On Construction of the Virtual backbone in Wireless Mesh Networks

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***Abstract* —** This paper deals with the selection of backbone nodes among end-user nodes in the wireless mesh networks. Although current IEEE 802.11 standards does not allow direct client-client or wireless AP-AP communication in the infrastructure mode, new concepts on mesh networks is arising in which all types of wireless links (i.e. AP-AP, client-client and client-AP) can be formed. This will lead to the connectivity between nodes across the entire network region through multi-hopping. In this context, we propose a backbone selection algorithm such that best links and nodes are used with the connectivity being preserved as long as possible. We present the preliminary simulation result of our scheme in terms of packet delivery ratio and energy consumption.

***Keywords* — virtual backbone, mesh networks, ad hoc networks.**

1. Introduction

As a special type of ad hoc networks, wireless mesh networks (WMNs) are becoming more popular in form of community networks, mesh-MAN, wireless mesh LAN etc. A part of WMN is composed of wireless infrastructure that includes dedicated mesh routers (or mesh access points, APs). Rests are the end-user devices (stations) that connect to APs or among themselves in ad hoc fashion for communicating with each other. This type of architecture in which APs and clients combine to form a single network is also called as *hybrid mesh* [1]. APs are generally assumed to have multiple interfaces, higher transmission power and connected to the regular power source. Few of them might also be linked to the external network that acts as a gateway for providing the Internet and other network facilities to the stations. Unlike APs, stations have limited capability in terms of transmission power, network interface and other resources. While some stations like stand alone computers are linked to AC power supply, others might be battery operated, so has a limited life. Nevertheless, all stations are assumed to function as a router and route traffic for other stations or APs in the same network.

In this paper, we exploit the ad hoc networking capability of the stations for extending the coverage of the network region by selectively including them as a part of the infrastructure mesh also called as a virtual backbone. Let us consider the example of campus-wide network, where APs are installed in different points of a campus area. Covering the entire region directly by APs might not always be feasible due to cost of the device, installation difficulty and other terrain features. There can be situation at times when the nearby AP malfunctions and creates coverage holes either due to technical failure or natural disaster. In some cases, hotspots for using the network access changes to different areas where there are no pre-installed APs but there is a sudden increase in the number of users. In such scenarios, we propose to construct a virtual backbone of stations supported by one or more APs so that the efficient way of accessing the network can still be autonomously managed.

Virtual backbone can be defined as the set of nodes composed of stations and APs that are connected with each other through wireless link or the set of links among the same set of nodes. Such set of nodes are also called as the connected dominating set (CDS) [2]. In wireless scenario, virtual backbone is dynamic because, nodes in the backbone can frequently change due to link failures, node failures and node mobility. However, constructing virtual backbone has an advantage of reducing interference, performing efficient broadcast and multicast and also saving total energy by excluding weak nodes (e.g. limited battery powered stations) to participate from the normal operations of the network. Moreover, as the network matures and demand increases, cost of setting up additional APs can also be reduced to some extent. This is achieved by dynamically selecting the stations and by including them as a part of a backbone set instead of installing new AP in the network region.

Several papers provide solutions for constructing virtual backbone in ad hoc networks. Due to absence of infrastructure in such networks, creating backbone node set entirely depends upon the type of heuristics focused on retaining connectivity and maintaining minimal number of backbone nodes in the set. However, some level of redundancy is also desirable in case when node changes its location or fails to function and upset the connectivity and instigate reconstruction. Unlike ad hoc networking case, wireless mesh network as mentioned above consists of a robust infrastructure of interconnected APs. Hence, our approach of constructing a backbone set starts from the dedicated APs which are automatically a part of a backbone set. APs then subsequently select other stations in absence of any backbone nodes in the region for extending the network coverage. We use simple heuristic based on energy and speed of the stations to be as a part of the backbone set. At the end of this process of selection, we will have several stations belonging to the backbone set, which are connected to the AP, either directly or through other stations in the set. Other stations are directly linked to at least one of the node in the backbone set for accessing the network facilities. After this initial setup, we propose a backbone maintenance process, through which the events of nodes moving out of the set, or presence of new stations not connected to any backbone node are handled. The purpose of this process is to autonomously maintain the virtual backbone with less overhead, so that the connectivity and network access remains in act. Additionally, we propose one example of efficiently using virtual backbone depending upon the node capability.

In the following sections we first review the literature on virtual backbone construction both in ad hoc and mesh networks; next we describe our algorithm in detail, than show the performance results and finally provide the conclusion.

2. Related Works

Virtual backbone set construction as described in previous section requires choosing a number of dominating nodes distributed in the network. In this section we investigate the distributed algorithms that use different techniques for constructing MCDS.

Simplest approach of selecting the backbone node is based upon number of neighbors or degree. The node with the higher degree is more susceptible to be the backbone node. This approach has been proposed in [3] by Das et al by running distributed algorithm for finding minimum dominating set (MDS). This algorithm selects MDS at first then constructs the spanning forest and finally creates the spanning tree, which connects the entire graph. This approach has very high time complexity and message complexity. The next approach by Wu and Li [4] first finds the dominating set and prunes off the redundant nodes to shape the connected dominating nodes based on ID and the degree of nodes. This algorithm also runs in two phases where each node first broadcasts to its neighbors. The node selects itself to be dominating if there are no another adjacent dominating node and it has more than two non-adjacent neighbors. Note that the heuristics used by both previous algorithms are same and do not consider mobility, energy or link status information.

Stojmenovic in [5] presents the cluster-based approach for constructing the subset of connected dominating set. Cluster heads here are the node that are not adjacent to each other, hence is called maximal independent set (MIS). These cluster heads are connected through border nodes (nodes that are dependent on cluster heads), which forms the connected dominating sets. Node is selected as a cluster head if its ID or the ordered pair of degree is highest among the other neighbors. The algorithm gives color attributes to the nodes as a black, gray and white for backbone node, border nodes and the node without backbone respectively. Finally the algorithm is converged at the point when all the white nodes are converted to either black or gray. Comprehensive analysis for message and time complexity of these protocols for connected dominating sets is provided in [2].

Similar approach of [5] for constructing maximal independent set is followed by [6] for selecting a subset of the network nodes called virtual dynamic backbone protocol (VDBP). It forms dominating set through intermediate nodes between the dominating nodes that keeps the route information for forwarding traffic. Different heuristic is proposed in this protocol as compared to all previous protocols, that incorporates the link failures. Normalized link failure frequency (NLFF) of the node is evaluated locally and election for the cluster head selects one with the minimum NLFF value. $NLFF_i$ is defined as the ratio of link failures over total number of links for particular node i. There could be likely cases in this algorithm that nodes with no link losses but very few neighbor can be selected increasing the number of backbone nodes [7].

Our approach of selecting the backbone node differs in two aspects as compared to previous works. Firstly, we consider presence of infrastructure of seed backbone nodes that already exist in the network in form of dedicated APs. Secondly, we select the backbone node based upon the local computation of willingness value based on energy and speed of the node and consider the likeliness of this node to act as a backbone node. We run a selection algorithm in the seed node that (s)elect the neighboring nodes to be included in the backbone set.

Most of the research around backbone formation focuses on reducing the size of the backbone nodes that leads to energy conservation however, might also degrade the network performance because of congestion and resource competition [8]. The computation of willingness is motivated from the fact that the reasonable number of backbone nodes would be selected in the network with the higher energy and lesser mobility.

Wireless mesh networking is relatively new field both in research and actual implementation. Recently, some work for optimal placements of APs in the network region have been proposed [9] [10] [11]. These works mainly focus on the infrastructure meshing of APs such that the requirements of the network are fulfilled with minimal interference and cost. Backbone construction algorithm in mesh networks has been explored in [11] but it also only considers dedicated APs for the selection of backbone nodes. In our paper, we concentrate on hybrid mesh architecture where communication occurs between: (1) client-client (2) client-AP and (3)AP-AP. We use APs as a seed that helps in sprouting more backbone nodes that are included in the client mesh. Unlike previous techniques of backbone selection randomly or through neighbor election, the consideration of APs makes our algorithm effective and different in the hybrid mesh network scenario. In the following section we describe our proposed scheme in detail.

3. Proposed Scheme

The main objective for constructing virtual backbone in this paper is to select stations capable of routing and forwarding to be the part of infrastructure of a hybrid mesh network, for providing connectivity to the stations that are in the coverage holes, where dedicated APs cannot directly reach. Moreover, selection of this set needs to ensure the formation of virtual backbone such that it lessens message overhead during unicast and broadcast/multicast of messages from any stations or APs and save energy consumption of limited powered stations that are present in the network. This section is divided into three

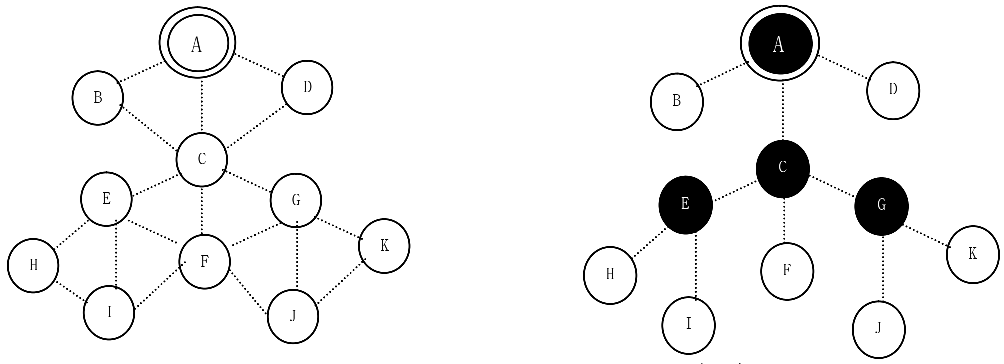

Fig.1 (a) Original Network (b) Network based on backbone selection

parts. First we describe the construction of virtual backbone, next we present different causes for disturbance in the backbone and describe a backbone maintenance algorithm, and finally explain one example to utilize the backbone in the mesh networking environment.

In the first phase, we provide algorithm to select the backbone nodes among the stations. The constructed backbone will be the part of distribution system where stations can connect to communicate with each other. The second phase is required for maintaining the virtual backbone, in case when the backbone node fails to function or moves out of the network due to mobility.

3.1. Backbone Node Selection

Backbone node selection phase starts from the dedicated APs that are already installed in the network region. As soon as the APs are powered up, they are automatically a part of the backbone node set. So, they are also considered as the seed for selecting other stations that shall be included as a part of a backbone node set. The stations inside the network region periodically sends active discovery message called the HELLO messages in the channel to find backbone nodes in the network. HELLO packet is embedded with *node identity, number of neighbors, one hop neighbor-list* and the *willingness value*. Node identity uniquely identifies the station or dedicated APs. The one hop neighbor list and the number of neighbors are asynchronously collected while stations broadcast their HELLO messages. This information might not be precise since the nodes might enter and leave the network region within some instantaneous time period. Willingness value is computed as a ratio of residual energy and speed. A node with high willingness value is more liable to participate as a backbone node and has higher residual energy or a long-term power source and comparatively lesser mobility. Other factors like the link quality, data rate, and number of peers etc., can make this selection process more rigorous, but currently we maintain this simple heuristic to decrease overhead and complexity of the algorithm. However, using any other rigorous metrics is always possible in our scheme, depending upon the requirements of the application. AP receiving the HELLO messages from the stations selects the backbone nodes (or coordinators) among their one-hop neighbors based on their received coverage information and the willingness value. Coverage information is represented by the list and the number of one-hop neighbors of a node and helps in avoiding the selection of multiple coordinators for same set of nodes. The willingness value provides the heuristic for selecting more reliable nodes as a coordinator. Hence, AP selects the most willing and appropriate stations as a part of backbone node and broadcast the new selected backbone node-list to its one hop neighbors. Upon receiving the backbone node-list, if the station is included in the list, it sets itself as a backbone node and executes the same algorithm based on the collected HELLO messages from its neighbors. It further selects the coordinators for the region that does not have a backbone node. From Fig.1 (b) we can see that the selection of coordinators (represented as black node) expands from the node that has bidirectional links with APs. When the network region is covered, further selection of backbone node is stopped ensuring the convergence of our algorithm. If the node is not in the backbone-list which is sent from the coordinator, it associates itself with any of the backbone node which is its direct neighbor. Our backbone construction algorithm requires two timers per each node, one for sending periodic HELLO message and another for updating the neighbor list based on the received HELLO messages.

Now, we illustrate the backbone node selection process with the help of the following example (Refer back to Fig1). Let us consider node A as the dedicated AP already deployed in the network region. Node A listens to the HELLO packet sent from node B, C and D. Assuming that node C's willingness is above the threshold, A selects the node C as another backbone node and send the announcement message with C and itself in the backbone node-list. B and D are not selected in the list as they do not cover any other nodes except the one that is already covered by A itself. Similarly, node C now being a part of a backbone node chooses among node E, F and G to for a coordinator. In this example we see that since E and G covers new nodes, they are selected as a backbone node by node C. Finally, we see that all nodes are either a backbone node or associated to one of the backbone nodes, successfully terminating the process of backbone node selection. The following algorithm is used for the backbone node selection process.

Algorithm1: Backbone node Selection

```
backbone node selection() {
Let BN be a backbone node list
BN = {nodeid};              //insert itself
for all one-hop neighbors i
  if ((willingness_i > threshold) & (coverage(i))
  BN=BN + {i};
}
```

Algorithm2: For checking coverage of the node

```
coverage(i) {
 sort one-hop neighbors based on degree
 if (degree_i > threshold)
     return true;
   else return false;
}
```

Fig 2: Algorithm to select the backbone node.

The Algorithm1 given in the above figure first assigns itself in the backbone node list (BN list), which is either by done by AP or already selected backbone node. It then checks the willingness value and the coverage of each one-hop neighbors (using Algorithm2 where node degree of the i^{th} neighbor is compared with the other one-hop neighbors in the same level) and assigns it to the BN list. Since the BN list computing node knows the 2-hop information, it can more accurately check the set-cover, however it severely increases the complexity of the algorithm. A set-cover algorithm is a well known NP-complete problem [12]. Therefore, we use a simple approach to check the coverage by sorting the one-hop neighbors in the ascending order according to the number of neighbors and select the ones which have more neighbors then the threshold.

3.2. Backbone Maintenance Phase

Second phase of our scheme handles the failure of backbone node and any other station mobility. There can be three possible cases that need to be handled in a different manner. (1) Failure of dedicated AP:- For some reason if the dedicated AP fails to function, stations will try to find another AP in the nearby region. Since the virtual backbone is normally rooted from such device, finding another AP shall restart the entire backbone selection process. (2) Failure of other backbone nodes:- Unlike dedicated APs which might not frequently fail, stations might either be mobile device or under the control of the user and can be manually turned off for e.g. notebooks and PDAs. Whenever this type of backbone node is lost, it is necessary to select another coordinator. This process is initiated by sending HELLO message with an empty co-ordinator field by the nodes seeking for another coordinator in the neighborhood. Any neighbor receiving HELLO message with an empty co-ordinator field re-send its HELLO message to its own co-ordinator. Finally, the backbone node re-runs the backbone selection algorithm locally to decide for a new co-ordinator for the uncovered 2-hop neighbors. If in the other hand, none of the backbone node exists it is thought that the network is partitioned. (3) Third case includes the mobility of the station, which does not directly affect the backbone set. However, if the co-ordinator does not periodically receive the HELLO message from its dependent neighbors for sometime, it assumes that the neighbor is lost and updates its neighbor table according to the timer.

Referring to the Fig1 b again, the first case can be handled if there is another AP nearby any stations. For the second case let us suppose that node E fails to function. When node H and I finds that its co-ordinator is missing, it reset and broadcast their HELLO packet. Node F receives the message from I and sends its own HELLO to C with new coverage information. Node C than selects a new co-ordinator as F and re-broadcast the new backbone node-list. In the third case, if node H fails, node E updates its neighbor information based on its timer.

3.3. Utilization of the backbone node

In this subsection, we illustrate the use of backbone nodes in the hybrid mesh scenario. This example is just a special case of using backbone nodes for efficiently transmitting the data from AP to the particular station in the mesh network. Note that there can be several other ways to perform data transmission depending upon the variety of routing protocols available for mesh networks. Let us consider a situation in which AP receives the data for the particular station from the external network. Upon receiving the data, it can directly unicast it towards that station through the associated backbone node. This type of network structure does not require sending route requests since the path information can be proactively stored in each backbone nodes for the stations. Therefore overhead of control packets for path discovery can be minimized. Similarly, for broadcasting the packets over a mesh network, it will be sufficient to send packets to each connected backbone nodes.

4. Performance Evaluation

4.1 Simulation Model

For the performance evaluation, we implemented backbone node selection algorithm in ns-2.28[13] network simulator, on top of basic-802.11 MAC protocol. We used AODV[14] routing protocol to route packets from a single CBR source to the destination. 100 nodes are randomly deployed on a 1000x1000 grid with one source and one destination placed in two corners of network region. We used two-ray ground channel propagation model.

The algorithm was evaluated based on two metrics for network performance and energy consumption and compared with basic 802.11 without any backbone protocol implemented. In figures (Fig 3 and 4) we denote this as ‘without BSA’ (backbone node selection algorithm) and our scheme as ‘with-BSA’. For evaluating network performance, we computed packet delivery ratio defined as the number of packet received from at the destination to the number of packets sent during the test duration of 300 seconds. The source send fixed number of packet every second (from 5 to 45 packets) that allows constant bit rate (CBR) traffic of 20 to 180kbps. We used the energy model of ns-2 that requires 1.6w for transmitting and 1.2w for receiving. Based on this energy model, we evaluated energy consumed per node for our scheme and basic 802.11. Energy consumption rate is defined as the total amount of energy consumed divided by the number of total number of nodes and simulation time.

4.2 Simulation Results

The purpose of backbone node selection algorithm is to select nodes to ensure the connectivity of the network through backbone nodes. Hence, the nodes that does not belong to backbone node set do not take part in routing data traffic and remain in sleep mode, while source, backbone nodes and the destination remain awake, all the time during data transmission.

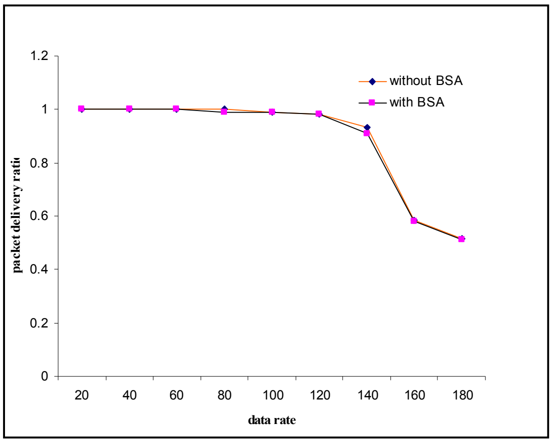

Fig3: Packet delivery ratio

From Fig 3, we see that the packet delivery ratio for our scheme and basic-802.11 is nearly similar. The delivery after 140 kbps decreases sharply due to two reasons. One is due to interference and another most importantly is due to the depletion of node energy. From the traces we can see that number of nodes energy starts depleting to 0 (which was initially 300w uniformly given to all nodes).

Energy consumption of node increases with the data rate because more number of packets is needed to be transmitted and received. In our scheme, not all the nodes remains in a radio-turn on mode thus can conserve the energy waste from idle energy, except for the source, destination and backbone nodes. The continuous use of backbone nodes for delivering all traffic also contributes in the drop of packet delivery ratio in our scheme shown in Fig. 3. However, it is guaranteed that having a virtual backbone conserve significant amount of energy consumption, which

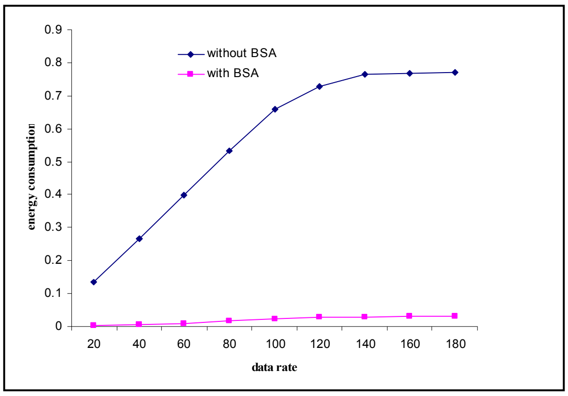

Fig4. Energy consumption

is vital for low power devices present in the network. Fig.4 shows that our scheme can significantly conserve energy compared to the ones that has no backbone construction protocol. In case of basic-802.11 (i.e. without BSA) total network consumption increases rapidly when the data transmission increases, whereas in our scheme, the rate of decrease is lesser since only backbone nodes take part in data transmission and rest of the nodes remains in radio-turn off state if there is no transmission required for them. In Fig.4, the rate of energy consumption declines after 120kbps, because in basic-802.11 scheme, the energy of nodes decreases to zero for same number of nodes and simulation time.

5. Conclusion

In this paper we developed a backbone node selection and maintenance algorithm for mobile stations to be included as a part of infrastructure for wireless mesh networks. Based on simple metrics of packet delivery ratio and energy consumption, we showed that the despite of constructing virtual backbone out of randomly deployed nodes, performance maintained, while total energy consumption of the network is decreased. In the real scenario with more number of dedicated APs and connected power devices deployed in the scene, network shall be more reliable. Moreover, with the virtual backbone, since lesser node participate in communication, lesser will be the interference that shall increase the spatial reuse and the utilization of limited bandwidth. As a part of the future work, we will compare our scheme with other backbone selection algorithm in wireless mesh network scenario.

REFERENCES

[1] I.F. Akyildiz, X. Wang, W. Wang, "Wireless Mesh Networks: a Survey," *Computer Network*, Elsievier, 2005.

[2] P.-J Wan, K. M. Alzoubi, O. Frieder, "Distributed Construction of Connected Dominating Set in Wirelss Ad Hoc Networks", *Infocom '02*, 2002 7.

[3] B. Das, R. Sivakumar, and V. Bharghavan, "Routing in Ad-Hoc Networks Using a Spine", *International Conference on Computers and Communications Networks '97*, Las Vegas, NV. September 1997.

[4] J. Wu and H. Li, "On calculating connected dominating set for efficient routing in ad hoc wirelss networks", *Proc of the 3rd ACM*

international workshop on Discrete algorithms and methods for mobile computing and communications, 1999, pp. 7-1

[5] Stojmenovic, M. Seddigh, J. Zunic, "Dominating sets and neighbor elimination based broadcasting algorithms in wireless networks", *Proc.IEEE Hawaii Int. Conf. on System Sciences, January* (2001)

[6] U. C. Kozat, G. Kondylis, and M. K. Marina, "Virtual Dynamic Backbone for Mobile Ad Hoc Networks," *in Proc. IEEE ICC-2001*, June (2001)

[7] U.C. Kozat and L. Tassiulas, "Network Layer Support for Service Discovery in Mobile Ad Hoc Networks," *Infocom '03* Apr. (2003)

[8] H. Liu and R. Gupta, "Selective Backbone Construction for Topology Control in Ad Hoc Networks," *1st IEEE Int. Conf on Mobile Adhoc and SensorNetwork*, Oct. 2004

[9] P-H. Hsiao and H. T. Kung, "Layout Design for multiple collocated WMNs," *Proceedings of IEEE VTC'04*, 2004.

[10] L. Qui, R. Chandra, K. Jain, and M. Mahdian "Optimizing the Placement of Integration Points in Multi-hop Wireless Networks," *Proc of IEEE ICNP*, Berlin,, Oct 6-8 2004.

[11] H.J. Ju, I. Rubin "Mesh topology construction for Interconnected Wireless LANs," *SECON 05*, 2005.

[12] V. Chavatal, "A Greedy Heuristic for the Set-Covering Problem", *Math. of Operation Research*, Vol. 4, No. 3, pp 233-235, 1979.

[13] http://isi.edu/nsnam/ns/

[14] C. E. Perkins, E. M. Belding-Royer, and S. Das, "Ad hoc on demand distance vector (AODV) routing," draft-ietfmanet-aodv-10.txt, *Internet Draft*, IETF, March 2002.