressed in this paper is to find the smallest tree connecting the MAP to a subset of APs such that all users will have coverage from some AP in the computed tree. This problem is exactly the MXCDS problem defined below.

- **Exclusive Dominating Set (XDS):** Given a graph G with two vertex partitions V_a and $V_u = V(G) - V_a$, and a node $MAP \in V_a$, XDS is a subset of V_a which includes the MAP such that each vertex in V_u has a neighbor in the XDS.
- **Exclusive Connected Dominating Set (XCDS):** An XDS $S \subseteq V_a$, such that the induced subgraph of S in G, denoted by $G[S]$ is connected.
- **Minimum XCDS (MXCDS):** The smallest XCDS.

The analysis, and algorithms presented in this paper can be easily extended to the generalized version where multiple APs have backbone connection. We can transform the problem with multiple MAPs to a problem with single MAP by *fusing* the nodes corresponding to the MAPs. For purpose of simplicity, in the rest of the paper we assume that there is only a single MAP.

Although the MXCDS problem has similarities with the Steiner tree and the MCDS problems, there are clear differences. The Steiner tree problem does not include the notion of two sets (The AP-Set and the User-Set). Thus as shown in Figure 2 (a), the solution to the Steiner tree problem with the MAP and the user nodes as the terminal nodes, may include APs as well as users. Hence, our problem cannot be modeled as a Steiner tree problem. As shown in Figure 2 (b), the solution to the MCDS problem may also include the nodes from the user set and may not include the MAP. Hence, the notion of MCDS does not correctly model our problem. Figure 2 (c) shows the MXCDS which consists of the minimum number of nodes from the APs that cover all the users, such that the selected nodes include the MAP and induce a connected subgraph.

We define the selected APs (SAP) as the APs with associated users and the gateway APs (GAP) as the APs that do not have associated users but which provide connectivity between the MAP and the SAPs. Dominating APs are all APs in a tree consisting of SAPs and GAPs. In Figure 2 (c), X and Z are SAPs and U and W are GAP.



(a) Steiner Tree (b) MCDS (c) MXCDS

Fig. 2. Steiner Tree, MCDS, and MXCDS. Although technically MCDS and MXCDS are set of vertices, the links providing connectivity between them are also shown highlighted.

III. OPTIMIZATION METRIC FOR THE SUB-STRUCTURE

In this section, we derive the metric to optimize the construction of the sub-structure. Let us assume that there are n APs selected in the solution to MXCDS. The MAP is one of those APs. Let the number of leaves in the tree joining them be n_l, and the number of APs with associated users in their cells be n_u. Note that $n_u \geq n_l$ as all APs that are leaves in the tree, must have associated users in their cells. There are two choices for communication between the APs: unicast or local broadcast. However, the communication on the last hop from the AP to its associated users is assumed to be a local broadcast transmission. Using unicast on the last hop for distributing broadcast data may increase reliability but at the cost of higher bandwidth requirement.

The bottleneck in this architecture is the channel in the AP network (AP-net). In order to precisely derive the criteria to optimize, we first compute the number of transmissions that occur in the AP-net channel. This reflects the amount of load on the AP-net that directly impacts the broadcast throughput. Note that for reliable communication there may be recovery traffic and retransmissions which are ignored in this discussion.

We analyze the three different channel configuration cases separately. The analysis is summarized in Table I.

- *Uni-channel:* All users and APs are communicating in the same channel. In the case of unicast in the AP-net, there will be a transmission on all links on the tree. In addition, all APs with associated users in their cells will require a total of n_u additional transmissions. So the total number of transmissions in the channel is $n-1+n_u$. For broadcast transmissions in the AP-net, the total number of transmissions will be n.

TABLE I

OPTIMIZATION FUNCTION: THE NUMBER OF TRANSMISSIONS THAT OCCUR IN AP-NET CHANNEL.

	AP-AP unicast	AP-AP broadcast
Uni-channel	$n-1+n_u$	n
Dual-channel	$n-1$	$n-n_l$
Multi-channel	$n-1$	$n-n_l$

- *Dual-channel:* This configuration assumes that APs are equipped with dual interfaces. The primary interface is dedicated for communication with other APs. The secondary interface is configured to a secondary channel for communication with users in its cell. All users have a single interface configured to the same secondary channel. Since transmissions to the users are in a different channel, we only need to count the transmissions within the AP-net. For AP-AP unicast communication, there will be $n-1$ transmissions over the links of the tree and for broadcast communication, there will be $n-n_l$ transmissions by the internal (non-leaf) nodes of the tree.
- *Multi-channel:* This is like the bi-channel scenario, but nearby interfering cells are assumed to have different secondary channels. The number of transmissions in the AP-net is similar to Dual-channel case.

For the case of unicast transmissions in the AP-net, reducing the total number of nodes in the tree n is critical. In addition, for the uni-channel scenario, the number of APs that have associated users, n_u needs to be minimized too.

Broadcast transmissions in the AP-net require optimizing n for the uni-channel scenario, but for the other two scenarios, the number of internal nodes in the tree or $n-n_l$ is the criteria to optimize.

Reliability in the AP-net is extremely critical for high delivery ratio of broadcast data. We therefore do not consider the case of broadcast transmissions in the AP-net. We note that it is possible to enhance broadcast transmissions in the AP-net with recovery and reliability mechanisms. In the rest of the paper we assume that the transmissions in the AP-net is unicast and the transmissions from the AP to the users are broadcast. Although $n-1$ and $n-1+n_u$ are two different optimization functions, we note that n is larger than n_u, and assume that optimizing n will also optimize n_u. For simplicity of the protocol design, in the rest of the paper we assume n to be the only function to be optimized for all the three channel configurations. We therefore propose a single distributed solution for the three configurations.

IV. DISTRIBUTED APPROACH

In this section, we propose our distributed solution: *normalized cost based association for computing the dissemination structure (NCADS)*. Distributed computation of the data dissemination tree requires smart association by the users followed by efficient tree computation and maintenance involving the selected broadcast APs and the MAP. For the latter we use known techniques for tree computation and maintenance based on ad-hoc multicast protocols such as MAODV (Multicast Adhoc On-demand Distance Vector). Our focus is on the former problem of associating with APs in such a way that it will result in an efficient broadcast tree. The goal of the distributed protocol is threefold:

- The computed sub-structure must minimize the number of selected APs.
- The number of overhead packets generated by our approach should be minimized.
- The dissemination sub-structure must adapt quickly for mobile users.

Our main aim is to optimize the number of APs selected by making the user's choice effective. To this end, we use a greedy approach motivated by a greedy solution to the MCDS problem [4]. We use the following observations to optimize the total number of selected APs that handle the broadcast traffic:

- The APs that are already a part of the dissemination substructure should be given preference by users looking for APs to associate with. This will reduce the number of overhead messages in constructing the sub-structure.
- The APs that are in range of a large number of users have a higher potential for serving a large number of users. So APs with more in-range users, must be preferred.

Our proposed approach requires each AP to advertise a metric called *normalized cost*, that is defined later in the section. Among all APs that are in-range, each user selects the one with the lowest normalized cost for broadcast communications. In the remaining section, we present details on the metric, the process of selecting the AP based on the metric, multi-association and AP switching, mechanisms for handling user mobility, and extensions for handling limits on number of users per AP.

A. Metric computation

Based on the above discussion, we derive the following cost metric - normalized cost. Normalized cost of an AP that provides the broadcast service is defined as the cost incurred per user for the addition of that AP to the tree and is represented as

$$\textit{Normalized Cost of AP} = \frac{H}{N}. \tag{1}$$

where H represents the number of intermediate APs that need to join the sub-structure to connect the AP with the already existing tree using the shortest path between them. N represents the potential number of users that are benefiting or that may benefit if this AP joins the tree. Ideally N includes all the users that are in range of the APs on the shortest path to the current tree. A naive approach of adding up the number of users in range of each AP on the path will result in overcounting due to overlapping coverage regions of adjacent APs. So, in this paper we assume that N corresponds only to the users who are benefited by the AP under consideration.

Each access point computes its Normalized-Cost and sends out beacons to the users advertising its Normalized-Cost. Each user selects the AP that advertises the least Normalized-Cost. We have compared Normalized-Cost metric with the following two metrics as part of performance evaluation:

- *Signal-Strength:* Among the APs that are in range of the user, the one with the strongest signal is chosen for association by the user.
- *Hop-Count:* This metric is closer to our Normalized-Cost metric. The users select the AP which has the least number of hops to the existing tree.

In Section V, we compare our metric with the above two commonly used metrics and establish that Normalized-Cost metric performs better than the signal strength and the Hop Count metrics.

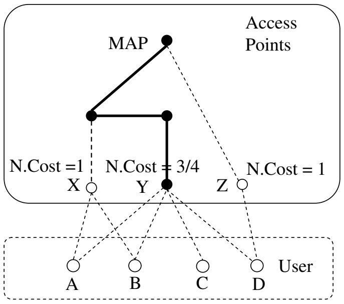


Fig. 3. An Example: The highlighted links and nodes carry the broadcast traffic in the mesh for the Normalized-Cost metric.

Assume that the current tree only includes the MAP. To illustrate the significance of the Normalized-Cost metric, consider the network shown in Figure 3 having 6 APs and 4 users. We compare the number of APs chosen when each of the three metrics - Signal-Strength, Hop-Count and Normalized-Cost are considered by the users to choose from the set of access points it can hear. When Signal-Strength is considered, A would choose X; B and C would choose Y; and D would choose Z. Hence, all the three access points need to be a part of the tree for this scenario. When the Hop-Count is used as a metric, A chooses X because X has lower cost (2) compared to Y (3). Similarly B chooses X, D chooses Z, and C chooses Y as that is the only access point it can hear. Hence, again, 3 access points need to be a part of the tree for this scheme to work. Consider the Normalized-Cost based scheme where the cost of X is $2/2 = 1$, Y is $3/4$ and Z is $1/1 = 1$. Thus, all users select Y for association and hence only one AP needs to join the tree. *We thus observe that in comparison to Hop-Count, the Normalized-Cost based association algorithm has higher chances of convergence.* This significantly reduces the amount of traffic in the AP backbone and helps improve the throughput for unicast traffic.

B. Metric based AP selection

For the broadcast traffic, the users associate with the AP that advertises the least normalized cost. The user either performs active scanning or passive scanning to determine the best AP for association.

Active scanning is a process in which the wireless node cycles through all the channels and sends a "Probe Request" to all APs within its range and waits for a "Probe ACK" from these Access points within a time period. In *Passive scanning*, the user cycles through all the channels and listens to beacons from APs that are within its range in that channel. Passive scanning is useful in the uni-channel and dual-channel scenarios, as the APs advertise in a fixed channel.

When the network starts up, the APs learn about the number of in-range broadcast users when the users report to them. Hence, the users start active scanning and the broadcast users send "Probe Request" with a broadcast service ID. Unicast-only users do not specify the broadcast service ID in their "Probe Request". On reception of the "Probe Request" message from the users, APs record the number of users in their range who are participating in the broadcast service and send out beacons advertising their Normalized-Costs. The computation of the Normalized-Cost requires H, which is learned using a DSDV like protocol in the AP-net. The user selects the AP with the least Normalized cost and sends "Association message" to the selected AP. The AP updates its associated user list on receiving the "Association message". The association is then maintained by periodic "Association update" messages.

C. Multi-Association and AP switching

As per the normalized cost based algorithm, the users do not necessarily select the AP providing the best signal for its broadcast service. But selecting the AP providing the best signal strength is advantageous for unicast traffic as that would increase the unicast throughput. Optimization of other metrics for unicast traffic can be considered, but it is orthogonal to our research. Hence, it becomes necessary to maintain two associations - one with the AP providing the best signal strength for the unicast traffic and another with the AP advertising the least Normalized-Cost for the broadcast session. All APs and users in the mesh network are assumed to be synchronized. The users switch in time between the best signal AP and the least Normalized-Cost AP during the unicast and the broadcast sessions respectively.

The cycle length and the broadcast period can be configured by the network provider and can be advertised in the beacons. The AP maintains 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. The APs transmit the broadcast packets from its broadcast queue. During the broadcast session, the broadcast packets from the APs have higher priority in comparison to the unicast packets. If there are no broadcast packets to be sent during the broadcast session, then the AP starts sending unicast packets with normal priority. This ensures that broadcast packets are transmitted with high priority in the broadcast period without changing the existing IEEE 802.11 protocol. After the broadcast session, the users switch back to the AP providing the best signal for its unicast flows and during this session, the broadcast packets are held in the queue.

All APs and users are synchronized to switch between broadcast and unicast services at the same time. If an AP or a user is still in the process of transmitting a unicast packet at the beginning of the broadcast session, they wait till the unicast transmission is complete and then switch sessions. Unicast-only users and users who associate with the same AP for both unicast and broadcast traffic will continue to stay with the same AP.

D. Handling user mobility

When a user moves in or out of the range of an AP, the APs update their user tables and send out the modified cost values in their subsequent beacons. In the uni-channel and dual channel cases, each user sends regular "Association Update" message to the AP it has been associated with and waits for an "Association Update" response from the AP within a given time. If it times out, the user determines that it has moved out of the range of the associated AP and hence starts active scanning by sending out "Probe Request" messages. The new APs in the user's range recalculate their number of users they currently support and start advertising the new cost. In the multi-channel scenario, if a mobile user loses its association with the AP and receives no acknowledgment for its association update message, the user performs active scanning in all the available channels and selects the AP with the least cost.

E. 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 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 Request" message with a NACK, forcing the user to associate with another AP. Another way will be to advertise progressively higher costs as 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).

V. PERFORMANCE ANALYSIS

In this section we present a thorough comparison of the NCADS protocol using simulations in the Network Simulator ns2 [3]. We compare its performance with two other association strategies: signal strength based association (SSA) and hop count based association (see Section IV-A for their description). The metrics of evaluation are: the number of APs in the subtree, the number of control messages to compute and maintain the broadcast sub-tree (i.e. 'JOIN', 'PRUNE', and etc.), the number of data packets transmitted in the subtree, and the number of unique data packets received by the users. Our study is mostly based on the multi-channel configuration. The highlights of our evaluation for the seven components of our study are as follows:

1) *User density:* We observe that with increasing user density the number of dominating APs in NCADS increases. However, NCADS has the lowest number of dominating APs and the lowest number of control messages in all user density. For the case of 50 users, the number of dominating APs in NCADS is 33% lower than SSA.
2) *AP density:* With increasing AP density, the number of dominating APs in NCADS decreases. When the separation between APs in the grid becomes 50m or larger, on an average NCADS performs 45.03% better than the SSA in terms of the number of dominating APs. The number of dominating APs chosen based on NCADS is one-fourth of the number of dominating APs chosen by the SSA, for an inter-AP separation of 30m.
3) *Delivery ratio of packets at the users:* NCADS receives 21% more packets in comparison to SSA at a packet transmission rate of 100 packets/sec (800 Kbps).
4) *Three channel configurations:* When there is traffic in the network, the multi-channel configuration typically performs the best but the other two configurations have higher packet delivery ratio due to multiple coverage.
5) *User speed:* NCADS has lowest number of dominating APs at all speeds. In terms of the number of APs, NCADS performs 30.74% better than the SSA at a maximum user speed of 15 m/sec.
6) *Impact on unicast:* When NCADS is used for broadcast association, the unicast peer-to-peer TCP throughput goes up by 18.7% on an average compared to that achieved when SSA was used for broadcast.
7) *Optimality:* The number of dominating APs and selected APs (SAPs) of NCADS are 29.8% and 25.4% more than the optimal tree computed by ILP (Integer Linear Programming), respectively.

For our simulations we use a grid topology of 10x10 APs and 100 users. The distance between neighboring APs, D, is 80m and radio propagation range of AP, R, 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 8 m/s with 2 sec pause time for the random way-point model for all experiments, unless mentioned otherwise. The users associate with APs using active scanning. The unicast data rate is 11 Mbps and the broadcast data rate is set to 1 Mbps. We used the length of AP switching cycle as 150ms and broadcast period as 50ms.

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 local subnet interface. The neighboring APs are configured in such a way that they are on different channels on the local subnet interface. 13 channels are assigned to the local subnet interfaces of APs. In the uni-channel scenario, APs and users have one wireless interface and they share a single channel. In a dual channel scenario, the AP has two wireless interfaces and the user has a single wireless interface. Priority queuing is used to give higher priority to the control packets when compared to the data packets.

A. *User Density*

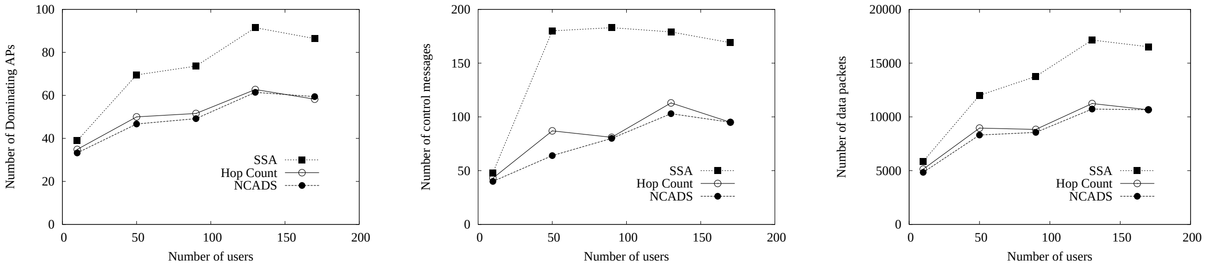
Figure 4 (a) shows that the number of dominating APs with respect to the number of users. As the number of users increases, the number of dominating APs also increases. We observe that NCADS has the lowest number of dominating APs. For the case of 50 users, the number of dominating APs is 33% lower than the SSA. Figure 4 (b) shows the number of control messages sent by APs in the broadcast subtree. The control messages include all the tree management messages. NCADS has the lowest control packet overhead (43.7% lower than the SSA when the number of users is 170), since NCADS has lowest number of APs in the broadcast tree. Figure 4 (c) shows the number of data packet transmissions in the tree. As the number of users increases, the size of the tree increases. This increases the data traffic in the tree. However, NCADS has 54.9% lower number of data packet transmissions than that of SSA. Hence, NCADS generates lower backbone traffic load.

Hop count algorithm has better performance than the SSA in all scenario and has similar performance with respect to NCADS (lower performance within 10%). This could be attributed to the nearly uniform distribution of the users in the network. The Impact of N on NCADS is not pronounced when compared to the Hop count H. However, in a highly random distribution of users, the NCADS is expected to have higher chances of convergence.

B. *AP Density*

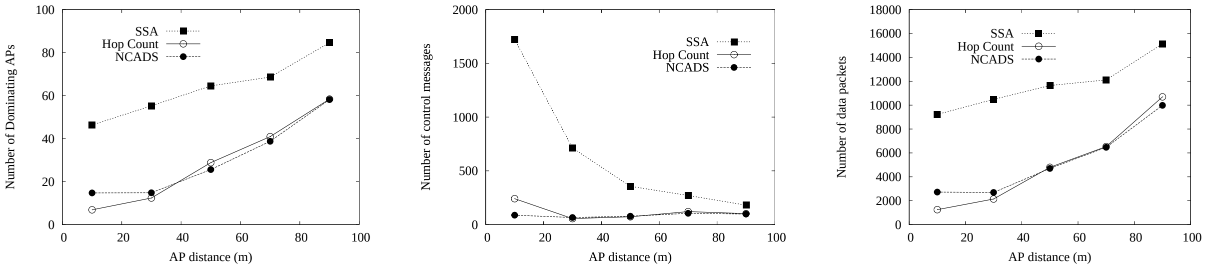
Figure 5 (a) shows the number of dominating APs versus the separation of adjacent APs. As the density of APs decreases, the number of dominating nodes increases. In the denser AP topology (i.e., AP distance is 10m), hop count algorithm has the best performance, since many users are within the range of the MAP. Hence, they can associate to the MAP directly. NCADS has fewer dominating APs when the distance between neighboring APs becomes 50 m or larger and at an average performs 45.03% better than the SSA.

Figure 5 (b) represents the number of control messages sent by APs. In dense case (i.e., AP distance is 10m), the SSA has a very high number of control message overhead compared to others, since users change association very frequently. The total number of data packets forwarded on the broadcast tree is shown in Figure 5 (c). As the distance between adjacent APs increases, the number of data transmissions also increases.



(a) (b) (c)

Fig. 4. Impact of user density on (a) the number of dominating APs, (b) the number of control message, and (c) amount of data forwarded on the broadcast tree.



(a) (b) (c)

Fig. 5. Impact of AP density on (a) the number of dominating APs, (b) the number of control message, and (c) amount of data forwarded on the broadcast tree.

NCADS performs 60.3% better than the SSA beyond an AP separation of 50 m.

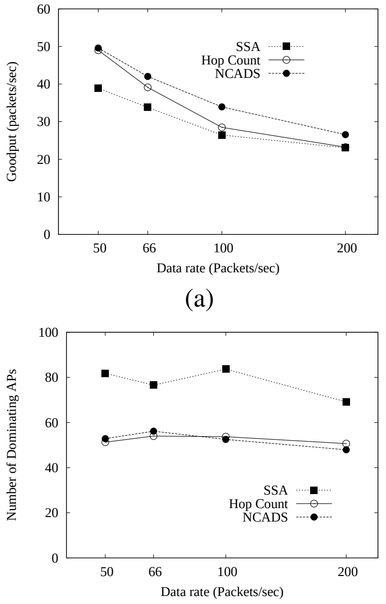
C. Delivery Ratio

Figure 6 (a) shows the number of successfully received broadcast data packets versus users with varying data rates. The data packet size is 1024 bytes. As the data rate increases, the delivery ratio goes down, since the number of packet loss rate increases. However, NCADS performs 21% better than the SSA at the rate of 100 packets/sec (800 Kbps). Figure 6 (b) shows that the number of dominating APs is stable across different data rates as the control messages have higher priority in the interface queue than the data packets.

D. Channel Configuration

From Figure 7 (a), we can observe that the number of dominating APs in the multi channel scenario is 31.9% lesser than the single channel case and 27.8% lesser than the dual channel case for 70 users. The reason is that in the single and dual channel cases, there are higher contention of control messages and scanning messages. This leads to loss of more messages and thus incorrect metric computation, which results in increased number of dominating APs.

Figure 7 (b) shows the total number of received data packets of three channel models of NCADS. In this scenario, the MAP sends 1024 byte packets every 5ms. In single channel and dual channel case, users can hear packets from several APs around it. Thus, if the neighboring APs of a user are part of the dominating AP, the user can receive a data packet multiple times. This leads to a better goodput for uni-channel and dual-channel configurations.



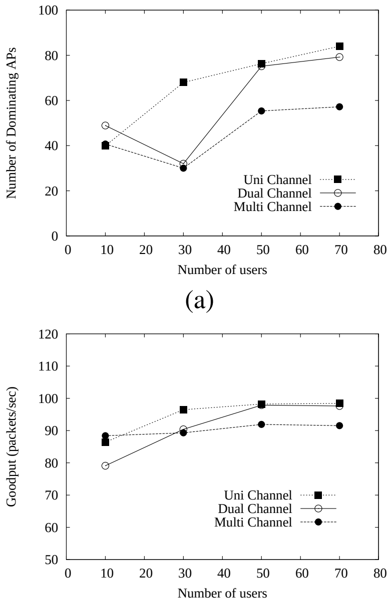
(a)

(b)

Fig. 6. Impact of data rate on (a) the number received broadcast packets and (b) the number of dominating APs.

E. Impact of user speed

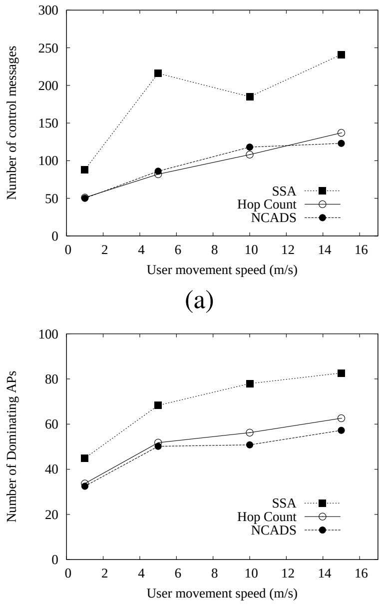
The movement of users causes changes in user-AP association. With higher speeds, users will be frequently changing associations, resulting in more control messages. Figure 8 (a) shows the increased number of control messages with the increase in speed of the user from 1 m/sec to 15 m/sec.



(a)

(b)

Fig. 7. Impact of channel scenario of NCADS on (a) the number of dominating APS and (b) the number of received data.



(a)

(b)

Fig. 8. Impact of user speed on (a) the number of control messages and (b) the number of dominating APs.

NCADS and hop count based algorithms have low control message overhead compared to the SSA. This is due to the smaller number of dominating APs for NCADS as shown in Figure 8 (b). The figure shows that the number of dominating APs increases as the user speed increases. In terms of the number of APs, NCADS performs 30.74% better than the SSA at a maximum user speed of 15 m/sec.

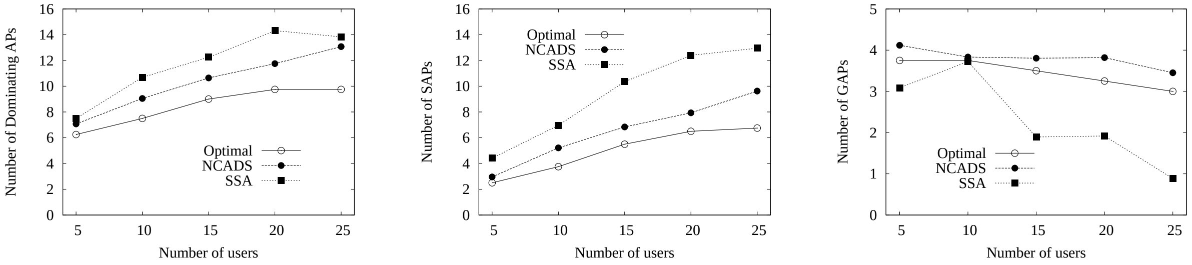
F. Impact on unicast traffic

To see the impact of association algorithms on the unicast traffic performance, we simulate TCP flows working with broadcast traffic. In the simulation, there are 100 broadcast users and 50 non-broadcast users which do not participate in the broadcast session. Each user connects a TCP flow to the user which is randomly selected and there are 150 TCP flows. Broadcast data rate is 100Kbps CBR with packet size of 1024bytes. Figure 9 (a) shows that comparison of TCP throughput (sequence number) achieved with NCADS and SSA. Each point represents a flow. X-axes is the TCP throughput achieved with NCADS and y-axes is the TCP throughput achieved with SSA. There are few flows which have high throughput and, however, throughput of most flows (93%) are less than 1000. However, in Figure 9 (a), we can observe that the throughput of TCP achieved with NCADS is higher than that of SSA. This can be observed more clearly in Figure 9 (b). Figure 9 (b) draws the distribution of TCP throughput with NCADS and SSA by sorting the data of Figure 9 (a). It is clear that TCP throughput of a flow depends on the location and distance of the sender and the destination of a flow. However, we can observe that overall TCP throughput achieved with normalized cost as the metric for broadcast association is 18.7% higher than the TCP throughput achieved with SSA. Since fewer APs are only selected for broadcast with NCADS, the unselected APs can get involved in unicast thereby improving the unicast throughput.

G. Optimality of NCADS

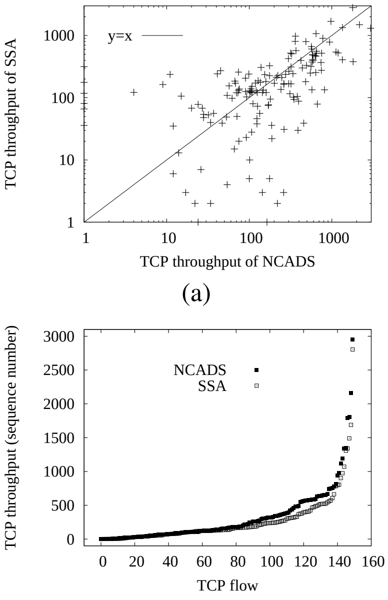
In this section, we evaluate the optimality of NCADS. To calculate the optimal broadcast tree, we use ILP (integer linear program). It takes non polynomial time to calculate the optimal tree of MXCDS. Thus, we use small number of APs (4x4 APs) and users (upto 25 users) to evaluate optimality of NCADS.

Figure 10 shows the average number of dominating APs, SAPs, and GAPs of each SSA, NCADS, and optimal association. As the number of users increases, the number of dominating APs and SAPs increase as well. We can observe that the number of dominating APs of NCADS is closer to the optimal SAP than that of SSA. The NCADS and SSA have 29.8% and 47% more SAPs at 25 users than optimal SAP, respectively. The NCADS and SSA have 25.4% and 29.5% more dominating APs at 25 users than optimal case, respectively. We can observe that the number of GAPs decreases, as the number of user increases in Figure 10 (c). However, NCADS has more GAPs than SSA. The GAP does not forward broadcast packets to its user channel resulting in reduced broadcast load on the channel. Thus, under the given dominating APs, more GAPs decreases broadcast traffic load than smaller number of GAPs. However, the number of GAP is increased, when tree is not optimal. From the Figure 10 (c), we infer that NCADS achieves lower broadcast traffic load on user channel than SSA and, however, has larger broadcast tree than the optimal tree.



(a) Dominating APs (b) SAPs (c) GAPs

Fig. 10. The number of (a) dominating APs, (b) selected APs (SAP), and (c) gateway APs (GAP) with respect to the number of users.



(a)

(b)

Fig. 9. TCP throughput (sequence number): (a) comparison of TCP throughput with NCADS and signal strength algorithm: Each point represents one TCP flow, and (b) the distribution of TCP throughput.

VI. 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], [5]. Several companies including Mesh-networks, Firetide, Strix, and BelAir Networks have various products based on the concept of mesh networking.

In [6], 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 [7], 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 [8]. In [8], 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 [9]. 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. The problem of unbalanced AP load under the signal strength based association is discussed in [10]. In [11], [12], new metrics are studied to select an unicast AP instead of signal strength. Packet error rate and number of users are used in [11] and SNR, AP load, and residual time are used to initiate handoff. However, these work do not consider load-balancing between APs. Recent work [2], [13] has explored the idea of association control to balance the network load and provide max-min fairness among users. The authors in [2] prove that balancing the network load is equivalent to achieving the max-min fairness. In [13], analytical model is formulated for the AP selection as an optimization problem to maximize different utility functions. Although our objective is different from [2], [13], in the presence of unicast flows load-balancing and fairness will make the MXCDS problem more challenging.

The overhead of AP scan is studied in [20]. Authors proposed the *SyncScan* to reduce AP scan overhead by synchronizing short listening period at the users with periodic *beacon* transmissions from each APs. We can reduce the number of channel to be scanned by using *neighborhood graph* idea [21].

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 [14], [15]. The importance of constructing and maintaining an MCDS in an ad-hoc network has spurred research on finding better approximation algorithms [16], [17], [18], [19].

VII. DISCUSSION AND FUTURE WORK

In this paper, we have focused on unreliable data dissemination with the goal of distributing data efficiently. To keep our discussion and study focused, we have ignored various other facets of the problem. We outline some such extensions that we are currently pursuing.

Multiple MAPs: In the more general case, there may be multiple APs with backbone Internet connection. Although we noted in Section II that theoretically the problem is equivalent to the problem with a single MAP, there are some details that need to be worked out for the distributed protocols with multiple MAPs.

Coverage from multiple APs: In the uni-channel and dual-channel scenarios, it is possible to configure the users to receive packets from nearby APs to which they are not associated. In such scenarios the reliability of data reception can be improved while constructing the sub-structure to guarantee coverage from multiple APs for each user. To benefit from multiple coverage in the multi-channel scenario, users need to be equipped with multiple wireless cards.

Supporting QoS: Real time flows typically have various QoS requirements such as end-to-end delay and jitter. Our study in this paper has not considered such QoS requirements.

Reliable data dissemination: For applications such as scientific data visualization, or software upgrades, the data dissemination scheme needs to be enhanced with recovery mechanisms for lost packets. If the fraction of lost packets is significant, the recovery traffic will impact the protocol's performance. Mechanisms to enhance the proposed approaches to handle reliability is part of research.

Ad-hoc communication between users: The construction of the sub-structure did not explore user to user communication. If the users are allowed to receive traffic from other users and if APs are allowed to receive traffic from users, the problem becomes equivalent to multicasting in an ad-hoc network. This may work well in a uni-channel scenario. However, for the bi-channel and the multi-channel scenario with single adapter users, solutions such as [6] can be used to enable simultaneous user operation in infrastructure and ad-hoc modes.

VIII. CONCLUSION

The need for easily deployable and quickly reconfigurable Wireless LAN architectures has led to research on network of APs with wireless inter-connection. In this paper we systematically studied the problem of optimizing the broadcast traffic load in the mesh using the novel concept of multi-association, where users maintain multiple associations for unicast and broadcast traffic. We proposed a distributed approach for associating with the AP for broadcast traffic using a new metric called the *normalized-cost*, that is advertised in the beacons from the APs. Using simulations, we observe that the number of APs handling the broadcast traffic can be reduced by up to a factor of 6 using our approach as compared to the traditional approach of associating with the AP with best signal strength. This results in a heavy reduction in control and data packet overhead, leading to a higher packet delivery ratio. Based on our evaluation, we claim that the concept of multi-association with the normalized-cost metric is highly suited for supporting broadcast services in Mesh-networks.

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